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RESISTIVITY TECHNIQUE FOR MONITORING SOIL SALINITY

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PREFACE

Soil salinity is of major concern in irrigated agriculture. High soluble salt concentration is often a factor limiting crop production. For proper water management, it is important to have a reliable method of assessing soluble salt concentration and its change with time and space. A common procedure for determining the soluble salt concentration is to measure the electrical conductivity of a saturated soil extract. In terms of the soluble salt concentration under field conditions, this procedure is a rough approximation. Another procedure involves measuring the conductivity of soil aqueous extracts obtained by placing a porous cup in the soil under negative pressure. Such a procedure is adaptable only for wet soils. In order to overcome these limitations, attempts have been made to develop insitu methods of assessing soil salinity.

The National Institute of Hydrology established the Hydrological Investigations Division in 1985 with the major objectives of studying hydrological parameters using geophysical and nuclear techniques. In this report, an attempt has been made to review the present status of in-situ methods, especially resistivity technique, for monitoring of soil salinity.

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SUMMARY

Soil salinity problem in agricultural fields arises due to excessive soluble salts present in the soil, the inorganic electrolytes in the soil solution being the major contributors. Conventionally the salinity of the soil is measured in the laboratory for which soil and/or soil water samples may be collected and analysed in different ways, which involves much labour, time and expenses. For these reasons, a rapid, inexpensive in-situ or remotely sensing method which makes use of the spatially varying soil salinity-bulk electrical conductivity relation, will be of great help in modern agriculture. The resistivity method, which has served the groundwater exploration purposes for nearly a century has been proved to be of much use in establishing the soil salinity-electrolytic conduction relation.

In this report the relationship between conductivity and soil salinity, why and how the soil resistivity is converted into the conductivity values, the advantages of the field techniques over the laboratory techniques are presented. Various methods applicable for in-situ measurement of soil salinity have been briefly discussed. For the bulk soil conductivity sensors, the basic concepts, theory and principles, effects of water content and entrapped air on electrical conductivity-salinity relationship, the various calibration procedures and field application of four-electrode method have been comprehensively reviewed. Light has also been thrown upon the new techniques such as Electro Magnetic (EM) induction method and Time Domain Reflectometry (TDR) method with their advantages and disadvantages outlined. Finally a comparison of various methods for measuring salinity intrinsically, has also been made.

1.0 INTRODUCTION

1.1 General

The soil is the active transition zone between the lithosphere and atmosphere where the various processes responsible for the transformation of the matter and energy occur. This is the base for the agriculture upon which 50% of our country's economy is dependent. The salinisation problem of these soils has been known from historical times.

The soil deterioration occurs mainly due to the very low efficiency of the majority of irrigation systems. The hydrological processes are closely linked to the migration of salts in the soil. Water logging is also a common feature in most of the irrigation systems around the world. Soil deterioration under continuous irrigation can only be prevented by a mix of ameliorative measures under proper management. To combat soil salinity problem the most essential tool is the diagnosing or measurement of soil salinity for which a rapid, inexpensive method is imperative.

In the succeeding sections a brief review of different methods for measuring, mapping and monitoring soil salinity has been made.

1.2 Electrical Conductivity for Soil Salinity Measurement:

The total salt content is the single most criterion for evaluating irrigation water quality. The total content may be expressed either in terms of electrical conductivity (EC) or in units of ppm or m $E_q\ 1^{-1}$. It is important to know the total concentration of dissolved solids rather than any specific ion because it is the total concentration to which most crop plants respond during growth process. Generally, an increase in the salt content of irrigation water will result in an increase in the salinity of the soil solution.

The electrical resistance of the soil water is inversely proportional to the amount of electrolytes that is present. The relationship is not exact, but, is close enough for all practical purposes. The reciprocal of the electrical resistance is the conductance and this is directly proportional to the electrolytes present in the soil water.

Most soil minerals are insulators. Conduction, therefore, occurs through the interstitial water which contains, especially in saline soils, appreciable amount of dissolved electrolytes. In addition, soil may conduct current via the exchangeable cations that reside on the surfaces of the charged soil minerals which are electrically mobile to various extents. Surface conductance may be appreciable in soil with high clay content which contain little soluble salt but appreciable amounts of exchangeable sodium. This latter contribution to electrical conduction is expected to be negligible in saline soils because of the greater abundance and mobility of soluble electrolytes than exchangeable cations. Hence, the conductivity of a saline soil should depend primarily on the interstitial electrolyte solution, on the effective soil porosity, and on the degree of water saturation. Therefore, for a given soil type, one should be able to correlate soil conductivity with soil salinity, especially if such measurements are made at a constant water content.

Conductance is measured in mhos (from reciprocal ohms); for comparative purposes results are reported as electrical conductivity (EC). Often the EC is replaced by K or σ, but, the meaning is identical. As in most cases conductivities are much less than one mho/cm, it is conveniently presented as milli mhos/cm (mmho/cm) or micro mhos/cm (μmho/cm).

1.3 Determination of Soil Salinity

The proper management and treatment of saline soils requires an accurate knowledge of the concentration and extent of soluble salt in such soils. Visual observations of soils and of plants growing on them are rarely adequate for diagnosing salinity problems, except in extreme cases, since salinity may reduce crop yields as much as 25% without visible symptoms (U.S. Sal. Lab. Staff, 1954). To evaluate the effects or success of various management programs and treatments, it is desirable to monitor soil salinity levels periodically. When such repeated evaluations are compounded with the extensive requirements of a single sampling period, the expenditure of effort and time on soil sampling procedures with present day methods are increased proportionally. For the above reasons a method for determining soil salinity directly in the field without recourse to sampling, subsample manipulation and analyses would be invaluable both for practical and research applications.

The estimation or determination of soil salinity can be made from measurements:

a) On aqueous extracts of soil samples,

b) On samples of water, per se , obtained from the soil,

c) insitu, using either buried porous salinity sensors which imbibe and equilibrate with water or four electrode probes, or time domain reflectometric electrode systems, and

d) remotely using electromagnatic induction electrical conductivity sensors.

Ideally it would be desirable to know the concentrations of the individual solutes in the soil water over the entire range of field water content and to obtain this information immediately in the field. No practical methods are available at present to permit such determinations, although determinations of total solute concentration (i.e., salinity) can be made with insitu or remotely using electrical signals from appropriate sensors. Such immediate determinations are so valuable for salinity diagnosis, inventorying, monitoring and irrigation management needs that in many cases they supplant the need for the more conventional analytical procedures. If a particular solute concentration is needed then either a sample of soil or of the soil water is required. However, the latter method require much more time, expense and effort than the instrumental methods. Thus a combination of the

the various methods minimizes the need for sample collection and chemical analysis, especially when monitoring solute changes with time and characterizing large fields or projects. The choice of the method depends upon the purpose of the determination, the number and frequency of measurements needed and the accuracy required.

1.3.1 Laboratory methods

Soil salinity measurements can be made in the laboratory either on aqueous extracts of soil samples or on soil water samples. In the method of measuring salinity on aqueous extracts, soil samples are collected from the field, processed, saturated soil pastes are prepared and analysed for ion concentration, electrical conductivity and osmotic potential. Electrical conductivity of the extract is expressed as EC_e or σ_e and are determined at a temperature of 25°c and the relation between EC_e and ion concentration (c) is $c = EC_e \times 12$ at the higher concentrations and $c = EC_e \times 10$ at the lower concentrations (Meiri and Levy, 1973). As saline soils are usually extremely variable in their salt content and as factors like climate, microtopography, soil structure and texture, and agricultural management influence the salt distribution, a good sampling program is important for obtaining representative data. The method of preparation and analysis of saturated soil paste have been described in a Hand book (No. 60, U.S. Salinity. Lab. Staff, 1954).

Salinity, sodicity and individual solute concentrations of soil water samples may be determined using conventional methods of chemical analysis. A major task is to find a practical way of obtaining the samples of soil water, without unduly altering their composition in the process. Methods of soil water sampling may be classified as follows: displacement; compaction; centrifugation; molecular adsorption; suction and pressure membrane extraction. Of these, only suction extraction is commonly used for monitoring purposes (Rhoades, 1984). Displacement method has been decribed by Adams (1974); a combination displacement/centrifugation method has been developed by Mubarak and Oslen (1976, 1977); adsorption techniques are described by Shimshi (1966) and by Tadros and Mc Garity (1976), and centrifugation techniques have been developed by Davies and Davies (1963), Yamasaki and Kishita (1972), Gilman (1976) Dao and Lavy (1978) and Kinniburgh and Miles (1983). Soil water samples are collected insitu by means of vacuum extractors (Reeve and Doesing, 1965; Meiri and Levy 1973). Ceramic extraction cups are also used (Rhoades, 1978).

Though the Laboratory analytical methods are reliable, the main drawback is the time requirement and the expenses involved.

1.3.2 Field methods

The proper management and treatment of saline soils requires knowledge of the concentration and distribution of soluble salts in the soil. The proper management of irrigation projects, furthermore, requires information on the time trends in soil salinity status and water table depths. To date, the only reliable diagnosis of salinity has required the analysis of soil sample brought into the laboratory, although less precise measurements may be made in the field with portable field kits (Bower, 1963; U.S.S.L. staff, 1954). In either case the many samples required demand much time and effort (Sayegh, et. al.,1958). Furthermore, to evaluate the effects of farm management practices and assess time trends, soil salinity levels must be monitored periodically. The extensive time and labour requirements for sampling adequately with conventional procedures tend to reach the point of impracticality (Rhoades, 1984). Besides salinity, water table trends should be monitored in irrigation projects. The four electrode soil salinity techique can be used to great advantage for these needs in diagnosing and monitoring (Rhoades and Ingvalson, 1971; Rhoades, 1976). The method measures soil salinity and depth to water table without requiring soil sampling, laboratory analysis, or numerous expensive in-situ devices. It is rapid, simple, inexpensive and practical.

The basic concept and principles of this method have been first put forward by Rhoades and Ingvalson (1971). Since then, the method has been used for detecting the encroachment of saline water bodies into soil (Halvorson and Rhoades, 1974), for mapping saline soils and subsurface materials, for monitoring reclamation of saline soils and for monitoring salinity in irrigation projects (Rhoades, 1976). In addition, new techniques have been developed for obtaining the necessary calibrations (Rhoades et. al. ,1977; Rhoades and Van Shilfgaarde, 1976).

2.0 REVIEW

2.1 Insitu Soil Salinity Measurement

In soil salinity measurements, for many purposes all that is required is knowledge of the total salt concentration of soil water, or total amount of soluble salt in the soil. The following four kinds of sensors capable of measuring total soil salinity or the total salt concentration of the soil water are in use, each with its own advantages and limitations.

i) Porous matrix sensors which imbibe and maintain diffusional equilibrium with soil water and measure its electrical conductivity directly;

ii) remote electromagnetic induction soil electrical conductivity sensors;

iii) four electrode soil electrical conductivity sensors (probes), and

iv) time domain reflectometry and insertion parallel guide electrodes.

The last three measures the electrical conductivity of the bulk soil σ_a or EC_a, which depends primarily upon the content and salt concentration of the soil water. Such sensors are being increasingly used in salinity assessment and management where immediate information and frequent monitoring of soil salinity in field situations are often required.

2.2 Porous Matrix Imbibition Sensors

The electrical conductivity of soil water σ_w, can be measured insitu by means of a buried imbibition electrical conductivity cell (Kemper, 1959; Richards, 1966; Oster and Ingvalson, 1967). The basic principle underlying the measurement is that soil water is imbibed into the porous matrix (usually ceramic) which contains embedded electrodes permitting the measurement of electrical conductance (L). σ_w is related to L by a cell constant. It is assumed that diffusional equilibrium has occured between the water imbibed in the porous matrix and the soil solution and that the water content in the porous matrix element is constant as the soil wets and dries. Commercially available units contain thermistors for measuring soil temperature (σ_w is referred to a standard temperature (25°C))and special housing and spring systems for enhancing contact between the porous matrix element and the soil.

Proper sensor operation requires that the porous matrix element should achieve a reproducible and fixed water content as the soil wets and dries, that the calibration curves should be stable with time for both the conductance element and the thermistor, and that salt diffusional equilibrium should exist between the water in the soil and that in the porous matrix. Even though the conductance element of the commericial unit made of fine pored ceramic with a bubble pressure of 15 bars, L decreases to some degree with decrease in the matrix potential (Ingvalson et.al., 1970; Aragues, 1982). It has been estimated that at -1 bar the decrease is about 10%. Consequently, sensor readings obtained in drier soils are not accurate (Rhoades, 1984). Upon rewetting, sensor conductance persumably returns to that of calibration.

Special sensors have been made from fine pore sized glass which remains saturated to matrix potentials of -20 bars (Enfield and Evans, 1969; Reicosky et. al. 1970). However, the attachment of lead wires to the electrodes stresses the glass in a manner which results in cracks, and the glass matrix sensor is thus too fragile for general use. The conductance of the porous element, L (d s), increases linearly with increasing electrical conductivity of the water in the porous matrix, persumablly, σ_w (d s m^{-1}). A typical calibration relationship has been given by Rhoades, (1984) as

$$L = 0.2 + 0.1\ \sigma w \qquad \ldots(2.1)$$

When σ_w is less than about one d Sm^{-1}, the relationship between L and σ_w is curvilinear i.e., L approaches zero as σ_w approaches zero. It has been reasoned that this might be due to the result of multiple pathways for electric current flow in the matrix -along the solid surfaces, in the solution and across surface/solution boundaries -hence the changing current flow pathway within the ceramic as σ_w changes.

The calibration characteristics of the conductance element and the thermistor have been found to change frequently over a period of several years (Wood, 1978). Since typical changes in thermistor calibration changes produce errors in σ_w of about 10%, imbibition sensors must be individually calibrated and should be recalibrated frequently if accurate results are needed (Rhoades, 1984). This requires their frequent removal and replacement. Use of replicates will reduce these calibration-shift errors.

Another limitation of imbibition salinity sensors is their slow response times. Response time is dependent on ion diffusions between the solution in the porous matrix and that in the soil (Wesseling and Oster, 1973). Response time depends on the thickness of the porous matrix conductivity cell, the diffusion coefficients of salts in soil and in the conductance element, and the fraction of the element surface in contact with the soil. The total response time in solution is about 10h under optimum conditions. However, response times in soils can be considerably longer (Wood, 1978). The response time increases with decreasing water content (Aragues, 1982).

The primary advantage of the porous matrix salinity sensor is its ability to continuously monitor σ_w at a selected location over a relatively long time. Sensor readings can be made as often as needed, limited only by limitations in response time that a greater time must elapse before a salinity sensor equilibrates with a soil solution. This has limited the usefulness of salinity sensors where soil salinity changes rapidly. Wesseling and Oster (1973), theoretically studied and examined in the laboratory, the response of salinity sensors under conditions of rapidly changing salinity. Oster and Ingvalson

(1967) utilised the salinity sensors to measure the Electrical conductivity of the soil solution insitu in a soil-plant system during irrigation cycles. The estimated accuracy of the measurement was about ±0.5 mmho/m.

Austin and Oster (1973) developed an oscillator circuit which enables automatic reading of salinity sensors, and is useful in automatic data collection. Similar data cannot be obtained with soil sample because of the spatial variation in salinity and changes caused by sample removal and dilution with water to obtain an extract.

Though the imbibition sensors are useful for monitoring salinity at a given location, they are not as useful for monitoring salinity on regional scale because soil is heterogenous, and volume sampled is small. Moreover, they are not suited for diagnostic or inventory purposes, because of lack of portability and relatively long response time.

The four electrode and EM induction devices are more suitable for such purposes.

2.3 Bulk Soil Conductivity Sensors

Soil salinity and soil water electrical conductivity can also be determined from measurements of bulk soil electrical conductivity made using the four electrode method, electromagnetic induction, and time domain reflectometry. Commercial equipments are available for all three methods. Using the TDR method the dielectric constant, ε and EC_a of the soil are determined from the time a voltage puls takes to pass through the soil, as guided by two parallel rods inserted in the soil, and the attenuation of the voltage respectively. With electromagnetic induction method, a flow of current in the soil is induced by the imposition of a primary electromagnetic field. An induced, secondary electromagnetic field is developed within the soil in proportion to σ_a thus permitting the latter to be measured. With the four electrode method, the resistance to current flow is measured between one pair of electrodes inserted in the soil while electric current is passed through the soil between another pair of electrodes. By employing appropriate geometry constant which varies with electrode configuration it is possible to determine soil electrical conductivity σ_a, from the resistance measurement.

The four-electrode conductivity technique can be used to great advantage for these needs in diagnosing and monitoring soil salinity (Rhoades and Ingvalson, 1971 Rhoades, 1974). The method measures soil salinity and depth to water table without requiring soil sampling, laboratory analysis, or numerous expensive insitu devices. It is rapid, inexpensive and practical.

2.3.1 Basic concepts

The well established four electrode Wenner method for the earth resistivity measurements was shown useful in assessing soil moisture by Kirkham and Taylor (1950), where they faced the problem of soil salinity which they reasoned as the main obstacle to the development of accuracy. Later, Shea and Luthin (1961) proved that the resistivity measured by this method can be used to determine the soil salinity. They modified the equation (Jeans, 1933)

$$\rho = 4 \P aR \qquad \ldots(2.2)$$

by applying a factor (n) to compensate the limitation of boundary condition imposed by the proximity of the soil surface

$$\rho = \frac{4 \P a R}{n} \qquad \ldots(2.3)$$

Where ρ = resistivity of the infinite medium.

a = electrode spacing

R = measured resistance

And for evenly spaced electrodes (Wenner, 1916)

$$n = 1 + \frac{2}{(1+4\lambda^2)^{\frac{1}{2}}} - \frac{1}{(1+\lambda^2)^{\frac{1}{2}}} \qquad \ldots(2.4)$$

Where $\lambda = b/a$

b = depth of electrodes beneath the soil surface.

Shea and Luthin also showed that if "b" is large in comparison to "a" then $\rho = 4\P aR$, Since "n" approaches unity and that if "b" is small in comparison to "a" then $\rho = 2\P aR$, since "n" approaches the value of 2.

Though this soil resistance itself could be used for assessing soil salinity, Rhoades and Ingvalson (1971) suggested that it will be convinient to convert the resistance data to soil conductivities. They gave several reasons for this; one is that there is a direct relationship between soil conductivity and soil salinity while an inverse relationship exists between soil resistance and soil salinity.

They calculated the apparent soil conductivity from the measured soil resistance by various methods as given below.

a) $ECa = 1/2 \ \P \ aR$ ...(2.5)

b) $ECa = 1/2 \ \P \ aRs$ ...(2.6)

Where, $Rs = R_x \times R_b/(R_x - R_b)$

Rs = resistance of soil solution

Rx = resistance of the exchangeable cations.

Rb = measured bulk soil resistance.

This modification was made by assuming that the soil solution and exchangeable cations affect the passage of current in the soil.

c) Plots between 1/R and a (as proposed by Narayan et. al. 1967) were made. Asbolute E Ca values were determined from the slope of such lines since $1/\Delta R = 2\pi EC_a \cdot \Delta a$.

This method assumes that a non-homogeneous material may be approximated by a series of resistors in parallel. The "a" value corresponding to any change in slope of such plots is supposed to represent the depth in the profile which separates material of differing conductivity.

d) This is a curve matching procedure and is suppbsedly the most scientifically justifiable method for determining depths to layers of differing resistivities and their corresponding values. This method is generally used for geophysical purposes.

Rhoades and Ingvalson (1971) converted a set of resistance data into soil conductivities by the above four methods. They found that this conversion of data made soil EC values nearly single valued for a given level of soil salinity, irrespective of inner electrode spacing which was not true with the use of resistance values. This conversion of data from resistance to conductivity corrects for differences of geometry of current flow as the depth of current penetration is increased and this was the reason given by them for using ECa, rather than resistance itself, for assessing soil salinity with depth in the profile.

Soil may conduct current through : (i) The interstitial water which contains dissolved electrolytes and

(ii) Via the exchangeable cations that reside near the surfaces of charged soil particles and are electrically mobile to various extents. The relative contributions of exchangeable cation to electrical conduction is small at high solution concentrations (Rhoades, 1976; Shea and Luthin, 1961). However, at low concentrations they may play an important role in determining bulk soil electrical conductivity (Nadler and Frenkel, 1980). The actual soil conductivity depends also on the water content, chemical composition of soil solution and exchangeable ions, percent clay in the soil and the interaction between the bulk and exchangeable ions. It should also be noted that the volume of the soil under measurement, entrapped air, soil properties such as texture and saturation percentage also play an important role in determining salinity from bulk electrical conductivity (EC_a).

Electrical conduction in saline soils is primarily electrolytic. As most soil mineral are insultators, electrical conductivity in most saline soil occurs primarily through the pore water which contains dissolved solutes. The contribution of exchangeable ions is constant in saline soil and is relatively small. The EC_a is also affected, especially in structured field soils by the number, size and continuity of the soil pores.

The dependence of EC_a on the electrical conductivity of the soil water (EC_w) on volumetric water content (θ), on soil pore geometry (T) and on surface conductance (EC_s) is given by (Rhoades, 1976),

$$EC_a = T \ EC_w \theta + EC_s \qquad \text{...(2.7)}$$

Where T is an empirically determined transmission coefficient dependent on θ , above a threshold value as

$$T = a\theta + b \qquad \text{...(2.8)}$$

With constants a and b determined by linear regression. Both T and EC_s are properties associated with thesoil solid phase, where as EC_w and θ are properties of the soil liquid phase. The T and EC_s are related to soil type; hence for a given soil type.

$$C_a = f(EC_w, \theta) \ T, EC_s$$

or

$$EC_a = A_1 \ (EC_w \cdot \theta) + B \qquad \ldots(2.9)$$

Where $A_1 = T$ and $B = EC_s$. If EC_a measurements are made at reference or calibration water content,

$$EC_a = f\,(EC_w)\,\theta\,, T, EC_s$$

or

$$EC_a = A_2 \ EC_w + B \qquad \ldots(2.10)$$

Since, for any given soil the electrical conductivity of a saturation extract (EC_e) is related to EC_w,

$$EC_a = f(EC_e)\,\theta\,,\ T,\ EC_s$$

or

$$EC_a = A_3 \ EC_e + B \qquad \ldots(2.11)$$

This soil salinity can be determined by measuring EC_a at reference soil water content using a calibration in form of the above equation (2.11) for a given soil type. For irrigated soils, EC_a measurements should be made after irrigation when the soil water content is at field capacity (Rhoades and Ingvalson, 1971) as this water content is sufficiently reproducible to establish practical calibrations (Wilcox, 1965). Under dry land conditions EC_a values preferably be measured in early spring on fallow land in order to take advantage of relatively uniform conditions when the soil is near field capacity (Halvorson and Rhoades, 1974). Normal variation in water content under these conditions will not interfere with salinity diagnosis. Calibration between EC_e & ECw and ECa have been success-fully determined for many soils under conditions of field capacity water content and used subsequently to diagnose and monitor salinity (Rhoades, 1978).

Several studies tried to evaluate the effect of soil water content on bulk soil conductivity. Shea and Luthin (1961) followed salt movement in a soil profile by permanently installing four - electrode units at various depths in the soil. They adjusted columbia fsl soil (fine sandy loam), artificially packed in a large tank, to various levels of salinity and water content by leaching with water of different salinities and imposing different suctions on the porous ceramic base of the tank, respectively. Errors upto about 14% could be obtained in salinity appraisal by them, without correlation for water content. The suction range they studied corresponded to from saturation to field capacity, i.e. wet conditions. When the water content decreased by drainage, salt was removed along with the water and the salinity of the remaining soil water remained nearly constant. In the normal field situation, the soil will generally be at field capacity or lower, and water losses by evapotranspiration will increase the soil water salinity. This interaction must be recognised in the field applications of the four-electrode technique.

Several studies were attempted to measure water content under field conditions using small, fixed spacing, four-electrode resistance devices (Edlefson and Anderson, 1941; Kirkham and Taylor, 1950). Edlefson and Anderson

(1941)observed that very small changes in soil water content, near the permanent wilting point, caused comparatively large changes in electrical resistance. Kirkham and Taylor (1950), using a small four-electrode device that spanned about 21 cm and could be inserted into the soil upto about 10 cm, compared the measured soil EC with gravimetric water contents and obtained a correlation coefficient of 0.83 but with high variability. In neither case was the dependence of the soil EC upon the water content determined in sufficient detail.

Rhoades, et. al. (1976) examined the functional relation between soil EC, water content, soil water salinity and pertinent soil properties and developed a simple capillary model to quantify these interactions assuming that liquid phase and surface conductivities (via exchangeable cations) behave as resistors in parallel. They studied EC in the laboratory as a function of water content (θ) and in-situ water conductivity (EC_w). They collected undisturbed cores of four soil types fsl,vfsl,l,cl using lucite column inserts which were tapped for later insertion of electrodes. They equilibrated the cells with waters of a desired EC_w and using a pressure membrane appratus, adjusted to a desired water content. They calculated the values of EC_a for each EC_w equilibration from measured four-electrode resistance and an appropriate cell constant. They evaluated the relationship between the EC_a and EC_w using the equation (2.7) given by Rhoades (1976). They suggested that such calibration eliminates the need to limit the four-electrode technique to soil that are not at a particular reference water content, like field capacity. It was shown that the contribution of the surface conductance is constant for the whole range of soil solution concentrations. This contradicts the conclusion reached by shainberg et. al.(1980) who showed that the equation (2.7) is valid only at a certain solution concentration. Below a limiting concentration the EC_a-EC_w relation becomes non-linear.

Nadler and Frenkel (1980) studied the soil electrical conductivity (EC_a) using the four-electrode method as a function of soil water electrical conductivity (EC_w) and water content in six soil types. They concluded that a linear relationship is valid only at salinities greater that 4 mmho/cm and that at very low salinity levels the contribution of surface conductance was not constant and had a higher contribution that EC_w to the measured EC_a.

They also suggested a method for calculating the partial contribution of surface conductance to EC_a as a function of EC_w and clay content, including a correction for dependence on the soil water content. The relationship given by them is similar to the one given by Rhodes et. al (1976) [eqn (2.7)] and is given below:

$$EC_a = \frac{1}{F} \left[EC_w \frac{\Theta\ act}{\Theta\ sat} + \delta\lambda\ C_a{}^{2+} - Q_v \right] \quad ..(2.12)$$

The ratio O_{act}/O_{sat} is the ratio between the volumetric water content of the soil at the time of measurement and its volumetric water content at saturation, δ is an empirical ratio between equivalent conductance of clay counter ions to the maximum equivalent conductance, $\lambda\ Ca^{2+}$ is the ion mobility of Ca^{2+}, Q_v is the volume concentration of clay exchange cations (meq/cm^3)., and 1/F is taken as equivalent to θT. The empirical parameter δ was evaluated by Shainberg et. al. (1980).

The effect of the varying water content (i.e., departure from calibration water content) on salinity determinations depends on whether or not salt loss occurs with loss of water. During drainage and immediately following an irrigation, salt loss occurs as the water drains to field capacity; EC_a is very sensitive to changes in θ during such times. After rapid drainage ceases following an irrigation and the soil is at field capacity, further major losses of soil water in cropped soil occur through evapotranspiration. At such times almost all of the salts in the water taken up by the plant are prevented from entering the plant by the root membranes and are left behind in the remaining water. Like wise no salt is lost through evaporations hence, the salt concentration (or electrical conductivity) of the remaining soil water is increased proportionately as θ is reduced by evapotranspiration. Because of this inverse proportional relationship between EC_w and θ, the product ($EC_w \times \theta$) found within a given soil volume at field capacity will not change appreciably as θ is reduced. Hence $EC_w . \theta \simeq K$ (a constant). As θ decreases below field capacity as a result of evapotranspiration, EC_a will show an approximately linear decrease according to the relationship given below , (Rhoades, 1984).

$$\Delta EC_a = [K] \; a \; \Delta(\theta) \qquad \ldots(2.13)$$

For typical soils the values of a and b in the equations (2.8) and (2.13) suggested by Rhoades (1976) and Rhoades (1984) respectively are such that the error in EC_a is not large with normal variation in θ from that of calibration of irrigated soil after rapid drainage has occured. Experimental data supporting these conclusions about the effect of $\Delta\theta$ on ΔEC_a during and following an irrigation were given by Rhoades et. al. (1981).

Frenkel et. al. (1983) studied the effect of entrapped air on EC_a by flushing CO_2 in the soil column which was leached by solution of differnt salinities, in the laboratory. They found that a small amount of air could cause a drastic change in the slope of the EC_a - EC_w calibration curve, which is the most important value of the calibration. They considered that this was due to (i) water content less than θ sat and (ii) the influence of θ on the transmission coefficient T. They also found from the data published by Rhoades et. al. (1976) that a small change in θ will produce a large change in T, as $T = f(\theta)$ They concluded that even under conditions where $EC_w . \theta$ is constant, as θ decreases, there will be a change in T which will cause a decrease in the slope of the calibration curve.

2.3.2 Bulk soil electrical conductivity-salinty calibrations

As discussed in the earlier sections the bulk electrical conductivity of the soil depends upon its texture and structure, its moisture content & the salinity of the soil moisture (Van Hoorn, 1980). If the salinity is the only variable factor, a relation can be established between the electrical conductivity and soil salinity. The bulk electrical conductivity-soil salinity calibrations may be obtained by three different ways depending on the availability of equipment, time and the desired accuracy (Rhoades and Ingvalson, 1971; Rhoades, 1976; Rhoades and Halvarson, 1977). The calibration method used most frequently to date has been to determine EC_a and EC_e, respectively at numerous field locations to obtain a suitable range in soil salinity and sampling population to establish an EC_e - EC_a correlation.

As soil salinity varies from spot to spot and with depth in saline soils, numerous samples have to be taken from below and within the centre two thirds of the spread of electrodes to obtain an EC_e value representative of the 0 to 1 m soil depth, a soil volume of about $3m^3$ must be adequately sampled, necessitating a fair amount of work if an accurate calibration is desired. Further the EC_a - EC_e calibration is limited to whatever EC_e range is found at the time of sampling. This calibration is popularly known as conventional calibration technique and also as soil sampling method (Halvarson et. al. 1977).

A more accurate calibration technique was developed by Rhoades et.al. (1977), using specially built four-electrode cells. Undistrubed soil cores are taken from field sites representative of the soil type for which the calibration is desired using lucite column sections as inserts which fit the dimensions of the corer. The four-electrode cells are similar to those developed by Gupta and Hanks (1972) for their laboratory studies on the influence of water content in the soil conductivity measurements. The EC_a of the undisturbed soil sample is determined by inserting stainless steel electrodes into the soil to a fixed depth, after slipping out the soil from the corer into the four-electrode cell and by using an appropriate resistance meter to measure the resistance. Prior to the actual measurement, appropriate cell constants (K) are determined for the four-electrode cells by filling them with known EC-solutions and measuring their resistance using the following equation (Rhoades et. al., 1977)

$$K = EC_{25} \quad R_t \quad \frac{1}{f_t} \qquad \ldots(2.14)$$

Where EC_{25} is the electrical conduction of the reference solution at 25°c, R_t is the measured resistance of the reference solution at its determined temperature t, and f_t is the appropriate temperature factor for correcting resistance and conductivity data as given in the Hank Book No. 60 of the U.S.S.L. staff (1954). Then the EC_a is calculated from the measured resistance, soil temperature and established cell constant (K) by using the following equation.

$$EC_a = k \quad \frac{f_t}{R_t} \qquad \ldots(2.15)$$

If there is an insufficient natural salinity range in the field, the measurement of EC_a shall be facilitated by leaching the four-electrode cells with solutions of desired salinities and then adjusted to desired water content. Alternatively, if there is sufficient range in salinity in the field which is at the desired water content, usually field capacity, three or four undisturbed soil samples can be collected in four electrode cells from field spots ranging from low to high salinity, and their EC_a determined. In either of the above two calibration approaches, the whole soil sample on which the EC_a was determined is then removed from the cell for determination of EC_e. This method maximizes the accuracy of the calibration because exactly the same bulk volume of soil is used for measuring both EC_a and EC_e. Rhoades et. al (1977) have shown that the four-electrode cell calibration technique yields essentially the same EC_a-EC_e calibration as that achieved with the conventional field method discussed previously but is more reliable as it results in higher correlation coefficients and lower standard error of estimate in the $EC_e = f(EC_a)$ linear regression.

The simplest method of EC_a - EC_e calibration make use of the soil EC-probe to determine the EC_a value of small bodies of soil which have been adjusted in the field to give a desired range of salinities. To accomplish this salinity adjustment, saline waters should be impounded in long column sections driven into the soil. The infiltrated water bring the soil beneath the impounded area to the desired range of salinity. When the soil has drained to about field capacity i.e. the reference water content, soil samples are removed from the salinized body of the soil with a commercial soil sampler. Then the soil EC-probe should be centred in the hole and the EC_a value corresponding to the depth interval shall be determined. After removing the probe the soil sample shall be removed and can be used to determine the EC_e, which shall be then used to establish the EC_a-EC_e relation for the soil type and reference water content.

Rhoades (1976) recommended this method, for this calibration procedure is by far the quickest and enables one to obtain satisfactory calibration. Numerous satisfactory field calibration have been obtained for many soil around the world and very similar calibrations have been obtained for soils of similar textures. (Rhoades and Ingvalson, 1971; Halvorson and Rhoades, 1974; Rhoades, 1976; 1980a; Halvarson et.al. 1977; Yadav et.al. 1979; Loveday, 1980; Van Hoorn, 1980; Nadler, 1981; Bohn et.al. 1982).

Rhoades, J.D., and J. Van Shilfgaarde (1976) concluded that calibrations between EC_a and EC_e were similar for soils of similar field capacity (water holding capacity) and that the calibration parameter (slope and intercept of EC_e VS EC_a linear plots) could be estimated from soil texture.

For a given level of soil water salt concentration EC_a will increase with θ (Rhoades, 1976). For routine uses EC_a V_s EC_e (essentially a dilution of EC_w) calibrations have been established for soils at near field capacity water content. That different soil types will have different calibration slopes is expected, as at field capacity, they will have different θT values because of their differences in texture and porosity. The intercept parameter of linear EC_a V_s EC_e calibration lines is related to EC_s and hence to the amount and mobility of exchangeable cations as shown in the equation (2.7) given by Rhoades (1976) and as discussed by Rhoades (1978) and Shainberg et.al. (1980). Thus the calibration intercept is expected to be related to soil texture and clay content.

Rhoades (1981a) showed that the slopes of the EC_a V_s EC_e calibration plots can be predicted from the soil saturation percentage or field capacity and from silt plus clay percentage and that the intercept can be predicted from clay percentage. He concluded that EC_e V_s EC_a calibrations can be approximated from texture classification as soil texture is related to all these soil properties. These findings permit the prediction of EC_a V_s EC_e calibrations for soils when calibrations are unavailable or unwarranted.

Nadler (1982) made use of the soil moisture release properties for calibration purposes. He developed a procedure to calculate the ratio between electrical conductivity of solution (EC_w) and of bulk soil (EC_a) as function of water content (θ) . F - ratio was used to calculate soil solution salinity from measurements of bulk soil electrical conductivity. An empirical approach was adopted to obtain the F - θ relationship by superimposing the complete suction water retention relationship on two

F-θ measurements at the same θ values. It was opined that this procedure improves the insitu soil solution salinity measurements and is especially useful if soil salt and/or soil water content are low.

Halvorson et.al. (1977) studied the soil salinity-four-electrode conductivity relationships for soils of Northern Great Plains (U.S.A). They investigated the influence of soil texture, soil geographic location and parent material, and calibration method on EC_a-EC_e linear relationship. They found that the clay content affected linear regression line slopes than other factors. Their conclusion and recommendations can be summarised as follows:

i) Compared with conventional field calibration methods, four-electrode cell and EC-probe calibration methods for establishing EC_e V_s EC_a calibration requires much less work and fewer samples, were easier to use and resulted in very similar calibration curves.

ii) The four-electrode cell and EC-probe calibration methods are more accurate as the EC_e values are obtained from nearly the same volume as EC_a values.

iii) To minimize the effects of texture and soil water content differences during EC_e V_s EC_a calibration procedures, they recommended leaching the desired soil type with salt solutions and using either the four-electrode cell or EC-probe calibration method to obtain needed EC_a data to correlate with corresponding EC_e values from collected soil samples, as it would minimize the number of samples needed for calibration purposes and result in reliable information.

iv) Geographical location or soil parent material had little influence on the EC_e V_s EC_a correlation.

v) The EC_e V_s EC_a correlation, is affected predominently by soil texture or clay content.

vi) A calibration made for a Soil texture class at one geographic location will apply to another location having a similar range in soil water and salinity unless if the soil within a texture class vary greatly in clay content, water holding capacity and surface conductivity.

2.3.3 Four-electrode method

In the conventional determination of soil conductivity, four electrodes are placed in a straight line with equal distances, a, between them. This configuration of electrodes is called Wenner array (Fig-1). The electrical resistance across the inner pair is measured while a constant current is passed between the outer pair. The apparent bulk soil conductivity (EC_a) is calculated from the following equation (Rhoades 1976).

$$EC_a = \frac{1000}{2\pi a} \frac{f_t}{R_t} \qquad \ldots(2.16)$$

Where R_t = measured resistance at temperature t.

f_t = factor to adjust the reading to a reference temperature of 25°C.

a = inter-electrode spacing.

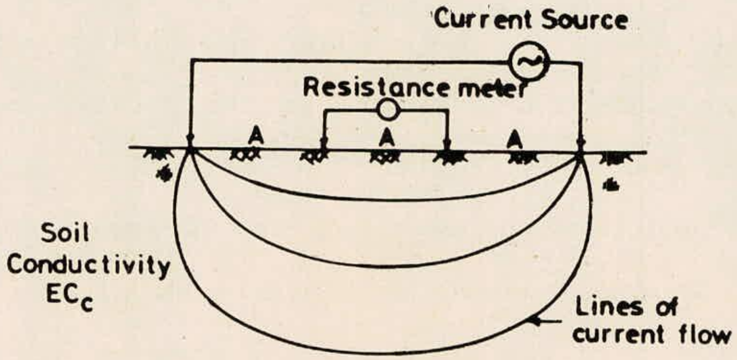


FIG.1. SCHEMATIC OF FOUR ELECTRODE SET UP IN WENNER ARRAY AND LINES OF CURRENT FLOW (AFTER RHOADES, 1976)

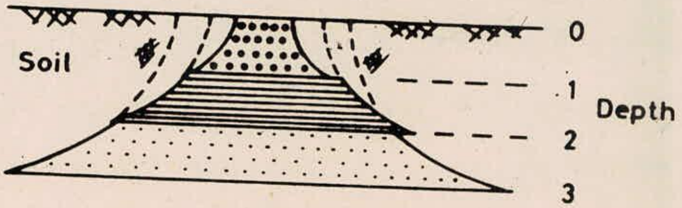
Details on design, construction and techniques on use of four-electrode sensors and equipment have been reviewed (Rhoades, 1976; 1978). The basic equipment needed for four-electrode soil conductivity determinations are very few. The specifications for the equipment involved such as electrodes, resistance meter, etc. have been outlined by Rhoades (1976).

In 1971, Rhoades and Ingvalson first showed that measurements of large volumes of soil (such as the whole root zone) can be made using a portable array of electrodes inserted into the soil surface and appropriate electric current source and resistance meter. In their study measurements were made and they tested the method in a series of field plots which were adjusted to various levels of salinity. They declared that the method was simple, rapid and eliminated the need for taking soil samples and making laboratory analyses for assessing soil salinity. They concluded that soil salinity can be assessed under field conditions from soil conductivity measurements made under standardised conditions. These conditions required that a relationship between soil conductivity and soil salinity should be established for the soil types in question, at a known water content. For this, they recommended that soil conductivities be measured just following an irrigation as in their opinion this water content is reasonably reproducible and is frequently available throughout the year.

Information about electrical conductivity within discrete soil depth intervals also can be obtained by this method. Halvorson and Rhoades. (1974) calculated the soil electrical conductivities of discrete soil depth intervals (EC_x) from EC_a values obtained with successively increasing inter-electrode spacings. The following equation (2.17) derived by modifying the equation given by Hummel (1931), was used:

$$EC_{(a_i-a_{i-1})}=[(EC_{a_i}.a_i) - (EC_{ai-1}.a_{i-1})]/(a_i-a_{i-1}) \ldots(2.17)$$

Where, a_i represents the depth of sampling and a_{i-1} represents the earlier depth of sampling. The equation is based on the assumption that the depth to which conductivity is measured is equal to the interelectrode spacing and the stack of soil electrical resistances of a sequence of soil layers is assumed to behave like resistors in parallel (Fig. 2; Barnes, 1954). They examined the use of soil conductivity values calculated from resistance measurement obtained with the four-probe Wenner electrode configuration to identify potential saline seep areas and estimate soil salinity in the fields which were located in the Northern Great Plains, U.S.A. The tests were conducted in the month of May and August, i.e. the periods in which the soil profile, in that location, will be at field capacity. They reported that significant correlations were obtained in those periods between apparent soil conductivity (EC_a) and electrical conductivity of saturation extracts (EC_{se}). They also declared that plots of EC_a v_s a



Development of Resistivity Layers with increasing Depth

FIG.2. MODEL OF THE SUCCESSION OF LAYERS DEVELOPMENT WITH INCREASING A SPACING AND CALCULATED AS EC_x (AFTER BARNES, 1954)

or EC_a values alone can be used to identify potential saline seep areas. They concluded that the method can aid in identifying potential or encroaching seep areas before condition become too saline and that the remedial measures can then be applied in and around the potential seep and recharge areas to intercept and use some of the subsurface water, thereby avoiding a salinity problem and further development of saline seep.

Measurements of small volumes of soil, where more precise information on the depth distribution of soil salinity is required, shall be made using the soil electrical concutivity probe, also called portable four-electrode salinity probe, developed by Rhoades and Van Shilfgaarde (1976). In their attempt to illustrate the utility of the probe, they compared electrical conductivities (EC_a) measured with the salinity probe in the field with soil sample salinities measured in the laboratory (EC_e) for the six most extensive soil types found in Wellton-Mohawk Irrigation and Drainage District of south-western Arizona, U.S.A.

Though the salinity probe can be used to accurately determine soil salinity of a discrete depth interval in the soil profile than the surface postioned four-electrode equipment, it does have some of the same limitations as soil samples and in-situ salinity sensors. The imitations being removal of soil with a soil sampling tube, although no analyses are required. Moreover it responds to a relatively small localized region within the soil. EC_a readings determined with the surface positioned Wenner array are better suited to provide an index of bulk soil salinity. Whereas, the salinity probe is particularly well adapted when more precise information on soil salinity variation with depth or within small localized soil regions is required . Thus ,the two techniques complement each other (Rhoades and Van Schilfgaarde, 1976). The Wenner array and salinity probe method are most useful for diagnosing and mapping soil salinity. Though the portable salinity probe was designed for field salinity appraisal, salinity monitoring requires repeated measurements be made over an extended period of time at the same location. For such uses, implanted probe offer certain advantages, such as repeated measurements at the same spatial position in the soil can be obtained, and complications which may arise from repeated coring of access holes in the sampling area are minimized (Shea and Luthin, 1961). For these reasons, an inexpensive four-electrode unit known as burial type probe has been developed by Rhoades (1979).

A multi-electrode probe (MEP) was designed by Nadler et.al. (1982) which, as reported by them enables repeated measurements at the same spot, especially in a field where soil texture may change over small distances. The probe consists of a rod with fifteen staineless steel rings and a switching box for selecting different four-electrode combinations which will be of much use in inhomogenous soils. For single-point monitoring purposes, these burial type units are much useful (Rhoades, 1984).

Rhoades et.al. (1981) made use of a special data aquisition equipment along with four-probe sensors. In their study they proved that measurements of bulk soil electrical conductivity (EC_a) can be used to schedule irrigations, monitor the depth of water penetration and obtain a desired leaching fraction. They suggested that some irrigation systems could be automated with burial type four-electrode probes to schedule and control irrigations. In their study scheduling of irrigations was based upon neutron-probe readings, pan evaporation, and the ratio of drainage to irrigation volumes. Electrical conductivity (EC_a) measurements were made throughout several irrigation cycles using a specially designed data logging system.

Special meters have been developed for the four-electrode salinity probe by Austin and Rhoades (1979). This compact, low cost circuit for reading four-electrode salinity sensor was developed by them to replace commercially available instruments for measuring soil electrical resistance by four-electrode method which were designed for geophysical purposes and were large. Performance of the circuit was evaluated and was reported to be agreeing within 2% of values determined with the commerical meter.

Gupta and Hanks (1972) developed a four-electrode cell for laboratory studies on disturbed soil samples. This was developed by them when they required some method that would be capable of measuring salinity in place in a system where rapid water movement occured. The time-lag was the main draw back in salinity sensors. Though the four-probe system of measuring electrical conductivity of soil eliminates the time lag error, in their opinion it introduced the problem of calibration (as influence of water content). However, the main advantage was that the method was useful for measuring the salinity status of water flow studies in soil column where water content can also be measured simulataneously.

In their method they measured the soil salinity, for checking the validity of the method, either in saturation extracts, EC_e, or in 1:5 soil water extracts, EC(1:5), rather than the water contents at which the four-electrode conductivities were determined. The EC_a increased markedly as the water content or the salinity increased, as shown by their data. Their data fit equations of the form $EC_a/EC(1:5)$ or $EC_a/EC_e = a\theta + b$. Where "a" and "b" are contants determined from the regression analysis and θ is the water content. Though the data were informative these are subjected to some limitations as listed by Rhoades et.al. (1976) viz.

1. They were obtained in artificially packed samples and cannot be applied to field soils,

2. They were related to soil water salinities determined at water content other than those at which EC_a values were measured and

3. They were not related to such variables as surface conductance and tortuosity.

For undisturbed soil core samples, Rhoades et.al.

(1977) developed a four-electrode cell similar to that of the one developed by Gupta and Hanks (1972). They reported that, using undisturbed, soil filled four-electrode cells simplified the obtaining of soil salinity-soil electrical conductivity calibrations applicable to field use. The greater accuracy of the cell calibration was probably due to using the same volume of soil to determine both EC_a and EC_e. They recommended this method as they believed that it would advance the adoption of soil electrical conductivity determination for determining soil salinity.

To assess soil salinity from measurements of the soil electrical conductivity (EC), two factors must be known (Nadler, 1980):

i) The relation between the two parameters for the soil under measurements.

ii) The volume (or depth) of soil under measurement, especially when the Wenner-array technique is being used in the field to measure EC.

Rhoades (1976) has concluded that the volume of soil measured in a single EC_a determination is about πa^3, where "a" is the inner electrode spacing in the Wenner method. But according to Rhoades and Van Shilfgaarde (1976) the volume of soil measured by the Wenner method is equal to $5\pi a^3/6$. Rhoades (1978) has given that while salinity probe is used the volume of the soil under measurement is about 2350 cm^3.

Nadler (1980) doubted the validity of these techniques and devices, if these were used to measure EC within volumes of soil smaller than the minimum needed, as implied by the data of Gupta and Hanks (1972). He studied the effects of the electrode spacing and current density on the determination of the electrical conductivity of the soil solution in the laboratory. He found that the depth sensed by a Wenner Configuration would be deeper than the inner electrode spacing for most field situations and especially where there are large variations in conductivity (due to salinity or water content) with depth. He also suggested that the laboratory calibration of the salinity probe should be done in a volume of about 2.5 litres or greater as the volume sensed by this method is greater when the water content is low. He theoretically discussed the ratio between apparent resistivity and real resistivity of a soil layer as a function of (i) layer thickness/electrode spacing ratio (ii) the soil layer thickness and resistivity of an underlying layer,& (iii) horizontal distance of different medium from the current electrode. From the theoretical discussions and laboratory experiments he found tnat horizontal and vertical variabilities may affect field resistivity measurements obtained by the Wenner Configuration. One may approach either a horizontal boundary where a sharp drop (or increase) in resistivity occurs (e.g. a saline seep or a stony medium) or a layered soil without being aware of it. In such cases changes in measured resistivity may be related to variation in electrical conductivity levels with depth. He concluded that since the salinity probe volume requirement is lower than the Wenner Configuration, horizontal and vertical variabilities are considerably less significant.

The depth to which average soil EC_a is measured with the horizontal array method may be varied by varying the spacing between the electrodes. The effective depth of measurement of soil EC_a is about equal to one third of the spacing between outer electrode, provided the soil is essentially uniform in physical properties to this depth. A single calibration, such as that appropriate to the surface soil cannot be applied to the subsoil if its texture is appreciably different than that of the surface soil. For such cases, Rhoades (1984) recommended the use of the four-electrode salinity probe to determine the soil EC_a in each discrete stratum or depth interval. Salinity can then be interpreted from calibrations appropriate to the soil type of each stratum.

2.3.4 Electro Magnetic (EM) induction method

The typically appreciable variability of soil salinity combined with its dynamic nature makes salinity characterisation or monitoring of large field a labour intensive task if conventional soil sampling methods are used. The EM sensor is well suited for measuring and monitoring soil salinity of large areas because it provides a remote, rapid measurement that can be made almost as fast as one can traverse the area.

To date, most of measurements of bulk electrical conductivity have been made using four-electrode techniques. All of these systems require contact between the soil and electrodes; four individual electrodes must be inserted into the soil surface and individual leads of wire strung to them from the generator/meter to make the measurement. With the salinity probe, a soil core must be removed from the soil profile and the probe inserted into the cored hole. Although these procedures and equipment are practical, measurements of EC_a without soil contact or coring holes through the soil profile could be faster and eliminate poor electrode-soil contact problems that sometimes are encountered in dry soils.

In electromagnetic techniques current can be supplied to the soil through induction, thus no electrodes are needed and it is possible to take continuous readings along a transect. Inductive electromagnetic techniques are widely used in prospecting and generally employ a transmitter and a receiver coil. When the transmitter coil is energised circular electrical currents are induced in the soil. This induced current flow is proportional to the electrical conductivity (EC) of the conducting body. The current flow, in turn, creates a secondary electromagnetic field, the strength of which is proportional to the current flow and hence to the EC of the conductor. EC of the conductor can be related to the magnitude of the induced secondary EM field on the conductor. Thus EC_a can be measured without probe-soil contact using inductive electomagnetic techniques with separated transmitter and receiver EM coils and appropriate circuitary.

The main obstacle to its use in the past for salinity measurement was that the value of EC_a sensed by the EM unit is the result of the cumulative contributions of the individual soil conductivities of the various strata above a certain depth in the soil (analogous to EC_a as determined using the horizontally positioned four-electrode array). Furthermore, the relationship between depth and the relative contribution of the different depth intervals to the overall EM reading depends upon the orientation of the transmitter coil with respect to soil surface (Rhoades and Corwin, 1981)

For porfiling EC_a from EM measurements practical techniques have been developed to over come the above mentioned difficulties (Rhoades and Corwin, 1981; Corwin and Rhoades. 1982). The series of equations which gives the actual EC_a within a given soil depth interval from measurements of the apparent bulk soil electrical conductivity made with the magnetic coils of EM instruments, positioned first horizontally and then vertically, for the soil depth increment X_1-X_2, fit to the form (Rhoades, 1984)

$$EC_{(X_1-X_2)} = (K_1 EM_H - K_2 EM_V)/K_3 \quad \text{...(2.18)}$$

Where EM_V and EM_H are apparent bulk soil electrical condutivities measured electromagnetically at the soil surface in the vertical and horizontal positions, respectively; X_1-X_2 is the soil depth increment; K_1, K_2, and K_3 are appropriate constants for the depth increment.

De Jong et.al., (1979) reported the usefulness of the method appreciating its ability in sensing continuously along a transect which can be of great use in selection of sampling sites. They also measured the soil salinity using the electrical conductivity of saturated paste extracts (EC_e, mmhos/cm) and insitu using the four-electrode method with the Wenner array (EC_{aw}, mmhos/cm) for verification purposes. For the test they made use of factory calibrated, commercially available instrument EM-31, which had a fixed inter-coil spacing of 3.7 m with the coils arranged coplanar. They found the measurement depth to be twice when the coils were parallel to the earth than when they were perpendicular. They also reported that the depth of measurement was greater when the electrical conductivity of the soil increases with depth and less when the soil is more conductive than the subsoil. They assessed the variation in the apparent electrical conductivity (EC_a) with depth by varying the height of the instrument and the coil orientation relative to the soil surface. They reported that soil texture has a pronounced effect on the relationship between EC_a and EC_e. All the preliminary data obtained during their study led them to conclude that electromagnetic induction techniques have considerable potential for providing a rapid and easy method for detecting and mapping saline areas.

Rhoades and Corwin (1981) have shown that bulk soil electrical conductivity, EC_a, of increment depth levels within the soil profile can be obtained from above ground electromagnetic measurements of apparent electrical conductivity on artificially salined pachappa soils, using multiple regression co-efficients which relate electro-magnetic conductivity to EC_a. This method required the solution of a complex system of simultaneous equations. They used the EM-38 instrument of M/s Geonics. Four electrode measurements of EC_a were also made simultaneously using both salinity probe and Wenner array device. After the comparison of the results obtained by different methods, statistical relations were established between EC_a - depth values and and the EM reading obtained at various heights above the ground. They concluded that appropriate calibrations are apparently needed for different geographical areas, but such calibrations can be relatively easily obtained using the salinity probe. They advocated for the EM method, that once the calibration were made the device can be used to collect the data much more rapidly than with other techniques.

Corwin and Rhoades (1982) made an attempt to measure the soil salinity in three different areas of Southern California by EM method using EM-38 device. Direct measurements of EC_a were also taken using a four electrode salinity probe. The results of the EM method were calculated adapting the established co-efficient approach. This was compared with the results obtained using the multiple regression coefficient method given by Rhoades and Corwin (1981). They found that the established co-efficient approach superseded the multiple regression method atleast by three advantages.

i) The established co-efficient approach requires fewer EM readings and is less involved than the other method.

ii) The multiple regression method is used to obtain co-efficient relating soil electromagnetic conductivity measurement to bulk soil conductivity where as the established coefficient approach relies upon coefficients which are derived from inherent response curves for homogeneous media, and

iii) The multiple regression coefficient technique has the limitation of being site specific in its application, while the established coefficient technique appears to be quite general.

However, they confessed that there is some sacrifice of accuracy when using the established coefficient approach which they related to the influences of varying quantities and types of magnetic materials present in different soil types.

If further work is directed towards understanding the effect of magnetic susceptibility upon these methods to improve the accuracy as suggested by Corwin & Rhoades (1981), there is no doubt that this will prove to be the most effective and time saving method for measuring soil salinity.

2.3.5 Time Domain Reflectometry (TDR) method

The time domain reflectometry (TDR) is comparatively a new method in the field of soil salinity. The TDRs have been used for years, for cable testing. This is a technique operating over a range of radio frequencies, which can be used to measure the high-frequency electrical properties of materials. In soil applications TDR is used to measure the dielectric constant (ε). The instrument set up involved is simple that it consists of a pulse generator, a sampler which transforms a high frequency signal into a low frequency out-put and an oscilloscope or any other display or recording device. In this method a step voltage pulse or signal is propogated along a transmission line. The signal's propogation velocity and the amplitude, and the polarity of the reflected signal are dependent upon the electrical properties of the materials making up the transmission line. Parallel pair transmission lines are usually used for measuring soil water contents. The parallel rods or wires serve as conductors and the soil, in which the rods are installed, serves as the dielectric medium. The pair of rods acts as a wave guide and the signal propogates as a plane wave in the soil. The signal is reflected from the end of the transmission line in the soil and returns back to the TDR receiver. The TDR system operates as a one-dimensional or linear radar system. The timing device in the time-domain reflectometer measures the time between sending and receiving the reflected signal. The time interval is directly related to the propogation velocity of signal in soil as the line length is known. The propogation velocity is indicative of the volumetric water content (Topp and Davis, 1985).

The TDR was first used by Feldegg (1969) for measuring dielectric constants. Later with some modifications Topp et. al. (1980) used this method for measuring the volumetric water content in soil samples. The dielectric constant (ϵ) was obtained by them with the following equation:

$$\epsilon = (\frac{Ct}{2L})^2 \qquad ...(2.19)$$

Where, C = velocity of light in free space (3×10^8 m/Sec),

t = transit time,

L = length of the parallel transmission line (dual rod Probe).

Dalton et. al. (1984) studied the feasibility of the method in measuring electrical conductivity of the soil (σ) and there by the soil salinty. They derived

$$\sigma = \frac{\epsilon^{1/2}}{120 \pi L} \ln \frac{V_T}{V} \qquad ...(2.20)$$

Where, ϵ = dielectric constant

L = length of the parallel transmission line

V_T = magnitude of the voltage pulse that enters the parallel electrode

V_R = magnitude of the reflected wave

They also made use of an equation (2.21) similar to the one that was derived by Rhoades, (1976) to relate the medium's electrical conductivity (σ) and soil water electrical conductivity (σ_w)

$$\sigma = \sigma_w \cdot \theta T(\theta) + \sigma_s \qquad ...(2.21)$$

Where, θ = soil water content

$T(\theta)$ = soil water transmission co-efficient

σ_s = solid phase conductivity

After a laboratory test of ten soil colums using the TDR method followed by the measurements of σ_w using the standard conductivity bridge, they declared that a close agreement between the two determinations was found. They suggested that when TDR is used with known relations between medium σ and σ_w, it will provide a powerful tool in soil water research because a single measurement can yield both θ and the soil water salinity.

The use of the TDR for measuring soil salinity is so new that it has been tried only in the laboratory and that the field attributes of the method has not been fully evaluated so far. However, it offers the distinct advantage of measuring both water content and soil electrical conductivity simultaneously.

2.4 Comparison of Different Methods for Measuring Soil Salinity

Only a few direct comparisons of the various instrumental and conventional methods of measuring soil salinity have been made to date. In India Yadav et.al (1979) measured soil salinity in a field experiment using four different methods viz, porous matrix salinity sensor (σ_m) vacuum cup soil water sampler (σ_p), soil samples (σ_e) and four electrode bulk soil conductivity sensor (σ_a) with surface Wenner array methods). These investigators found a better linear correlation between σ_a and σ_e ($r = 0.93$) than between σ_e and σ_m ($r = 0.78$) or between σ_e and σ_p ($r = 0.78$)

They concluded that, for purposes of diagnosing the salinities of soils of an extensive area, it is advisable to use the four-electrode technique because it is rapid, simple and gives a large spatial coverage. Loveday (1980) compared the results of salinity measurements using four-electrode (surface Wenner array) technique with those of soil sample extracts in a survey of fifty sites in Australia. The water contents of the soils at the time of measurement were not controlled and were not generally at field capacity. In spite of this, he obtained relatively high correlations between σ_a and σ_e, though variance was high. He attributed this to field variability effects and concluded that the four-electrode method was good for gross survey work but not accurate enough for predictive purposes. However, Loveday used only two 5 cm-diameter cores taken from within the Wenner array span of electrode for soil samples and assumed the small sample represented ground truth (Rhoades, 1976).

Van Hoorn (1980) compared salinities measured using sample extracts with both, those obtained by four-electrode surface array and four-electrode salinity probe methods in large experimental tanks. From the results obtained he concluded that, though either Wenner method or EC probe can be used to measure the electrical conductivity of bulk soil, as the accuracy of the Wenner method in low, it can only be used for detecting great differences in salinity. For amore precise survey work, for example, classification of non-saline, moderately saline and strongly saline soil, the EC probe is useful even though it takes more time to obtain measurements than the Wenner method.

Nadler and Dasberg(1980) evaluated soil salinity measurements made with in-situ cermic porous matrix sensors,four-electrode salinity probe,a four electrode wenner array & soil sample extracts(1:1) in small salinized field plots. They found good correspondence between expected salinity and both soil extract salinity and four-electrode probe salinity, but not with porous matrix salinity sensor salinity. They attributed latter discrepancy to time-lag problems. They concluded that the Wenner array method could be used more reliably under drier soil conditions than the four-electrode probe which requires better electrode-soil contact for accurate measurements.

Rhoades (1984) ,recommended a combined use approach to facilitate the tedious, time consuming and costly aspects of soil sampling. In this approach various techniques should be used complementarily. The EM-sensor should be used for the first survey of the area to isolate areas of similarity and differences, and the four-electrode probe should then be used to acquire more detailed information of local areas and to acquire field information of variability within the homogeneous areas identified during the EM-Survey. The fewest appropriate number of samples can then be taken from the different areas for detailed chemical analysis of the salinity composition, if desired using the σ_a variability information obtained with the four-electrode probe. He also reported that good results were obtained by him with the four-electrode and EM-methods for soil salinity appraisal, in numerous locations in the U.S.A., and other numerous application including salinity diagnosis, mapping and monitoring saline seep and water table encroachment identification, irrigation scheduling and control, and leaching fraction assessment.

3.0 REMARKS

Abundant literature published so far on the applicability of the resistivity technique in solving the age old problem of soil salinity measurements have given rise to a fairly clear idea about the various problems one may have to face while making use of the technique. Several methods based on different principles and involving simple and inexpensive ones to highly sophisticated instruments are in use. Based upon the accuracy desired, availability of time, and the purpose of determination, a suitable method should be chosen. This report has reviewed the various methods available for field evaluation of soil salinity.

Ideally, it would be desirable to know the exact measure of the soil salinity which is possible by collecting representative soil samples followed by laboratory analyses or by making use of the porous matrix imbibition sensors. Both these techniques involve much time and are highly expensive. Moreover, they do not permit the monitoring of the whole field.

The bulk soil conductivity measurements seem to be plausible for overcoming these limitations. While adopting bulk electrical conductivity technique, due consideration should be given to the dependence of soil EC upon the water content and electrical conductivity of water content (EC_w), as the water losses by evapotranspiration will increase the soil salinity. A convenient way to overcome the effect of water content on the soil salinity is to measure resistivity at a uniform soil moisture level, e.g. the field capacity. In order to consider dependence of soil resistivity on the water content, calibrations should be made at various water contents.

The effective use of salinity probe requires a good contact between probe and soil, which limits its use to water contents not much lower than the field capacity. Moreover, salinity sensors have a rather long lag period and seem suitable for a higher range of salinity.

It has been shown that as the accuracy of the four-electrode resistivity method is low, it can only be used for detecting great differences in salinity, e.g. differences between non-saline, and saline soils or in saline seepage areas. Especially in a layered soil the interpretation of the resistivity measurements is not straight forward, but can be overcome by suitable calibration procedures. For a more precise work e.g. classification of non-saline, moderately saline, and strongly saline soils, or advising farmers on the possibility of sowing crops with different salt tolerances, the EC-probe should be used. The measurements should be made under the same conditions of soil moisture and a sufficient number of replicates should be made to obtain reliable results.

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