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CHAPTER 10

FIELD AND LABORATORY MEASUREMENTS[a]

INTRODUCTION

Developing management practices for salt-affected soils and low-quality irrigation waters includes determining the salinity of the soil and the water, the origin of the various salts, and the crops that can be grown. Gathering this information can be very time- and resource-consuming because salt-affected soils tend to be extremely variable with time and space. In this chapter, soil and water sampling methods and the storage of samples will be discussed. References for the more commonly accepted procedures are listed.

REMOTE SENSING

Remote sensing refers to taking observations or measurements with devices that sense and record reflected or emitted energy without touching the subjects of interest. Several such methods for salt-affected soils currently exist.

Aerial Photography. Of the different types of film used for remote sensing, color infrared film has produced the most useful data on how the salinity-induced plant stress varies. With this film, dark-green vegetation produces a bright red image; light-green foliage produces a pink image; barren saline soil produces a white image; non-saline soil a gray, bluish-gray, or greenish-gray image; senescent and salt-stressed crops a reddish-brown to reddish-black image; clear water a very dark-blue to black image, and sediment-laden water a blue image. Thus, plants' responses to salinity, soil, and water can be readily identified.

Modern image analysis systems can digitize infrared photographs, cluster the scene into classes of salinity severity, and produce fractional area estimates that fall into each class. The response of crops to salinity severity usually varies from season to season and from crop to crop and depends mainly on patterns of precipitation and the crop's tolerance to salinity. Infrared photography is also very useful for recording year-to-year and crop-to-crop responses to soil salinity and changes in management practices.

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The volume and depth of soil (for which salinity is measured) is determined by the distance between the outer two electrodes. With the probe configuration of Rhoades and van Schilfgaarde (1976), a hole is cored for each sampled site. In dry or stony soils, establishing uniform soil contact with the electrodes may pose a problem. These systems provide quick, easily-obtained measurements of total salinity without the need for taking soil samples to the laboratory.

Salinity measurement by electromagnetic induction consists of inducing current flow in a hand-held primary electromagnet, which, in turn, induces current flow in the primary conductor. The induced current flow in the soil creates a secondary electromagnetic field. The secondary-field strength is proportional to the current flow in the secondary conductor, the soil. Since the current in the soil is a function of the electrical conductivity of the soil, the instrument can be calibrated so that the secondary field strength measured by the instrument provides a measure of the electrical conductivity of the soil. Using this principle, Rhoades and Corwin (1981) developed an inductive electromagnetic soil conductivity meter that could rapidly measure soil salinity. The instrument is placed on the soil surface or at some distance above the surface, making soil sampling and holes for electrodes unnecessary. It can be used to survey salt-affected soils, map saline seeps, and estimate salinity at different depths (Corwin and Rhoades 1984; Rhoades et al. 1989a).

Time domain reflectometry (TDR) is currently being developed for simultaneously measuring volumetric water content and bulk soil electrical conductivity. TDR measures these two parameters *in situ* on a given sample volume for a given point in time. It combines the principle that the relative dielectric constant of a soil is primarily related to its water content and the fact that the propagation velocity of a voltage pulse along the transmission lines is a function of the electrical conductivity of the soil. Soil voids cause reading errors, and the method is inaccurate above a certain electrical conductivity. Dasberg and Dalton (1985) give a detailed explanation and history of the method, and compare it with other methods.

SAMPLING OF SOIL

Once a sampling strategy has been chosen, 0.5 kg to 1.0 kg soil samples are taken from each depth or horizon and chemically analyzed. Larger samples are needed for physical measurements. Care must be taken to avoid contaminating the samples with soil from other depths. The samples should be crushed or broken up, air-dried, passed through a 2.0-mm sieve, thoroughly mixed, and placed in durable, labeled containers. Labels should include the date, the upper and lower depth limits, and the site. The approximate field moisture content, the name of the person who collected the sample, the soil surface conditions, the crop's appearance, history, and yield, the next crop to be grown, and the quality of available irrigation water should also be noted. Samples should be kept dry and free of contamination.

SAMPLING OF WATER

If well water is used for irrigation, samples should be collected after the pumps have run for at least half an hour. This removes standing water from the well casing and the area around the well, ensuring a representative sample. Usually, the well-water quality will not change during the growing season. In a few cases, where the water level is substantially lowered during the pumping season, the quality may change, justifying periodical sampling throughout the irrigation season.

Irrigation water quality remains constant when the water is from large storage reservoirs, but it may vary during the irrigation season when the water comes from small storage systems and stream systems that have annually fluctuating flows or accumulate subsurface irrigation return flow or spring water. Samples should be collected only during the irrigation season and when changes in quality are suspected. Once the annual patterns of quality in a well or stream water are established, samples should be collected only when changes are suspected.

Water samples of 0.2 l to 0.5 l (0.5 to 1.0 pint) are sufficient for analysis. The sample containers should be clean and free of oil, salts, and other chemical contaminants, rinsed with the water to be sampled, and have tight closures. Labels should include the date, time, and location of sampling, the approximate water flow, the crop to be grown, the irrigation method, and the name of the person collecting the sample. The samples should be refrigerated at about 4°C or 40°F and analyzed as soon as possible. They should not be frozen.

WATER TABLE DEPTH AND GROUND WATER QUALITY

To remove excess salts from the root zone, the water table must be deep enough to allow drainage and salt leaching below the root zone. The required depth varies with soil texture, degree of stratification, quality of subsurface and irrigation water, type of crops grown, and application rates and methods of irrigation.

To determine the effects of a water table on soil salinity, it is necessary to determine the depth and salinity of the ground water. When the water table is close enough to the surface to be of concern—usually less than 2.0 m—auger holes, observation wells, or sand points inserted into the saturated zone allow for sampling and monitoring of water depth. With the required equipment, a well can be rapidly installed by jetting water under pressure through the casing of the well and lowering the casing as the cavity is created. To prevent the hole from caving in, slotted pipe or a sand point should be inserted into the hole to below the water table. The wells must not pass through clay or cemented layers below perched water tables. Otherwise, the water level of the well may fall as water drains through the well and into a vadose zone below or rise when artesian water flows into the well from beneath the restrictive layers. Water samples should be collected for chemical analysis. To ensure fresh samples, two or three well volumes should be pumped from each hole before sampling. The same procedures used to store and to

analyze well water samples and soil extracts are used to store and analyze these samples.

When a monitoring well is hand-augured or made with a coring machine, soil samples should be kept by depth increments. The samples' texture, structure, and degree of cementation reveal the type and amount of soil stratification above and below the water table. With the methods used for the other soil samples, these samples can be analyzed for various salts and physical properties, such as hydraulic conductivity and texture.

Two alternatives to observation wells are piezometer tubes and tensiometers. A piezometer is an observation well with an open bottom that measures the positive hydraulic head at a given point. A tensiometer is a piezometer closed at the bottom with a porous cup that is used to measure negative hydraulic head at a given point. They are installed similarly to observation wells (Cassell and Klute 1986; Reeve 1986). They can be used to measure the hydraulic head at a given depth and, in the case of clay lens or cemented soil layers, the hydraulic head above, below, and across the layers can be measured. However, they also have some disadvantages. Piezometers are more difficult than observation wells to sample for water. Tensiometers are not used to collect water samples.

The direction of ground-water flow and the hydraulic gradient can be determined if at least four wells or piezometers are inserted in a rectangular pattern over the area of interest to measure the absolute water surface elevation or hydraulic head. These two parameters are useful for determining if an effective drainage system can be installed. How often the water table is measured depends on the aquifer's responsiveness to such events as on-site or up-slope irrigation, precipitation, and the absence or presence of water in irrigation conveyance systems. A log can be maintained during the growing season to determine whether a change in measurement frequency is needed.

CHEMICAL ANALYSES

The chemical species of interest in salt-affected soils include: the soil solution ions, namely, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), bicarbonate (HCO_3) and carbonate (CO_3); the same ions in the irrigation water; the exchangeable cations, namely, Ca, Mg, Na, and K; and the precipitated salts, namely, calcium carbonate (lime) and calcium sulfate (gypsum). These ions are often referred to as the macroions in salt-affected soils and irrigation waters. Other informative measurements include pH, EC_e, and saturation-paste water content. Other parameters that can be calculated from these data include the sodium adsorption ratio (SAR), the adjusted SAR of the irrigation water (SAR_{adj}), the exchangeable sodium percentage (ESP), and the salt mass per unit volume or area.

Boron (B) concentrations in irrigation waters and soil solutions produce plant injury at much lower concentrations than other ions. Thus, B should be considered more a toxic element than a salt. Because

B toxicity often is associated with salt- and sodium-affected soils, it will be considered here, as well as in Chapters 4 and 7.

The methods of analyzing soil paste, soil water extract, and bulk irrigation and drain water discussed here will be restricted to those appropriate to soils and waters with a pH of 6.5 to 10.0 and concentrations of salt that adversely affect yields. Unless noted otherwise, the same analytical procedure can be used for irrigation waters, drainage waters, and soil extracts. For the reader's convenience, procedures will be referenced and restricted to those that are generally accepted and standardized. Many other research-level procedures exist, but they are inapplicable to data-gathering at the management level.

Saturated Soil Paste Electrical Conductivity. In the past, much of the data on soil salinity was obtained by using a 50 ml cylindrical conductivity cell filled with a saturated soil paste to estimate soluble-salt concentrations. Because of the ease and speed of use, this "Bureau of Soils Cup" was used to map and diagnose salt-affected soils. When Reitemeier and Wilcox (1946) determined that plant responses to soil salinity more nearly correlated with the electrical conductivity values of the saturation paste extract, its use was discontinued. A theoretical relationship between the electrical conductivity of the saturation soil paste and the electrical conductivity of the saturation paste extract has since been developed to overcome the cell's shortcomings. This was done by developing a simple method of determining the volumetric water and volumetric solid contents of the saturation paste, the conductance of the sample surface, and the current pathway of the water in the cell. The cell, an electrical conductivity bridge, a portable balance, and the appropriate graphs can now be used to accurately estimate the electrical conductivity of the saturation paste in the field (Rhoades et al. 1989b).

Saturation Paste Extracts. To apply and interpret data about salinity uniformly from one soil or crop to another, a standardized extraction procedure is needed. Data from soil solution samples with a moisture content that represents field conditions are ideal, but ways to obtain them are presently unavailable. The use of saturation paste extracts is the standard way to measure and interpret soil salinity as a bulk measurement and individual ion concentrations. This is the lowest soil-to-water ratio that can be easily extracted with vacuum, pressure, or centrifugation, while providing a sample of sufficient size to analyze. The water content of a saturation paste is about twice the field capacity for most soils. The concentrations of salt and individual ions have been diluted by about the same ratio between field conditions and the extract for all samples. Exceptions include sandy soils, organic soils, and soils containing gypsum. This standardized extraction procedure enabled the development of crop tolerance tables that can be interpreted across soil-texture classes (U.S. Salinity Laboratory Staff 1954; Rhoades 1982b). Most data on the salt tolerance of a crop are expressed in terms of the electrical conductivity of the saturation paste extract (Bresler et al. 1982; Maas 1986). The relationship between cation solution concentrations and exchangeable cation concentrations in soils, used to predict exchangeable sodium percentage (ESP) from sodium adsorption ratio

(SAR) data, is also based on the dilution ratio of the saturation paste extract (U.S. Salinity Laboratory staff 1954).

Extraction ratios of soil-to-water by weight, e.g., 1:1, 1:2, and 1:5, are often used, especially by commercial soil testing laboratories. These extracts require less skill and time to prepare than saturation paste extracts. Any dilution above field conditions introduces errors in the interpretation of data. The greater the dilution, the greater the deviation between ionic ratios in the sample and the soil solution under field conditions. These errors are associated with mineral dissolution, ion hydrolysis, and changes in exchangeable cation ratios. Soil samples containing gypsum deviate the most because the calcium and sulfate concentration remain near-constant with sample dilution, while the concentrations of other ions decrease with dilution. The standardized relationship between the extract and the conditions of the soil solution in the field for different soils is lost with the use of preset soil-to-water ratios.

Samples to be used for saturation paste extracts should be air-dried, crushed, and passed through a 2-mm sieve. As the name implies, saturation pastes contain enough water to fill voids without leaving excess water on the surface after samples have set. Saturation pastes are prepared by adding distilled water to a soil sample and mixing the two to obtain a glistening surface. The sample should flow together slowly behind a spoon or spatula as it is drawn through the mix. Most saturated pastes will not stick to a clean spatula. When the container is gently tapped on the bench top, the paste's surface should still glisten, but free water should not be standing on the surface. After the container is closed, the sample should be allowed to set for at least an hour and then its consistency rechecked. If water remains on the surface, the sample is too wet and dry soil is added. If the sample has stiffened, more water is added, the sample is allowed to set, and then rechecked. The sample is covered with an airtight lid and allowed to set long enough to establish equilibrium between the soil minerals and the water (at least four hours, but preferably overnight). After equilibrating, the samples are thoroughly remixed and their pH measured with an electrode and pH meter. The pH of the saturation paste extract is generally less meaningful than the pH of the saturation paste for salt-affected soils. The two values are seldom the same for a sample. Existing criteria are based on the saturation paste's pH data.

Take a small (30g to 50g) subsample of the paste at this point. Weigh it, oven-dry it (105°C) overnight, and re-weigh it to determine the saturation moisture content. The moisture content in soils is determined by dividing the water weight by the dry soil weight.

The saturation paste is transferred to a Buchner or similar funnel fitted with a high retention filter paper, and the solution is collected into a bottle or test tube by vacuum extraction. The electrical conductivity (EC_e) is measured immediately and adjusted to 25°C (U.S. Salinity Laboratory Staff 1954). If HCO_3 and CO_3 are of interest, they should be determined at this time. Methods are discussed under procedures for anion analysis. Once the HCO_3 and CO_3 subsamples are removed, lime and gypsum can be prevented from precipitating in the remaining saturation paste extract by diluting the samples in half with distilled water, or adding acid to make the sample 0.1% nitric, sulfuric, or hydrochloric acid, depending on which anions are of interest. The extracts should be stored at 4°C or 40°F (do not allow to freeze) in containers with tight-fitting lids and analyzed for the ions of interest as soon as possible.

Soil Solution Extracts. Suction extraction through ceramic cups and thin-walled hollow tubing can be used to collect samples of the soil solution when the soil water potential is greater than about −30 kPa (−0.3 bar). If the metric potential is lower than this, the water moves toward the cup too slowly to permit the sampling. This method is used immediately after irrigation or from slightly above a water table. If a wastewater disposal field or a high water table is involved, suction extraction through ceramic cups can be used to monitor finite points in plots or fields. If the ceramic cups are not properly cleaned before they are installed, a potential for error exists. Suction-extraction preparation may include forcing 0.1 N HCl through the cups, followed by a liberal volume of distilled water. Timing in relation to irrigation or rainfall needs to remain consistent throughout a study, since the soil volume and solution location (in terms of pore size) changes as soil pores of various sizes drain.

Analysis procedures for saturation paste extracts and samples of irrigation and drain water are the same from here on. Once the liquid samples have been obtained, the solution electrical conductivity (EC) is the simplest analysis to make and the most widely used parameter for evaluating soil and irrigation water salinity (Rhoades 1982). Salt tolerance tables for most irrigated crops and a few ornamental plants have been developed. The electrical conductivity of a saturation paste extract is the only parameter necessary to use these tables to estimate the relative yield decrease caused by the soil solution's soluble salts (Bresler et al. 1982; Maas 1986; Chapter 13).

Saturation paste extracts of sodic soils (pH > 8.5 and EC < 4.0 dS/m) are usually dark in color due to suspended organic matter, which interferes with most analytical procedures. This material can be removed from the solution by adjusting the pH to 3.0 to 3.5 with a strong acid, then adding a small amount of an aluminum salt, and then centrifuging and filtering it (Robbins 1989).

Cation Analysis. Cation concentrations in irrigation waters, saturation paste extracts, and shallow water table and drainage waters are the second most useful data for diagnosing and managing salt-affected soils. The concentrations and ratios of cations are major factors controlling soil pH and the physical characteristics of salt-affected soils. Flame photometry is the most practical and widely used way to analyze Na and K. Any solid particles should be filtered from the samples and the samples then diluted to the proper concentration ranges. This is usually the only pretreatment needed to determine Na and K. Sodium is usually determined at 589 nm and K at 766.5 nm by flame photometry (Knudsen et al. 1982). Atomic absorption spectrophotometry is the most common way to analyze Ca and Mg in these samples. Elements that form stable oxysalts, such as aluminum, beryllium, phosphorus, silica, titanium, vanadium, and zirconium, reduce their sensitivity in aqueous samples.

These interferences are removed by adding 0.1% to 1.0% lanthanum or strontium chloride to the samples. Calcium is usually measured at 422.7 nm and Mg at 285.2 nm by atomic absorption spectrophotometry (Lanyon and Heald 1982). More recently, procedures involving ion chromatography (IC) have been developed to analyze alkali and alkaline earth metal ions (Nieto and Frankenberger 1985b). Gravimetric and colorimetric methods are available for these cations when instrumentation for the previously mentioned methods are unavailable. These methods are slower, involve more work, and are less sensitive to low concentrations and small differences among samples than the more commonly used methods (Knudsen et al. 1982; Lanyon and Heald 1982).

Anion Analysis. Gravimetric, volumetric, electrometric, and colorimetric methods have been used to determine concentrations of chloride in soil extracts, drainage effluents, and well waters (Adriano and Doner 1982). Ion chromatography has also been used to analyze Cl (Nieto and Frankenberger 1985a). All of these methods, except the gravimetric methods, are easily automated by reliable, available instrumentation. A variety of commercially available automated systems analyze chlorides simply, accurately, and reproducibly. Chloride is usually the predominate anion in salt-affected soils and nonreactive with other components. Due to its chemical inertness, Cl ion is often used as a conservative tracer for calculating leaching fractions and the relative proportions of water from different sources that enter soil water and irrigation systems.

Gravimetric, turbidimetric, titrimetric, and colorimetric methods have been used to determine sulfate concentrations in soil extracts and water samples (Beaton et al. 1968). Problems arise in choosing an extractant and defining what has been extracted and from interferences from suspended organic matter and clay particles in the sample solutions. More recently, IC methods to analyze sulfate have been developed that are free of the usual sulfate interferences, are faster, and will accurately detect sulfate at much lower levels (Adriano and Doner 1982; Nieto and Frankenberger 1985a).

Carbonate and bicarbonate ions are usually determined by titrating aqueous samples to pH 8.4 (carbonate) and then to pH 4.7 (bicarbonate) with a dilute solution of a strong acid, such as HCl or H_2SO_4, to determine carbonate and bicarbonate ions. The end points can be determined colorimetrically, using phenolphthalein for carbonate and methyl orange for bicarbonate, or potentiometrically, with a pH electrode and pH meter. These analyses can be readily performed manually or by automated instrumentation (Rhoades 1982b).

Flow injection analysis procedures and instrumentation have been developed to measure aqueous pH and electrical conductivity and analyze for the cations and anions of interest in saline and sodic soils and waters. This is an automated system for injecting a liquid sample and reagent(s) into a transport fluid. The sample and reagents pass through a reaction chamber and then through a detector. Available detectors include pH, electrical conductivity, calorimetric, turbidimetric, atomic adsorption spectrophotometry, and flame emission. The reagents, reaction chamber, and detectors are interchangeable, and their selection is determined by the parameters to be measured (Ranger 1981).

Exchangeable Cations and Cation Exchange Capacity. To quantitatively determine exchangeable plus soluble cations, the soil is extracted with a salt solution that provides a cation to replace the cations of interest. Neutral 1.0 M ammonium acetate is the generally used solution for sodium and potassium extraction (Knudsen et al. 1982), and 1.0 M sodium acetate adjusted to a pH of 8.2 is generally used for calcium and magnesium extraction. When lime and gypsum are absent, calcium and magnesium can be determined in the ammonium acetate extract. When lime is present, extracting at the higher pH of 8.2 limits lime solubility and overcomes most of the error in extracting calcium (Bower et al. 1952). When gypsum is present, measuring exchangeable calcium is impossible and meaningless. Once the extractable cation values are derived, the individual exchangeable cation values are calculated as the difference between the soluble and the extractable cations (U.S. Salinity Laboratory Staff 1954).

The cation exchange capacity (CEC) can be measured by washing the sodium-saturated samples from the calcium-magnesium analyses with ethanol and then replacing the sodium in the samples with ammonium. The exchangeable sodium concentration in this second washing equals the CEC (U.S. Salinity Laboratory Staff 1954). An independent procedure that uses a sodium acetate-sodium chloride saturating solution and a magnesium nitrate extracting solution can also be used to determine the CEC. This eliminates the ethanol wash cycles. However, the extractable concentrations of Ca and Mg cannot be obtained from this (Rhoades 1982a). The concentrations of calcium, magnesium, sodium, and potassium ion in these extracts are analyzed by the methods used for the water and aqueous extract samples, except the standard solutions are made up in the extracting solutions rather than in water.

Lime and Gypsum. The presence or absence of lime and gypsum in the soil should be considered when making management decisions in salt-affected soils. Soil carbonate content can be estimated from the volume of CO_2 gas evolved from a sample treated with excess HCl, or by the weight loss caused by the CO_2 evolved from samples treated with H_2SO_4 and $FeSO_4$. Gypsum can be semi-quantitatively measured by heating and weighing the water lost from the sample as the gypsum changes to plaster of paris. Gypsum can also be titrated with $BaCl_2$ and the $BaSO_4$ precipitate weighed (Nelson 1982).

Boron. After reviewing several analytical methods for B concentration measurement in water, soil extracts, and plant materials, Bingham (1982) indicated a preference for the azomethine-H method to determine B. He also described a mannitol potentiometric method, a tetrafluoroborate selective electrode method, and a total boron method, as well as hot water, saturation paste, and mannitol-calcium chloride extraction methods.

PLANT SAMPLING AND TISSUE ANALYSIS

The effects of soluble salts and exchangeable sodium on the growth and mineral composition of crops and ornamental plants have been

extensively discussed in the literature. Other chapters in this book have also covered some of these effects. Soil salinity or exchangeable sodium ratios do not uniformly affect Ca, Mg, Na, K, N, P, and S uptake ratios, and excesses and deficiencies in different plant species and varieties. For example, fruit and nut trees and woody ornamentals are more sensitive to Cl and Na uptake than field and forage crops (Bernstein and Pearson 1956). Plant maturity and soil nitrate availability also affect salt sensitivity in crops (Bernstein 1974). Pesticide injury and plant pathogens can, under certain conditions, produce changes in mineral balance or physical appearances similar to those caused by excess soluble salts or exchangeable sodium. Plant sampling and tissue analysis may indicate a reduction in yield or quality induced by salinity or exchangeable sodium, but the aforementioned difficulties have made tissue analysis generally ineffective in diagnosing and managing saline or sodium-affected soils. An exception is plant tissue testing for boron (B) toxicity. Boron tolerance and toxicity tables are available for a number of crops and ornamentals (Bresler et al. 1982; U.S. Salinity Laboratory Staff 1954; Wilcox 1960). Gaines and Mitchell (1979) described a tissue analysis procedure used to measure the B status of crops. Plant material was ashed at 600°C for an hour and dissolved in 0.18M H_2SO_4. The B concentration was then measured by the azomethine H procedure.

Plant sampling techniques for salinity considerations include choosing the part of the plant and the stage of the plant's maturity to be sampled. The mineral composition for a particular species is not fixed. The composition of a particular part of a plant also changes with age and the environment. Once the samples are collected, they are prepared for analysis, which usually includes decontaminating, drying, grinding, and ashing or extraction. The procedures vary according to the crop and sampling purpose (Jones and Steyn 1973). After the samples are extracted or ashed and redissolved, the solutions are analyzed by the same procedures that are used for soil extracts and water samples.

PHYSICAL MEASUREMENTS

Saline and sodic soils often exhibit undesirable physical characteristics that also contribute to the poor crop productivity. These may include a shallow water table, low aggregate stability, impervious subsoil layers or lenses, low infiltration rates, low hydraulic conductivities, and variations in horizontal or vertical textures. These physical characteristics also affect plant growth and the effectiveness of reclamation procedures. The following sections briefly review the most common methods to characterize soils physically as they relate to salt-affected soils. The chemical and physical characteristics in salt-affected soils interact strongly. The intensity of these interactions varies with soil texture and clay mineralogy.

Aggregate Stability and Size Distribution. Aggregates are made up of sand, silt, clay and organic particles that adhere to each other and form structural units in the soil matrix that can withstand disruptive forces. The size and number of cleavage planes between aggregates and interaggregate air pores greatly influence other physical properties, such as infiltration rates and hydraulic conductivity. Concentrations and kinds of solution ions, soil mineralogy, organic matter, iron oxides, and carbonate coatings largely determine aggregate stability. The disruptive forces of sampling and analysis differ from those encountered in the field, which include cultivation, wheeled traffic, freezing, and thawing. Because of this difference, most investigators use aggregate stability of one aggregate size fraction rather than aggregate size distribution (Kemper and Rosenau 1986). Aggregate stability is the fraction of the aggregates of a selected size that do not disintegrate to smaller particles upon sieving or sedimentation. The electrical conductivity of the water used for wet sieving should be equal to less than 0.01 dS/m, standardized, and specified when aggregate stabilities of sodic soils are reported (Shainberg et al. 1981).

Particle Size Analysis. Spatial variations in soil texture play an important role in the movement and distribution of water and salts in soils. Water will move into and through coarse-textured soils and soil horizons more rapidly than through finer textured clay soils or layers, unless they are highly aggregated or perforated by macropores. Finer textured soils draw water and salts up from a water table by capillary action from a greater depth than do coarser textured soils. The combination of restricted leaching due to low infiltration and percolation rates and greater upward flow of salt in clayey areas perpetuates salinity in areas with the finest soil textures. Clay content and mineralogy also greatly affect specific surface area, cation exchange capacity, and water retention. Consequently, lateral and vertical texture variations and how they relate to patterns of salinity observed in the field tell a lot about processes that cause salt accumulation and aid in reclamation (Wiegand et al. 1966).

Gee and Bauder (1986) summarize ways to pretreat and analyze samples for particle size. Saline and sodic soil procedures are essentially the same as for normal soils, except that saline soils should be leached with distilled water until the leachate EC drops below 1.0 dS/m; chemically pretreated to remove organic matter, iron oxides, and carbonate coatings that inhibit dispersion; and dispersed by turbulent mixing, mechanical shaking, or ultrasound cavitation in an alkaline dilute solution of sodium polyphosphate. Procedures for analyzing particle size in gypsiferous soils have been developed (Hesse 1976), as have procedures for removing gypsum from soil samples (Rivers et al. 1982).

Hydraulic Conductivity. Soil salts are transported as solutes in water, so water must move through the soil. When a shallow water is the source of salinity, the soils must be drained before soil salts can be leached. Hydraulic conductivity of salt-affected soils, which must be measured to determine the rates at which salts can be leached, can be measured in the field with a shallow (saturated) or deep (unsaturated) water table.

Hydraulic conductivity may be limiting at different positions in the soil profile, depending on the circumstances. In sodic soils, low hydraulic conductivity at the surface of the soil may control water movement throughout the profile, or a nearly impermeable layer deeper in the soil

can cause a perched water table to develop above which salts accumulate. High clay content can limit hydraulic conductivity throughout the root zone. Amoozegar and Warrick (1986) developed ways to measure the hydraulic conductivity of saturated soils in the field. Green et al. (1986) developed ways to measure the hydraulic conductivity of unsaturated soils in the field. These measurements can also be made in the laboratory on disturbed or undisturbed samples over a range of water contents (Klute and Dirksen 1986).

The most common way to determine the soil's saturated hydraulic conductivity in the presence of a water table is the augered-hole method. A hole is augered into the water table, with care taken to avoid puddling the walls. Water is pumped from the hole several times to ensure that water will flow freely into the cavity. The water level in the hole is allowed to equilibrate, and the water depth in the hole is measured. Water is again removed from the hole and the rate of rise is measured until one half of the original depth is reached. The water-rise rate in the hole, the depth of the hole below the water table, and its radius are the variables used to calculate hydraulic conductivity (Amoozegar and Warrick 1986).

When measuring hydraulic conductivity in the field, predominantly vertical flow during drainage is assumed. Of the four methods described by Green et al. (1986), only the unsteady drainage flux method, often called the instantaneous profile method, is described here. Soil in a 3.6-m square outer plot and a 1.2-m square inner plot, at a site where the water table is deep enough not to inhibit drainage, is thoroughly wetted and covered to prevent evaporation. The hydraulic head profiles are measured with tensiometers installed to different depths, and the water content profiles are measured in close proximity to the tensiometer by neutron scattering. These two measurements are made periodically in close time synchronization. The water fluxes determined from the changes in water content are divided by the hydraulic gradients for the same depth and time intervals to obtain the unsaturated hydraulic conductivity (Green et al. 1986). Watson (1966) summarized data-analysis procedures for this method. The method assumes vertical flow, nonhysteresis of the water content-pressure head relation, and isothermal conditions. It is not suited to soils whose horizons differ greatly in hydraulic conductivity or soils with water tables within about 1.5 m of the deepest depth.

When field measurements are impractical, hydraulic conductivity can be determined in the laboratory. Undisturbed soil cores are preferred to packed columns (McIntyre 1974). Klute and Dirksen (1986) consider cylindrical cores that measure 20 mm to 100 mm in diameter by 50 mm to 250 mm long to be reasonable sizes for laboratory analysis. The number and distribution of the samples should represent the field to be characterized (Chapter 9). The recommended test fluid is degassed 5.0 mM $CaSO_4$ solution, saturated with .2 to .3 g/l thymol to inhibit biological activity. The instantaneous profile method described for the field has also been adapted to the laboratory (Klute and Dirksen 1986).

Infiltration Rates. Getting water to move into and through soils to carry unwanted salts and exchangeable ions from the root zone is usually the primary consideration in reclaiming saline and sodic soils. As with other properties, infiltration rates are seldom uniform in salt-affected fields.

Infiltration-rate measurement procedures have been discussed for ring infiltrometers (Bouwer 1986), sprinkler infiltrometers (Peterson and Bubenzer 1986), and surface irrigation systems (Kincaid 1986). The measurement procedures should correspond to the site's irrigation methods. Infiltration-rate test conditions should duplicate the water quality, soil surface, duration of water application, and other conditions of the system. With all methods, care needs to be taken to avoid puddling the soil surface while applying the water and to avoid clogging the surface with fine particles suspended in water. If a thin surface layer is sodic, affected by water drops, or otherwise suspected of limiting infiltration, then infiltration before and after removal of the thin surface layer is suggested. For nonuniform profiles with layers of different hydraulic conductivity, the final infiltration rate equals the harmonic mean of the hydraulic conductivities of the various layers if the layers become less permeable with depth (Bouwer 1969).

Surface Topography. With natural vegetation and rain-fed (nonirrigated) agriculture, topography usually affects salinity patterns, since the only water normally available for leaching is precipitation. The precipitation in excess of infiltration does not remain on crests and slopes long enough to leach excess salts from the profile (Wiegand et al. 1966). Also, slope changes in irrigated fields can vary the rate of water intake along furrows. In the steeper parts of the field, leaching is insufficient to remove salt. At the same time, leaching may be adequate on the field's more level portion. Grading irrigated fields to uniform slopes and undercutting saline areas on level, non-irrigated cultivated fields has successfully been used to reclaim saline soils (Lyle and Allen 1966). These results demonstrate how important micro-topographical differences are to the salt balance and how valuable measuring the topography of the soil's surface is. In nearly level areas, the topographic effects can be documented visually or photographically by recording standing water or soil-drying patterns after irrigation or rainfall.

Other physical measurements, often made in research studies but seldom used in practical applications, include soil solution and plant sap osmotic potential, matric water potential-water retention curves, field capacity, available water capacity, solute diffusivity, and air permeability. Soil salinity and sodicity affect all of these physical characteristics.

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