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Water Resources Commission

Murrumbidgee Division

USE OF AN ELECTROMAGNETIC INDUCTION INSTRUMENT (TYPE EM-38) FOR MAPPING OF SOIL SALINITY

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ABSTRACT

Electromagnetic induction is shown to be a useful technique to map salinity of clay soils of the Riverine Plain of SE Australia. Readings of apparent conductivity are taken in both the horizontal (instrument flat on the ground) and vertical (instrument on its side, meter facing up) mode of the EM-38, of Geonics Pty. Ltd., Canada. These readings are sufficiently accurate to allow mapping of comparative soil salinity.

Calibrations of instrument readings with soil salinity data and moisture profiles are discussed and examples are given of farms surveyed by this technique. It is suggested that the availability of these types of maps is important for farm management decisions, for management of tubewell drainage schemes and soil salinity investigations.

INTRODUCTION

This study was carried out on alluvial clay soils of the Riverine Plain under irrigation near Griffith, N.S.W.

Problems of soil salting usually commence after watertables in irrigation areas have risen to equilibrium levels close to the soil surface. Van der Lelij (1981) showed that 36% of the agricultural farmland near Griffith is now used for rice growing. At the end of the rice growing season, in March, about 48% of the land not used for rice has a watertable within 1 metre and 20% within 0.6 metres from the soil surface.

Accessions to the watertable through ponding on rice fields are high which is partly offset by capillary rise in non rice land and in rice land after ponding. This creates conditions under which land is at risk of becoming salinised. The salting process is aided by lateral transfer of groundwater through aquifer systems and groundwater gradients induced by ponding of water on fields (van der Lelij 1980, 1981).

In order to plan remedial measures for the areas under threat of salting, it is necessary to assess the areas involved and the rate at which the salting processes take place. Mapping of soil salinity is an essential component of a reclamation scheme (Trewhella, 1981). With groundwater pumping from aquifers the quantity of effluent may need to be minimised where disposal problems exist. Pumping should be discontinued where soil salinity levels have declined to satisfactory levels. Soil salinity surveys could assist in management of such systems.

If a salinity survey is to be undertaken it is important to make distinction between the salinity of the topsoil, in which most of the plant roots are located, and subsoil salinity. Northcote and Skene (1972) categorised clay soils into three classes - (i) non saline, (ii) those with surface salinity (Na Cl) over 0.2% (about ECex 4 mS/cm), and (iii) those with subsoil salinity (Na Cl) over 0.3%. They consider that the diagnostic horizon should be located within 1 metre of the surface.

A problem with mapping salinity is the high inherent variability, caused by factors such as micro topography, puff and shelf soil characteristics, which affect water and salt movement. Large numbers of soil samples have to be taken to obtain meaningful averages.

The techniques used for salinity mapping are:

(a) soil sampling and laboratory analysis;

(b) aerial photography and soil sampling;

(c) remote sensing, such as Landsat imagery, and soil sampling;

(d) resistivity surveys using the Wenner electrode array.

Method (a) is very laborious and is usually incorporated as a part of method (b) to reduce the workload. Webster (1981) used these two methods in his assessment of the salinity problems in northern Victoria. Even so, accurate mapping is difficult to achieve and the relation between topsoil and subsoil salinity is not usually depicted. Method (c) is still in the developmental stage (Currey et al. 1981).

The 4-probe resistivity method (d) has been used for experimental purposes. This method uses four steel probes inserted at equal distances into the soil (Wenner array). An electrical current is passed between the two outer probes and a voltage drop measured across the two inner probes, allowing calculation of the apparent soil conductivity. Using this method Shaw (1980) mapped a relatively small area in the Darling Downs of S.E. Queensland and obtained good relationships between soil salt concentrations and resistivity. Loveday (1980), found that the correlation between soil salts measured from samples and the apparent conductivity measured by resistivity was insufficient for predictive purposes. Rhoades (1979), however, developed the methodology for using the four electrode probe and this modified technique is considered of great value for monitoring purposes.

Electromagnetic induction (EM) now provides another method to map salinity. Williams and Baker (1981, 1982) used such a method to map regional salinity in strata to 30 metres deep. They found that areas with relatively high subsoil salts could be easily delineated.

Rhoades and Corwin (1981) compared the EM technique with resistivity methods and found very high correlations. They reported that for measurement of apparent bulk soil conductivity (ECa), both methods give similar results but the four electrode probe gave better results for salinity profile interpretation.

Cameron et al. (1981) compared the Wenner array resistivity method with EM for mapping of salinity. The EM method proved much less time consuming. Correlations between average salinity to 1.20 metres, determined by the saturation extract of soil samples (EC ex), and instrument reading were high.

This paper describes the use and calibrations of the EM instrument EM-38, manufactured by Geonics Pty. Ltd. of Mississauga, Canada and marketed in Australia by Geoex Pty. Ltd. of Adelaide, S.A.

THE EM-38 INSTRUMENT

Principle

The principle of electromagnetic instruments is described in a series of technical notes by McNeill (1980 a, b). An electromagnetic field is induced in the soil and this produces electrical currents in horizontal planes at various levels. These currents produce a secondary magnetic field, which is sensed by the receiving coil. The ratio of electromagnetism received over that sent is a measure of ECa. This is read as conductance in milliSiemens/metre (mS/m) on a meter.

The magnetic permeability of soil particles is nearly that of free space, so that the EM approach exploits the dependence of soil dielectric properties on the ionic concentration in soil water, moisture content and clay content.

The frequency of the EM instrument is important from two aspects. Firstly, the frequency affects the alignment of dipoles in the soil, and this affects the relative contribution to the meter reading of soil moisture and the concentration of soluble ionic species in soil waters. At lower frequencies, the ionic concentration will tend to dominate (Schmugge et al 1980). Secondly, relatively low frequencies are required to achieve a low induction number, which is the ratio of intercoil spacing to electrical skin depth (McNeill, 1980a). Without a low induction number the instrument's response will not be linear with soil conductivity.

With EM instruments soil moisture appears to take the role of providing a medium through which electrical currents, which are related to ionic concentration, can be transmitted. It appears therefore that a threshold level of soil moisture is needed to obtain meaningful results. Below this threshold level the effects of soil moisture on ionic activity would affect the result.

Application

The spacing between the sending and receiving coils is 1 metre for the EM-38 instrument and this determines the depth of penetration of the electromagnetic field. The relative contribution of each depth to the induced EM field varies. Figure 1 shows this for the instrument in vertical mode and for the instrument in horizontal mode. Figure 2 shows the cumulative response.

In mapping of the distribution of salinity across a landscape it is necessary to distinguish between topsoil salinity and subsoil salinity.

Rhoades and Corwin (1981) describe how a salinity profile can be investigated by holding the instrument at various heights and reading the instrument. Regressions of these readings then allows interpretation of the salinity profile.

This technique, whilst useful, requires the taking of several measurements at different heights above the soil surface. Alternatively, the difference between the EM in the vertical and horizontal modes can be used to interpret the relative position of the bulk of conductivity. In the horizontal mode the surface horizons contribute most to the recorded EM value while in the vertical mode it is those from the deeper horizons. For instance, Figure 2 shows that for the Vo reading (vertical mode, instrument at soil surface level) 70% of the signal response comes from beyond 0.5 metres and 30% from within 0.5 metres. For the horizontal mode, these ratios are 40% and 60% respectively. As the instrument reading is an integration of information received from each depth, it follows that:-

$$Vo = 0.3\ S\ top + 0.7\ S\ deep \qquad \ldots (1)$$

$$Ho = 0.6\ S\ top + 0.4\ S\ deep \qquad \ldots (2)$$

where 5 is the apparent soil conductivity

Solving for S top gives:

$$S\ top = 2.33\ Ho - 1.33\ Vo \qquad \ldots (3)$$

If S top (apparent soil conductivity of the top 0.5 m) is a function of a number of factors, in which salinity dominates, then a multiple regression resembling equation (3) should give an estimate of salinity in the top 0.5 metres. This is further discussed in the results section of this paper.

Calibration Requirement

To assess the contribution of soil salinity to the EM readings it is necessary to calibrate the results against actual measurements on soil samples.

Correlation of the conductivity of the bulk soil with resistivity measurements using 4 widely spaced electrodes is good but subject to error when using a closely spaced Wenner array or the EM technique. The error may be due to soil sampling inadequacies rather than meter or instrument response inaccuracies.

Soil salts have been assessed as the Electrical Conductivity of a 1:2 (EC1:2) or a 1:5 (EC1:5) soil suspension, rather than the EC of a saturation extract (ECex). ECex is commonly used to assess the potential reduction in plant yield. However, to assess the quantity of salt per unit volume of soil EC 1:2 is a better estimate. Bulk density and the proportion of less soluble salts are the main factors affecting the correlation between the values. Dry bulk density of subsoils of Riverine Plain clay soils usually varies between 1.4 and 1.6 tonnes/m^3.

A total of 101 sites in the irrigated areas of the alluvial plain, near Griffith, N.S.W., have been examined. Readings were taken in both horizontal and vertical modes, with the instrument at the soil surface level. Soil samples were taken at depths of 0-0.05 m, 0.3 m, 0.6 m, 1.0 m and 1.5 m. The samples were analysed for total salts by measuring EC 1:2, and the soil moisture content. Groundwater samples were taken from those holes that filled overnight and were analysed for salinity.

RESULTS AND DISCUSSION

Soil Factor Correlation

Of the 101 sites used for calibration, 48 showed an increase in salinity with depth, 18 showed a decrease and the remainder showed a uniform profile. The increase was found to be sometimes gradual, and sometimes abrupt, and the depth at which the change occured was variable.

The ranges of salinity and moisture data recorded are in Table 1. Most sites have topsoil salinity below or close to the critical levels for plant growth (EC 1:2 about 1.6 mS/cm), although some values were very high (10 sites, EC 1:2 above 3 mS/cm). At these latter sites sodium chloride is the dominant salt while at the lower salinities less soluble salts such as calcium bicarbonates and sulphates usually dominate (Groenewegen, 1961).

At most sites the Vo reading was higher than the Ho reading, which is consistent with a higher salinity with depth. The correlation coefficients between the salinity values at various depths and the measured Vo and Ho readings are presented in Table 2.

A good correlation between soil salinity at 0.3 metres depth and readings of Vo (r = 0.80) and Ho (r = 0.90) were found. These correlations were improved when sites with gravimetric moisture content above 25% at 30 cm (P.30) were considered. This is demonstrated at table 2. Using the drier sites (P30 less than 26%) only showed a corresponding decrease in correlation. However, apart from this effect no correlation was found between instrument reading and moisture percentage at any depth for these sites.

A good correlation was found between adjacent levels of soil salinity indicating a possible relationship between the origins at each level (Table 3).

A separate study during 1981 showed a dependence of EM on soil moisture values, but this included sites which had soils with subplastic properties and were coarser in apparent texture and were outside the usual range of alluvial plain soils.

From this it would follow that soil salinity surveys should ideally be carried out when the soil profile is moist. This is usually the case at depths of 0.3 m and below in an irrigation area subject to high watertable conditions. Periods of low evapotranspiration such as autumn and winter are probably best.

The salinities at other depths to 1.5 m are also well correlated with Vo and Ho. The vertical mode gives better correlations below 0.6 metres and the horizontal mode within 0.6 metres from the surface, as expected from Figures 1 and 2, although the increases are small.

The correlations of the integrated salinity profile with Vo and Ho (not shown) were not better than with the salinity values at 0.3 metres (S30) alone.

Topsoil Salinity

The following regression, also shown in Figure 3, has been derived to predict the salinity at 0.3 m from readings of Vo and Ho.

$$S30\ (EC\ 1{:}2) = -0.653 - 0.0071Vo + 0.0202Ho\ (mScm)\ \ldots\ (4)$$
$$(r^2 = 0.84,\ sd = 0.48\ mS/cm,\ n = 101)$$

This equation is not unlike equation (3), which is an estimate for the average salinity in the top 0.5 metres of soil. The proportion of variability accounted for (84%) is only marginally better than a prediction from Ho alone (81%) but because of the need to incorporate both topsoil and deep subsoil effects, it is desirable to use both components Vo and Ho, rather than Ho alone. As only 18 sites out of 101 showed a decrease in salinity with depth the results might have been better if the site profile selection had been more balanced.

Since part of the variability not accounted for may have been due to sampling error in the S30 soil samples, measurements of the coefficient of variation of such samples were taken from each of two sites at 30 cm depth in a 5 by 5 pattern within a one by one metre square. It was found that the coefficients of variation (sd/mean) were 18 and 19%.

Soil salinity sampling error therefore accounts for some of the variability not accounted for in equation (4). Other possible sources error may arise from the shape of the salinity profile, meter error, reading errors, moisture variation, clay content variation, presence of gypsum and variation in bulk density.

Groundwater Salinity

Groundwater was found standing in 64 out of 101 holes to 1.5 m depth and the groundwater salinity of samples taken from these holes showed a 0.86 correlation coefficient with Vo, with the regression:

$$\text{GRW SAL} = -4.9 + 0.0778\ \text{Vo (mS/cm)} \qquad \ldots (5)$$
$$(r^2 = 0.74,\ sd = 3.2\ \text{mS/cm},\ n = 64)$$

Equation (5) may be used to describe the salinity hazard where topsoil salinity is not already high. The groundwater salinity is also related to the soil salinity at 100 cm depth ($r = 0.73$), with the average groundwater salinity being 6.3 times the average EC 1:2 measurement (mS/cm). This is about as expected for a saturated soil with a total pore volume of 40% and bulk density 1.55.

The meter measures ECa and not groundwater salinity per se. The ECa relates to the quantity of salts dissolved in soil moisture. It follows that if a proportion of this moisture was drained during reclamation, then the salinity or soil conductivity (ECa) will decrease. The change would depend on the effective porosity, which is the volume removed per unit drop of watertable. For clay soils this value may be as low as 1-2%, for sandy soils in excess of 10%. If the EM technique is used to follow the effect of subsoil drainage it would show greatest sensitivity to the presence of a saline watertable for the more sandy soils.

The subsoil below one metre often contains gypsum, which could affect soil salinity results. This may in part account for the relatively low correlation between Vo and S150. A reading of Vo taken on a mound of crystalline gypsum showed very low conductivity, confirming that the EM instrument senses ionic concentration, rather than total salts.

The clay content of the soils examined was in the range of 35-60%. A separate investigation, not discussed here, showed that the relationship between field textures of these soils and Vo or Ho was not significant.

Soil Salinity Mapping

As suggested by the manufacturer, an area can be mapped almost as quickly as one can walk. Variability in salinity may be high, affecting the number of points at which readings should be taken.

At figure 4 a transect typical for the Benerembah Irrigation District, near Griffith, is shown. It crossed recently drained rice fields, a 3 metre high "soil ridge" of lighter textured clay soils, a natural drainage line (linear depression), three irrigation channels and a prior stream formation in which very sandy, non-saline materials occur.

The variation in readings of Vo, taken at 20 metres interval, is large, nevertheless the principal terrain features stand out. For instance, the low salinity of the soil ridge, the prior stream, and land immediately adjacent to the irrigation channels is noticeable. The higher salinity of the levee soil next to the prior stream, the area adjacent to the linear depression and the farm lane can also be identified.

Salinity maps have wide application for farm management purposes (e.g., rice rotations), management strategies for tubewell drainage, and to assess an area affected by salinity. The sections surveyed showed that whilst a local variation may be quite large, particularly in cases of patchy salting, there is also an overall pattern, which can be found by taking readings on a grid with an interval of 100 metres or more.

The procedure to map soil salinity patterns on a 200-300 hectare farm is based on a 100 metre grid drawn on a copy of an aerial photogrpah, to recognise location in the field. Traverses, which should be normal to any lineal terrain features, are walked and readings taken at 100 metres intervals. Sections may be 200-300 metres apart, but sometimes closer together, depending on the variability found. The Vo and Ho readings are later plotted and converted to estimated EC 1:5 and/or estimated groundwater salinity. Figures 5 to 7 are examples of farms surveyed in this manner. The process takes about 2 days per farm.

In Figure 5 the higher salinity was found mainly at the eastern side of the farm where soils are known to be lighter in texture. There is no surface feature to explain the variation across the farm. At Figure 6 the presence of a slope towards the swamp and the presence of a prior stream to the north explains the salt distribution.

Figure 7 shows the area influenced by tubewell pumping for 15 years. The pattern of salinity was found to conform closely to features shown on the soil map. The light textured soils of the prior stream sediments are leached, by the pumping from the underlying aquifer, but the heavy clay soils are not. The salinity estimated from Em readings of the groundwater showed a similar pattern.

CONCLUSIONS

Easier mapping of salinity would be of considerable benefit to irrigated land management. The electromagnetic induction instrument EM-38 provides this requirement, at least for clay soils of the north eastern part of the Riverine Plain of S.E. Australia. Locations of high and low salinity may be detected, with an indication whether the bulk of the salts is in the top of the soil profile or deeper down. The speed at which these determinations are made allows rapid mapping of salinity, up to 200 hectares per day.

Correlations between measured soil salinity and the apparent soil conductivity (ECa) showed that dissolved salts are the dominant factor affecting the reading. Soil moisture is less important, but a threshold level is needed for the method to be most effective.

Salts need to be in ionic form and the medium has to be capable of passing electrical currents induced by electromagnetism.

A high proportion (84%) of soil salinity variation at 0.3 m depth may be explained by readings of horizontal (Ho) and vertical mode (Vo), but the standard deviation is fairly high, consistent with Loveday's (1980) observation for the Wenner array resistivity technique. This restricts the EM technique to mapping applications, rather than monitoring of salinity conditions at individual sites. The latter requires a higher degree of accuracy.

Estimation of deep subsoil salinity allows the mapping of a salinity hazard. The benefits of subsoil drainage schemes may be monitored as the watertable recedes and soil salt concentrations become less.

TABLE 1. RANGES OF DATA FOR EM-38 INVESTIGATIONS

n = 101

	MEAN	MIN.	MAX.	UNIT
Vo	213	83	449	mS/m
Ho	171	61	460	mS/m
SO	1.34	0.19	11.20	EC 1:2 mS/cm
S30 *1	1.29	0.22	6.10	EC 1:2 mS/cm
S60	1.63	0.28	7.90	EC 1:2 mS/cm
S100	1.85	0.21	8.80	EC 1:2 mS/cm
S150	2.18	0.24	8.10	EC 1:2 mS/cm
PO	17.0	3.5	35.9	%
P30 *2	26.8	9.5	34.4	%
P60	27.6	12.8	34.9	%
P100	27.3	16.8	33.8	%
P150	26.2	20.5	34.2	%

*1 S30 - Salinity at 30 cm depth * 2 P30 % moisture (W/W) at 30 cm depth

TABLE 2. CORRELATION COEFFICIENTS.

	ALL SITES n = 101		MOIST SITES n = 77 (P > 25%)		DRIER SITES n = 44 (P < 26%)	
	Vo	Ho	Vo	Ho	Vo	Ho
S0	0.45	0.67	0.56	0.74	0.38	0.58
S30	0.80	0.90	0.85	0.93	0.71	0.85
S60	0.81	0.81	0.84	0.88	0.70	0.71
S100	0.74	0.66	0.77	0.72	0.64	0.55
S150	0.47	0.38	0.40	0.31	0.62	0.49

TABLE 3. CROSS CORRELATIONS OF SOIL SALINITY PROFILES.

S0	1.00				
S30	0.74	1.00			
S60	0.50	0.80	1.00		
S100	0.23	0.56	0.87	1.00	
S150	0.05	0.30	0.47	0.63	1.00

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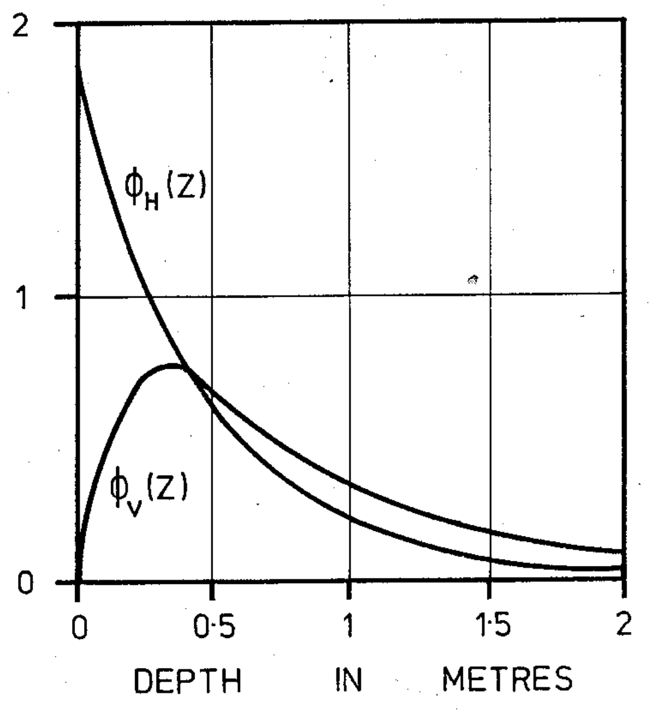
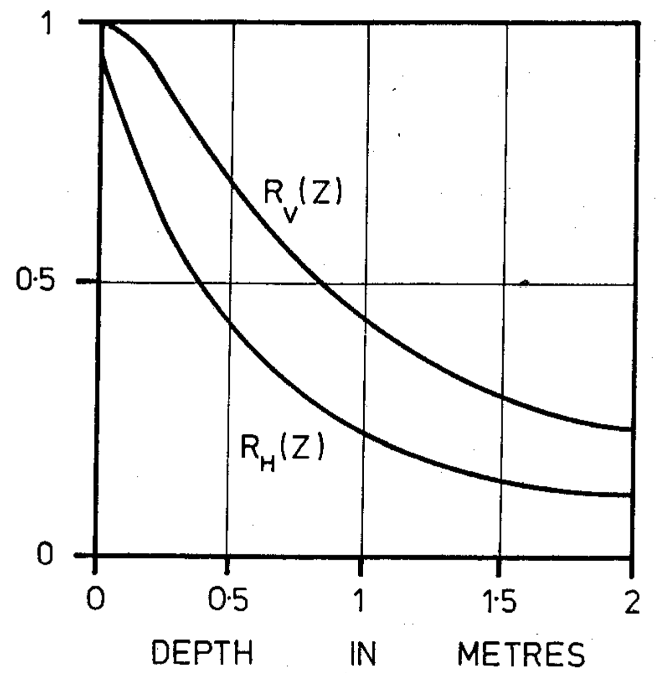
fig. 1

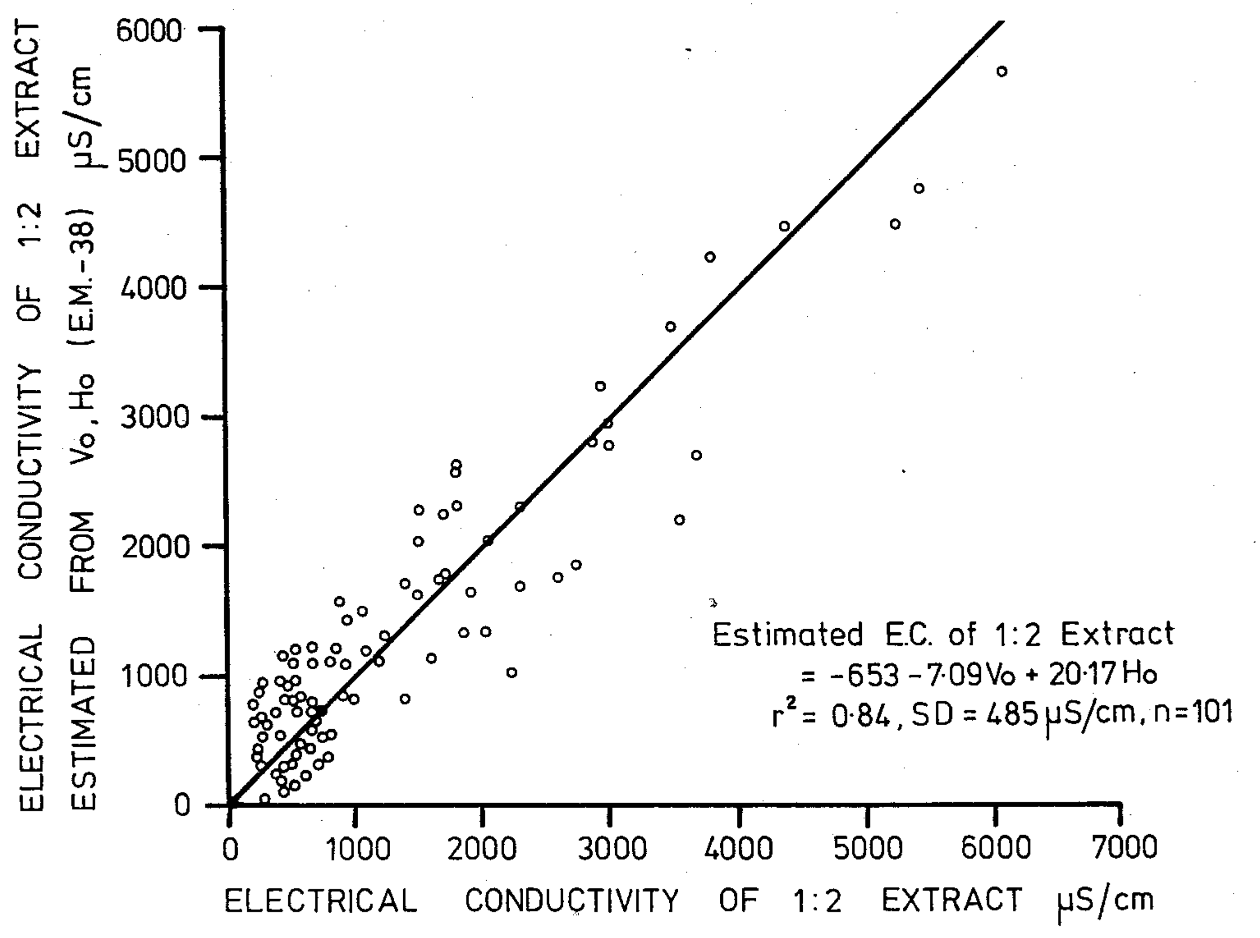


COMPARISON OF RELATIVE RESPONSES FOR VERTICAL AND HORIZONTAL DIPOLES OF E.M.-38 (from McNeil 1980a)

fig. 2

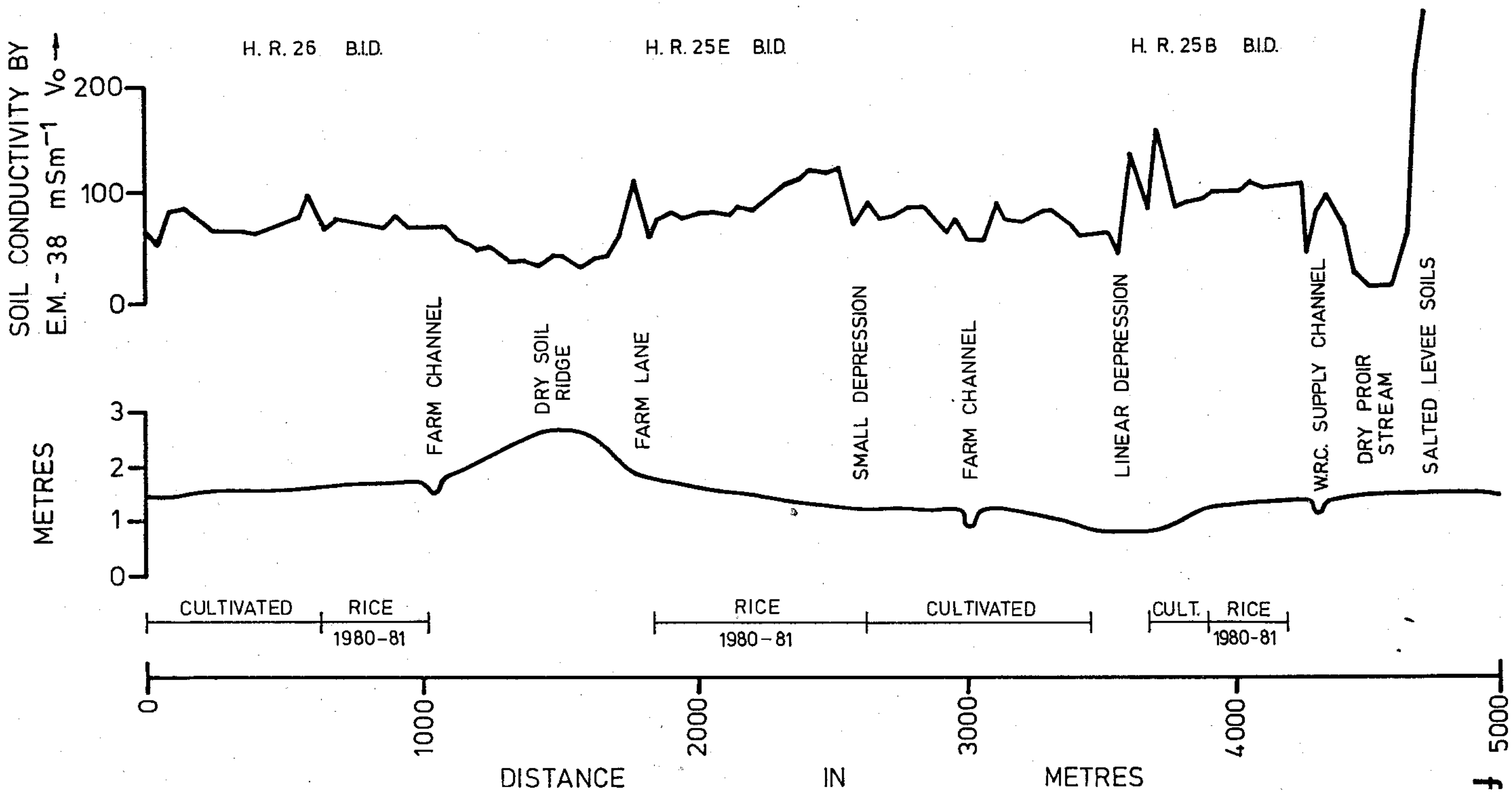


CUMULATIVE RESPONSE VERSUS DEPTH FOR VERTICAL AND HORIZONTAL DIPOLES OF E.M.-38 (from M[c] Neil 1980a)



MEASURED VERSUS ESTIMATED SOIL SALINITY AT 30cm DEPTH USING E.M.-38 INSTRUMENT.

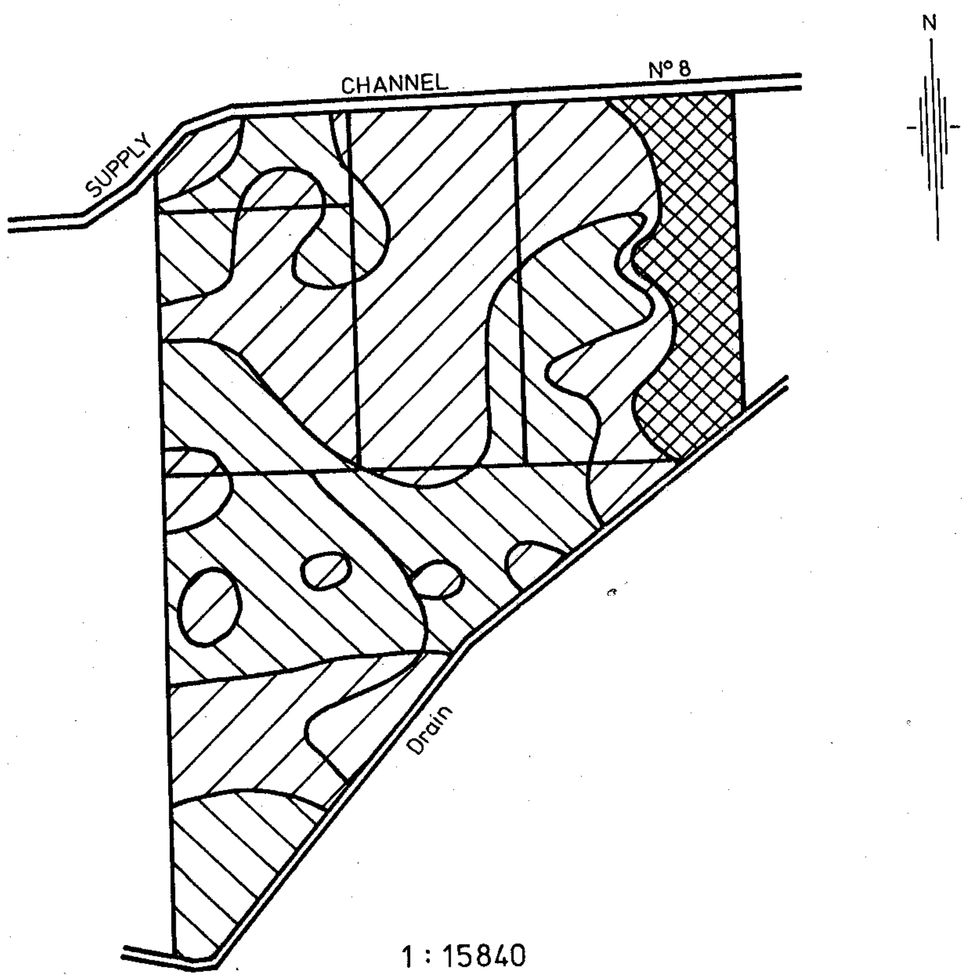
fig. 3



EAST TO WEST SECTION — BENEREMBAH IRRIGATION DISTRICT

fig. 4

fig. 5



1 : 15840

ELECTRICAL CONDUCTIVITY OF 1:5 EXTRACT AT 30cm
ESTIMATED BY ELECTROMAGNETIC INDUCTION.

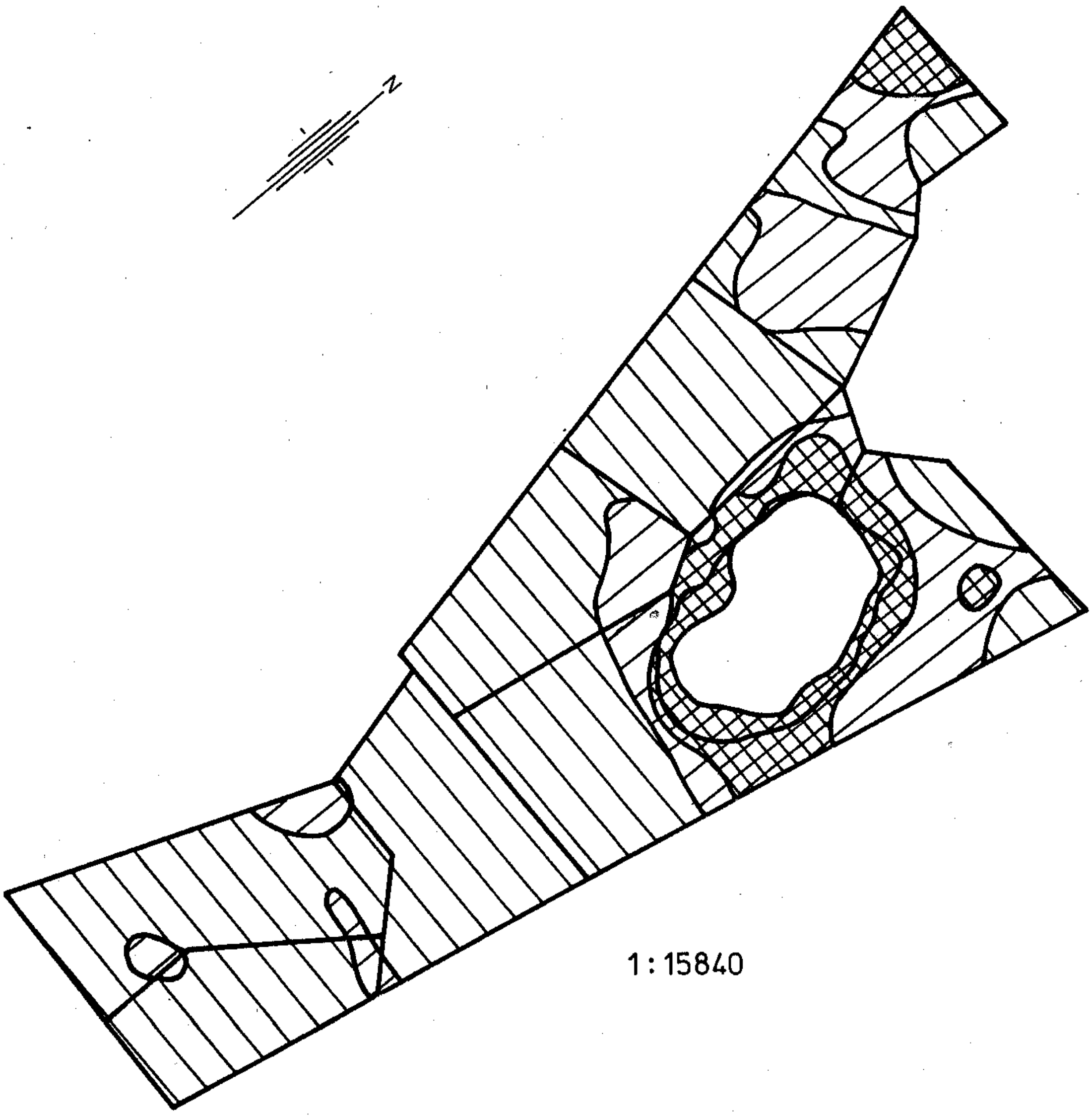
.... LESS THAN 60 mSm^{-1}

.... 60 TO 120 mSm^{-1}

.... OVER 120 mSm^{-1}

H. R. [redacted] BENEREMBAH IRRIGATION DISTRICT

fig. 6



ELECTRICAL CONDUCTIVITY OF 1:5 EXTRACT AT 30cm
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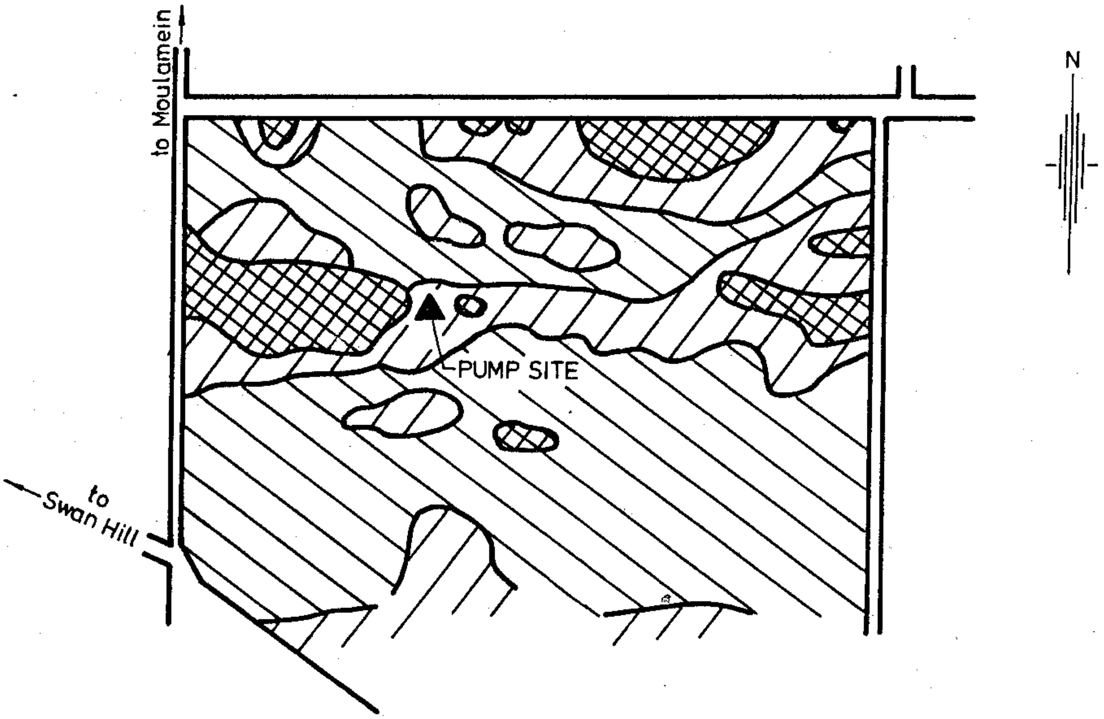
.... LESS THAN 60 mSm^{-1}

.... 60 TO 120 mSm^{-1}

.... OVER 120 mSm^{-1}

H. R. [redacted] BENEREMBAH IRRIGATION DISTRICT

fig. 7



1 : 30000

ELECTRICAL CONDUCTIVITY OF 1:5 EXTRACT AT 30cm
ESTIMATED BY ELECTROMAGNETIC INDUCTION.

.... LESS THAN 60 mSm^{-1}

.... 60 TO 120 mSm^{-1}

.... OVER 120 mSm^{-1}

FARM [redacted] AND OTHERS TULLAKOOL
IRRIGATION AREA.