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The spatial distribution of soil salinity:

Detection and prediction

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2 COMPARISON AND SENSITIVITY OF MEASUREMENT TECHNIQUES FOR SOIL SALINITY DETECTION

2.1 Introduction

It is a well accepted fact that land use and management practices in arid regions are hampered by soil salinity. Over the last few decades, the area in the Amu Darya river delta in Uzbekistan has experienced soil salinization due to intensive farming. Timely interventions such as leaching have become ever prominent with growing deterioration of the environmental conditions caused by the over exploitation of the Amu Darya and the desiccation of the Aral Sea. Salinity appraisal in the region, however, still relies upon traditional soil surveys with subsequent laboratory analyses for the total dissolved solids (TDS).

While TDS is an important estimate of the soil salinity, it requires considerable time and resources. Furthermore, plants in saline soil are generally responsive to the concentration of the soil solution (Richards, 1954). The electrical conductivity (EC) of the solution is highly correlated with total salt concentration. The conductivity of the saturation extract (EC_e) is recommended as a general method for appraising soil salinity in relation to plant growth (Richards, 1954).

Although both approaches, TDS and EC, provide good estimates of the salinity, there are variations within the devices used and methods of analyses. Measurement of the apparent soil electrical conductivity (EC_a) can be done using electrical resistivity (Corwin and Hendrickx, 2002; Rhoades and Ingvalson, 1971; Rhoades and van Schilfgaarde, 1976), time domain reflectometry (TDR) (Dalton et al., 1984; Wraith, 2002), or electromagnetic induction (EM) (Hendrickx et al., 2002; McNeill, 1980). The latter is currently becoming one of the most frequently used techniques for characterizing the spatial variability of soil salinity.

Derivation of solute concentration from EC_a is a two-step process (Hendrickx et al., 2002). First, the electrical conductivity of the soil water (EC_w) is derived from the EC_a using an empirical regression equation or a physically based model. Next, the EC_w is converted into the solute concentration, which depends on its ionic composition. There are several models (Mualem and Friedman, 1991; Rhoades et al., 1989), which are based on the general principle that EC_a depends on several factors such as soil porosity and permeability (Archie, 1942), clay content and degree of pore saturation

(Rhoades et al., 1976). A detailed review of various models and developments is given by Hendrickx et al. (2002).

Studies on the direct comparison of EC measured with the various devices with estimates based on conventional laboratory methods are scarce, particularly in countries of the Commonwealth of Independent States (CIS) where EC_e is not a widely accepted practice. Additionally, disparity between definitions of soil textural fractions by the Kachinsky classification (Kachinsky, 1958) adopted in CIS countries, and definitions used by the Food and Agriculture Organization (FAO) might hinder the use of models where clay content is an important factor. Moreover, both soil textural class definitions do not discriminate between which salt constituent is present or dominant in the soil solution. This information is essential if the knowledge of the particular solute concentration is needed for determination of salinity type, toxicity or soil sodicity.

The main objective of this chapter is to identify and compare quick and practical determination techniques for soil salinity appraisal. Additionally, the study explores the sensitivity of each device to the individual salt constituent, using regression trees, an advanced data analysis technique (Breiman et al., 1984).

2.2 Materials and methods

Electrical conductivity of the soil is measured in different ways, the most referenced is the electrical conductivity of the saturation extract, EC_e. Electrical conductivity of the soil paste is defined further in the text as EC_p. The apparent electrical conductivity of the soil, which is a measure of the bulk electrical conductivity of the soil, is termed as EC_a.

2.2.1 Instruments

Handheld conductometer (2XP)

CIS organizations responsible for monitoring soil and groundwater salinity increasingly use electrical conductivity of the soil paste (EC_p) as an alternative to the total dissolved solids analysed in the laboratory. Rhoades et al. (1989) points out that determining EC_p as an estimate of EC_e has been in use since early 1900 in the USA.

A locally made conductometer, X-Express (Agromeliotaraqqiyot, Tashkent, Uzbekistan) (assembled by A. Chernishev, *personal communication*, 2002), tested for a variety of soils in Uzbekistan at the Central Asian Irrigation Research Institute (SANIIRI) was used for the study. It has been proven to provide accurate measurements of EC_p, which correlated well with EC_e on a silt loam soil in Uzbekistan (Shirokova et al., 2000).

The model X-Express (2XP) has two electrodes (Figure 2.1). It measures the conductivity of the soil paste in a small glass where dry and manually ground soil (30 g) is mixed with distilled water at a 1:1 ratio. The temperature of the soil paste is measured with the same instrument. Standardization of the measured EC_p values to the reference temperature of 25°C is done using the formula provided by the USDA-Soil Salinity Laboratory.

$$EC_{25} = EC_{measured} / (1+0.02\,(T-25)) \qquad [1]$$

where:

EC_{25} - the conductivity [dS m^{-1}] of the solution at 25°C

$EC_{measured}$ - the measured conductivity [dS m^{-1}] of a solution at sample temperature

T - sample temperature (°C)

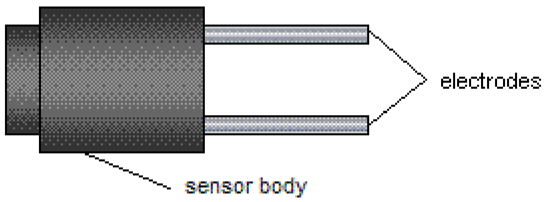

Figure 2.1 Sensor of the X-Express conductometer (Source: Chernishev, 2004)

Two-electrode conductivity probe (2P)

A two-electrode conductivity probe, Progress 1T (2P) (Agromeliotaraqqiyot, Tahskent, Uzbekistan) (assembled by A. Chernishev, *personal communication*, 2002), for field soil salinity studies measures EC_a and was tested earlier at the Central Asian Irrigation Research Institute (SANIIRI). The probe (Figure 2.2) consists of two 7-cm electrodes spaced 2 cm apart. The active part of the probe is 16 cm and measures the electrical conductivity of an approximately 20 cm layer, similar to the previous probe.

Measurements can be made at depths down to 80 cm and the probe is easy to insert into the soil due to the small 1 cm diameter of the probe. The older model did not have a temperature correction function integrated into the probe, therefore separate readings with a temperature probe were made during the measurements to calculate EC at a reference temperature of 25°C.

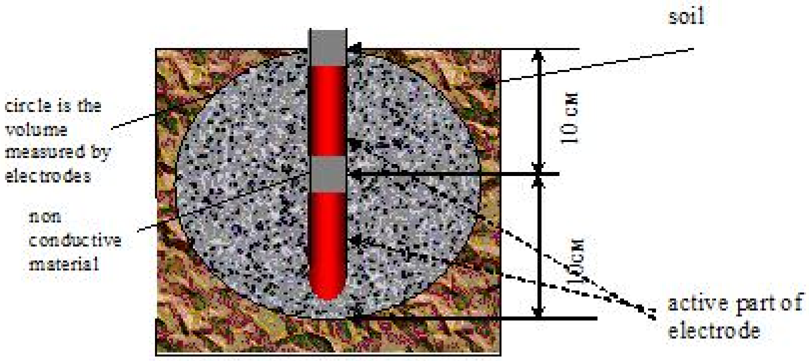

Figure 2.2 Schematic presentation of the two-electrode probe Progress 1T

Four-electrode conductivity probe (4P)

A four-electrode conductivity probe (4P) was developed by Rhoades and van Schilfgaarde (1976) based on the Wenner method. The probe has four electrodes (Figure 2.3). After an electrical current is induced between the two outer electrodes, the voltage drop between the two inner electrodes is measured. It offers EC_a measurements of smaller localized soil regions and more detailed assessment at given intervals through the soil profile, and thus is particularly helpful when salinity is highly variable between layers. However, several disadvantages exist. These include soil removal before probe insertion, which could be quite difficult in compacted soils, and the need for several measurements for the bulk salinity of a layer exceeding the sensor length. Additionally, soil moisture is a constraint factor in implementation of any type of sensors for field measurements. In this study, a commercially available probe (Eijkelkamp Agrisearch Equipment, Netherlands) was used for the measurements. The probe measures 110 cm and takes measurements of the 20 cm range interval corresponding to approximately 80 cm^3 soil volume.

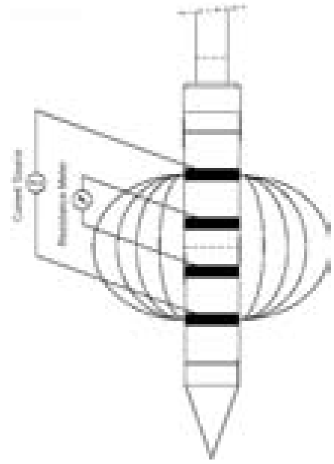

Figure 2.3 Sensor of the 4P conductivity probe (electrodes colored black)

Several electrical conductivity estimates were made in depths of 0-20, 10-30, 20-40, and 30-50 cm. The soil was removed with a gauge auger included in the set to the desired depth. The probe was inserted and the resistivity measured followed by measurement of a temperature correction factor. The EC_a then was calculated using the following equation provided by the manufacturer of the probe:

$$EC_a = k * f_t / R_t \qquad [2]$$

where:

EC_a – soil electrical conductivity [dS m^{-1}] at 25°C

k – cell constant of the probe 17.5 cm^{-1}

f_t – temperature correction factor

R_t – measured resistivity in ohms

Electromagnetic conductivity meter (CM-138)

Electromagnetic conductivity meter measures EC_a over a given depth (1.5 m in vertical position and 0.75 m in horizontal position). Of the variety of sensors, the electromagnetic induction (EM) technique is widely employed for salinity studies. The EM-38 of Geonics Ltd. (Canada) developed by Rhoades and Corwin (1981) is well documented (Corwin and Rhoades, 1982; Lesch et al., 1992; Robinson et al., 2004). Cheap and reliable prototypes of the instrument have become available, such as the CM-138 conductivity meter (GF-Instruments, Czech Republic). It has a dipole center distance of 1 m, operates at a frequency of 14.406 kHz, with a maximum effective depth of 1.5 m in vertical positions and half that in horizontal positions. The CM-138 measures apparent electrical conductivity. The schematic work principle provided in the manual is presented in Figure 2.4.

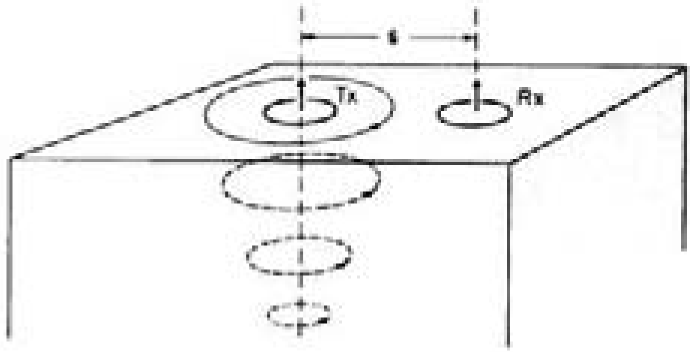

Figure 2.4 Induced current flow (homogeneous halfspace) (Source: McNeill, 1980)

The theory behind the electromagnetic technique can be found in Rhoades and Corwin (1981) and McNeill (1980). There are several advantages of the CM-138, an important one being rapid and undisturbed measurements. Contactless soil salinity measurements do not have to deal with poor sensor-soil contact in dry soils. Hence, the CM-138 can work in a variety of soil conditions, dry and wet, and is able to provide a rough vertical separation of salt distribution in the soil profile. With the latest developments, including the ability to mount the device on a mobile platform (Corwin and Lesch, 2003; Sudduth et al., 2003), it allows detailed mapping of the field. However, all these advantages come at the expense of a high price compared to the other salinity sensors. Electromagnetic devices are also sensitive to a wide range of metal objects. Additionally, latest studies by Robinson et al. (2004) report observations where high temperatures impaired EC readings. The latter is a technical shortcoming, which could be modified, rather than a principle drawback of the technique.

In an effort to measure salinity over shallower depths, several CM-138 readings held at different heights above ground were taken at each location. Measurements in the vertical mode were made at 0, 20, 40, 60, 80, and 100 cm above the soil surface (abbreviated CMv, CMv20, CMv40, CMv60, CMv80, CMv100, respectively), and in the horizontal mode only once on the soil surface (CMh). This approach was first tried by Corwin and Rhoades (1982) and might be a means of capturing soil-surface salinity. The automatic readings were recorded by the Hewlett Packard palmtop (HP-200LX) integrated into the control unit. Readings of CM-138 are automatically temperature compensated.

2.2.2 Site description

The experiment was conducted on the research farm (41°36'N, 60°31'E) of the Urgench State University, south-west of the city of Khiva (Figure 2.5). The area is located in the transition zone where alluvial soils in the north merge with desert sand of the south. Soils are mainly formed by the activity of the Amu Darya river and to a lesser extent by irrigated cultivation (Nurmanov, 1966). The last soil survey of the area conducted by the Soil Research Institute in 1997 defines soils of the area as meadow alluvial soils, with a light to medium loamy texture and underlying silt and sands. The middle part of the soil profile normally has thin loamy layers. FAO (2003) attributes these meadow soils on alluvium and sands to gleyic and calcaric Arenosols. Myagkov (1995) reports that the upper layer of the soils in this region consists of small to fractional alluvial deposits with a thickness varying from 0.5 to 1.5 m and an infiltration rate from 0.5 to 1.0 m day^{-1}.

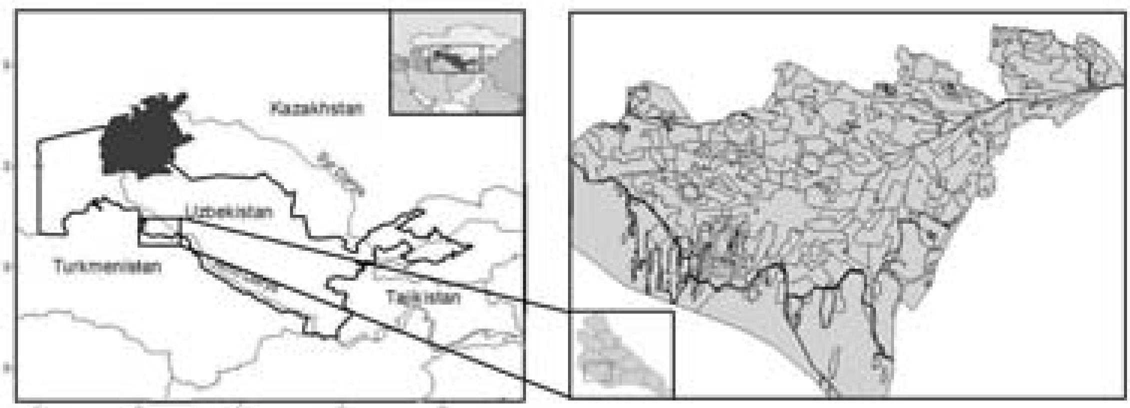

Figure 2.5 Research site location and the remote sensing image of the sampling area

Four soil pit excavations done in the area in June 2004 show that mean annual groundwater level can vary from as shallow as 100 cm in sandy fields to 180 cm in the loamy (I. Forkutsa, *personal communication*, June 2002). The sampling area (3 m x 4 km) includes soils varying from loamy to sandy. It has a relatively flat topography, with elevations ranging from 89 to 110 m above sea level. The southern part of the sampling area borders on the main drainage water collector (known as Ozerniy collector), which carries drained water from the fields out of the region to the Sariqamish depression. Most of the area is cultivated land. However, bare or abandoned land was also included in the study to possibly increase the variability of soil salinity. The main crops grown in the area are cotton (*Gossypium hirsutum* L.), wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.).

The climate is arid with an annual precipitation of about 100 mm (ranging from 35 mm to 170 mm during dry and wet years, respectively), about 70% of it occurring in the winter and spring. The area is irrigated by canals. Chub and Myagkov (1999) report that the TDS content of the river water at lower reaches of the Amu Darya can increase to up to 2 g l^{-1} during the low flow in the summer period, with a minimum of 0.7 g l^{-1} (data of river monitoring post; M. Ibrakhimov, *personal communication*, 2004). Mean daily temperatures vary from minus 15 to 10°C in winter (January average -8°C), and from 28-45°C in summer (July average 32°C).

2.2.3 Field survey

Field measurements were conducted from June to August 2002 in an area of approximately 1200 ha. Core sampling and EC measurements were done over a systematic 150 m by 200 m square grid designed for a parallel study. Some fields were sampled at a finer 40 m by 40 m grid (~3 ha) to study the effects of distance from water bodies, micro-topography, and to identify short range variation in successive geostatistical analyses. At each grid-node, soil core samples from 0-30 cm depth were taken, in duplicate, with a split tube sampler with an inner diameter of 53 mm. One sample was used for the analysis of the gravimetric water content and bulk density in the laboratory at UrSU. The second sample was air dried and analyzed by the Soil Research Institute (SRI) for organic matter (determined by the Turin method), saturation extract analysis (1:5 ratio) for total dissolved solids (TDS), soluble salts HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+} (by titration), Na^+ (by the difference between cations and anions), pH (by potentiometer) (Anonymous, 1977), and soil texture (pipette method) (Anonymous, 1963). Additionally, electrical conductivity (EC_p) of the air-dried soil sample was measured in the soil paste (1:1) by the 2XP handheld conductivity meter.

Electrical conductivity of the bulk soil (EC_a) in the field was measured using the three above-described devices: (i) CM-138, (ii) 4P and (iii) 2P. In order to check if 2P and 4P instruments measure similarly in the same solution, a bucket experiment with two solution types was carried out. Soil paste of low, medium, and high salinity was compared with distilled water with different amounts of salt diluted in it. Plastic buckets were used for this purpose, and electrodes were submerged into the solution to a depth of 25 cm. Readings at each salinity level and in the each bucket were taken in 5 replications.

Soil samples and measurements were, where appropriate, taken from the top of the ridge. To minimize interference from other devices, the CM-138 readings were taken first or within 2 m^2 around the CM-138 to speed up sampling, followed by soil core sampling. EC measurements were made immediately next to the core sampling spot.

Volumetric soil moisture content of the 0-30 cm depth was measured with two frequency domain moisture sensors ThetaProbe type ML2x (Delta-T Devices Ltd., UK). The sensor consists of a cylindrical head, containing an oscillator circuit, with four pointed rods (6.2 cm long) protruding from one end that are inserted into the soil. It was inserted vertically to obtain topsoil moisture content and horizontally along a 30 cm deep trench to obtain average readings for the soil moisture of the layer. In total, 6-7 readings were made per location and their average value was used for the analyses.

2.2.4 Data analysis

First, the validity of the EC_p measured with the 2XP probe was calculated by comparing those values with a calculated ECp using the soil parameters outlined in Rhoades et al. (1989) model. The Rhoades model considers the electrical current conductance through a soil, with three elements acting in parallel, (1) conductance through alternating layers of soil particles and interstitial soil solution (a solid-liquid series-coupled element, referred to as pathway 1 in Figure 2.6); (2) conductance through the interstitial soil solution (a liquid element, referred to as pathway 2 in Figure 2.6) (3) conductance through or along the surfaces of the soil particles (primarily associated with exchangeable cations) in direct contact with one another (a solid element referred to as pathway 3 in Figure 2.6)