Improvement and Management of Soils in Arid and Semiarid Regions in Relation to Salinity and Alkali

The development and maintenance of successful irrigation projects involve not only the supplying of irrigation water to the land but also the control of salinity and alkali. The quality of irrigation water, irrigation practices, and drainage conditions are involved in salinity and alkali control. In establishing an irrigation project, soils that are initially saline require the removal of the excess salts and may require chemical amendments in addition to an adequate supplv of irrigation water. On the other hand, soils that initially are nonsaline may become unproductive if excess soluble salts or exchangeable sodium are allowed to accumulate because of improper irrigation and soil management practices or inadequate drainage.

Basic Principles

Although farming practices may vary from one irrigated area to another, the following general principles related to salinity and alkali have universal application.

Plant growth is a function of the total soil-moisture stress, which is the sum of the soil-moisture tension and the osmotic pressure of the soil solution. Through controlled leaching, the osmotic pressure of the soil solution should be maintained at the lowest feasible level ; and, by a practical system of irrigation, the soil-moisture tension in the root zone should be maintained in a range that will give the greatest net return for the crop being grown.

Water flows in both saturated and unsaturated soil in accordance with Darcy's law, which states that the flow velocity is proportional to the hydraulic gradient and the direction of flow is in the direction of the greatest rate of decrease of hydraulic head. This principle makes it possible to determine the direction of flow of ground water by simple methods. A knowledge of the source and direction of flow of ground water is especially useful in solving drainage problems.

Soluble salts in soil are transported bv water. This is an obvious but basic principle pertaining to the control of salinity. Salinity, therefore, can be controlled if the quality of the irrigation water is satisfactory and if the flow of water through the soil can be controlled.

The concentration of soluble salts in the soil solution is increased as water is removed from the soil by evaporation and transpiration. Desiccation of surface soil by transpiration and by evaporation creates a suction gradient that will produce an appreciable upward movement of water and salt. This upward flow, especially if the water table is near the soil surface, is a process by which many soils become salinized.

Soluble salts increase or decrease in the root zone, depending on whether the net downward movement of salt is less or greater than the net salt input from irrigation water and other sources. The salt balance in soil, as affected by the quantity and quality of irrigation water and the effectiveness of leaching and drainage, is of paramount importance. If irrigation agriculture is to remain successful, soil salinity must be controlled (Scofield, 1940).

Equilibrium reactions occur between the cations in the soil solution and those adsorbed on the exchange complex of the soil. The use of amendments for changing the exchangeable-cation status of soil depends upon these equilibrium reactions. Adsorption of excessive amounts of sodium is detrimental to the physical status of the soil and may be toxic to plants. When the exchangeable-sodium content of soil is excessive or tends to become so, special amendment, leaching, and management practices are required to improve and maintain favorable soil conditions for plant growth.

Whether soil particles are flocculated or dispersed depends to some extent upon the exchangeable-cation status of the soil and, also, upon the ionic concentration of the soil solution. Soils that are flocculated and permeable when saline may become deflocculated when leached.

Irrigation and Leaching in Relation to Salinity Control

Irrigation is the application of water to soil for the purpose of providing a favorable environment for plants. Leaching, in agriculture, is the process of dissolving and transporting soluble salts by the downward movement of water through the soil. Because salts move with water, salinity depends directly on water management, i. e., irrigation, leaching, and drainage. These three aspects of water management should be considered collectively in the over-all plan for an irrigated area if maximum efficiency is to be obtained.

Irrigation

In subhumid regions, when irrigation is provided on a standby or supplemental basis, salinity is usually of little concern, because rainfall is sufficient to leach out any accumulated salts. But in semiarid or arid regions salinity is usually an ever-present hazard and must be taken into account at all stages of planning and operation.

The subject of water quality in relation to irrigation is discussed at length in chapter 5 and is mentioned here only to emphasize the fact that water quality must be considered in determining the suitability of soils for irrigation. In general, waters with high salt contents should not be used for irrigation on soils having low infiltration and drainage rates. The higher the salt content of the water, the greater the amount of water that must be passed through the soil to keep the soluble-salt content at or below a critical level. Experience indicates that there are soils in which low water-movement rates make the cost of drainage so high that irrigation agriculture is not feasible under present economic conditions.

Pumping from ground water for irrigation has several advantages. It often affords direct local control of the water table when water is pumped from unconfined or partially confined aquifers. This has been demonstrated in the Salt River Valley, Arizona, the San Joaquin Valley, California, and elsewhere. Wells can often be located on the farm, thereby eliminating the need for elaborate distribution systems. Water is available for use at all times, which provides maximum flexibility in irrigation. If it is pbssible to obtain irrigation water from both ground-water and surface supplies, a balance between the two sources can often be established to insure favorable drainage of the irrigated soils. Another indirect advantage of pumping water for irrigation comes from the fact that the direct visible cost of operating pumps causes the farmer to avoid the wasteful overuse of water which often is the cause of the need for drainage improvement.

Excessive losses from water conveyance and distribution systems must be prevented, otherwise drainage problems will be aggravated with attendant salinity hazards. Distribution systems and irrigation schedules should be designed so that water is available at times and in amounts needed to replenish the soil moisture without unnecessary use on irrigated fields and without regulatory waste of water which may directly or indirectly contribute to unfavorable drainage conditions. In some cases, water is used under continuous free-flow systems to maintain water rights rather than on a basis of consumptive use. Salinity and drainage problems could undoubtedly be alleviated in some areas by changing to a system of direct charge for the volume of water used.

The quantity of water available for irrigation may have a marked effect upon the control of salinity. In areas where water is cheap and large volumes are used, irrigation practices are often inefficient. Overuse and waste of irrigation water contribute to drainage difficulties and salinity problems. Efficient irrigation practices can be developed more readily in the planning of irrigation systems than by applying corrective measures on the farm. Limited quantities of water should be supplied, based upon consumptive use and leaching requirements, for the area in question. Where an abundant supply of water is available for irrigation, restrictions may become necessary if drainage problems arise. Water requirements for leaching are discussed in a following section.

Lining canals to reduce seepage losses and the distribution of water by underground pipe systems should receive careful consideration. Much can be done in the layout of distribution systems to reduce seepage losses by locating canals and laterals properly. In some areas, earth and asphalt linings for irrigation canals have been used successfully. The buried asphalt membrane lining used by the United States Bureau of Reclamation on a number of projects has been shown to be effective in reducing seepage losses. In the Coachella Valley, California, an underground concrete-pipe distribution system, and a concrete-lined main canal, serve approximately 70,000 acres of land. Reduction of seepage losses and improvement in drainage conditions were major factors in the selection of these facilities.

Automatic control of distribution systems, combined with lined canals and laterals, is being used successfully in Algeria and elsewhere to eliminate regulatory waste and to reduce the cost of operation. Automatic control makes water available at the farm at all times and allows water to be taken out or shut off from the main distribution system at laterals or at farm outlets at any time. All regulatory changes to maintain proper flow from the point of diversion to the farm are performed automatically. This eliminates waste on the farm and throughout the system. Older irrigation districts with drainage and salinity problems might well consider some of the advantages of the newly developed automatic distribution systems. A modernization of the distribution system in some cases may be the most economical way to solve a drainage problem.

The selection of an irrigation method for applying water to the soil is related to salinity. The method that is best adapted in any particular case depends upon a number of conditions: The crop to be grown, topography, soil characteristics, availability of water, soluble-salt content of the water, and salinity status of the soil. The primary objective of any irrigation method is to supply water to the soil so that moisture will be readily available at all times for crop growth, but soil salinity is definitely an influencing factor.

It is desirable, both for plant use and for leaching, to apply the water uniformly over the irrigated area.

The four principal methods used for the application of water are flooding, furrow, sprinkling, and subirrigation.

The flooding method should be favored if salinity is a serious problem. Wild flooding, border-strip or border-check flooding, and basin flooding are used. Wild flooding is not practiced extensively, except for pastures, alfalfa, and small grains. This method can be used only in relatively level areas where water can be flooded over the surface without the use of levees or borders for control. The border-strip or border-check method of irrigation utilizes levees or borders for control of the water. The water is not impounded by this method, except perhaps at the lower end of the strip, but is flooded over the surface and down the slope in the direction of the borders. It is adapted for use with alfalfa and grains and in orchards; but excessive water penetration near the head ditch and at the ends of the strips usually results. There is a tendency for insufficient penetration to occur midway or two-thirds of the way down the strip which generally causes salt to accumulate in this location.

The basin method of flooding is often used for orchards and various other crops in areas where water can be impounded in a rectangular basin. A variation of this method is the contour-basin method. Borders are constructed along the contours at intervals of about 0.1 to 0.2 foot. This allows larger basins to be made where there is appreciable slope. The basin methods of irrigation provide better control of the depths of water applied and greater uniformity in application than border or furrow methods.

Furrow irrigation is well adapted to row crops and is suitable for use where the topography is too rough or steep for other methods. With this method there is a tendency for salts to accumulate in the ridges, because the leaching occurs only in the furrows. Wide-bottomed furrows that resemble narrow border strips have certain advantages for wetting the soil surface uniformly and thereby controlling salt accumulation in a larger fraction of the root zone. Where the area is plowed and the surface soil is mixed occasionally, the increase in salt over a period of time may not be serious. If excess salt does accumulate, rotation of crops accompanied by a change in method of irrigation to flooding or ponding is often possible as a salinity-control measure. In the furrow and border-check methods the length of run, size of stream, slope of the land, and time of application are factors that govern the depth and uniformity of application. Proper balance among these factors, therefore, is directly related to leaching and salinity control.

Irrigation by sprinkling is generally more costly than by other methods and has not been used extensively until recent years. Originally this method was used primarily for orchards, truck crops, and nurseries ; but its use has been extended to include sugar beets, peas, beans, and many other crops. This method allows a close control of the depth of water applied and when properly used results in uniform distribution. It is often used in areas where the slope is too great for other methods. There is a tendency to apply too little water by this method ; and, unless a special effort is made, leaching to maintain the proper salt balance will not be accomplished.

Subirrigation is the least common of the various methods of irrigation and is not suitable for use where salinity is a problem. Even under the most favorable circumstances, this method does not appear to be suitable for long-time use unless periodic leaching is accomplished by rainfall or surface irrigations.

Leaching

The leaching of soluble salts from the root zone is essential in irrigated soils. The need for leaching can be illustrated by considering the effect that salts in irrigation water have upon the salinity of soil if no leaching occurs. Without leaching, salts accumulate in direct proportion to the salt content of the irrigation water and the depth of water applied. The concentration of the salts in the soil solution results principally from the extraction of moisture from the soil by the processes of evaporation and transpiration. Assuming no precipitation of soluble constituents during the salinization process, the depth of irrigation water (D_{iw}) of known electrical conductivity (EC_{iw}) that will contain sufficient salt to increase the electrical conductivity of the saturation extract of a depth of soil (D_s) by an amount ($\triangle EC_e$) can be calculated from the equation :

$$D_{iw}/D_s=(d_s/d_w)\quad(SP/100)\quad(\triangle EC_e/EC_{iw})\qquad(1)$$

where d_s/d_w is the ratio of the densities of the soil and the water, and SP is the saturation percentage.[6]

As an example, let: $EC_{iw}\times10^6=1{,}000$, $d_s=1.2$ gm. cm.$^{-3}$, $d_w=1$ gm. cm.$^{-3}$, and $SP=40$. Make the calculation for a change in electrical conductivity of the saturation extract of 4 mmhos/cm., or $\triangle EC_e\times10^6=4{,}000$. Substituting these values in the equation we find $D_{iw}/D_s=1.9$. Thus less than 2 feet of reasonably

[6] For the purposes of this problem, electrical conductivity of water is a satisfactory measure of salt concentration. If D_{iw} represents the depth of irrigation water applied and D_{sw} represents the equivalent free depth of this water after entering the soil and being concentrated by transpiration and evaporation, then $D_{iw}/D_{sw}=EC_{sw}/EC_{iw}$, where the right-hand side of the equation is the ratio of the electrical conductivities of the soil water and the irrigation water. The conductivity of the saturation extract EC_e provides a convenient scale for appraising soil salinity; therefore, consider the condition where the content of moisture in the soil is the saturation percentage and $\triangle EC_e$ is the increase in soil salinity produced by the water application under consideration. For this case, the depth of soil water (D_{sw}) contained in a depth of soil (D_s) is given by the relation

$$D_{sw}=\frac{d_s}{d_w}\cdot\frac{SP}{100}\,D_s$$

Substituting these values in the above equation and rearranging gives :

$$\frac{D_{iw}}{D_s}=\frac{d_s}{d_w}\cdot\frac{SP}{100}\cdot\frac{\triangle EC_e}{EC_{iw}}\qquad(1)$$

The equation makes it possible to calculate the depth of irrigation water per unit depth of soil required to produce any specified increase in soil salinity expressed in terms of $\triangle EC_e$, for any given conductivity of the irrigation water (EC_{iw}).

good quality irrigation water contains sufficient salt to change a l-foot depth of a salt-free loam soil to a saline condition, if there is no leaching or precipitation of salt in the soil.

Hundreds of thousands of acres of land in western United States have been profitably irrigated for many years with water having an electrical conductivity value approximating 1,000 micromhos/cm. It is apparent that considerable leaching has been provided, since almost enough salt is added to the soil each season to make the soil saline. With this quality of water, salinity troubles have occurred if the watkr table has approached to within 3 or 4 feet of the surface of the soil. In such cases extensive drainage and leaching operations have been necessary. Some areas have been abandoned, because it was not economically feasible to provide soil drainage sufficient to take care-of required leaching.

Leaching Requirement

The leaching requirement may be defined as the fraction of the irrigation water that must be leached through the root z&e to control soil salinity at any specified level.[7] This concept has greatest usefulness when applied to steady-state water-flow rates or to total depths of water used for irrigation and leaching over a long period of time. Obtaining calculated or experimentally determined values of the leaching requirement is complicated by many factors, but it is profitable to consider some simplified theoretical cases. The leaching requirement will depend upon the salt concentration of the irrigation water and upon the maximum concentration permissible in the soil solution. The maximum concentration, except for salt crusts formed by surface evaporation, will occur at the bottom of the root zone and will be the same as the concentration of the drainage water from a soil where irrigation water is applied with areal uniformity and with no excess leaching. Increase of the concentration of salts from the value existing in the irrigation water to the value occurring in the drainage water is related directly to consumptive use. On cropped areas this will consist mostly of water extracted from the soil by roots and so will depend on the salt tolerance of the crop. Expressed in terms of electrical conductivity, the maximum concentration of the soil solution should probably be kept below 4 mmhos/cm. for sensitive crops. Tolerant crops like beets, alfalfa, and cotton may give good yields at values up to 8 mmhos/cm., while a very tolerant crop like barley may give good yields at values of 12 mmhos/cm. or higher.

To illustrate the significance of the leaching requirement, consider first the simplest possible case with the following assumed conditions : Uniform areal application of irrigation water; no rainfall; no removal of salt in the harvested crop; and no precipitation of soluble constituents in the soil. Also, the calculation will be based on steady-state water-flow rates or the total equivalent depths of irrigation and drainage waters used over a period of time. With these assumptions, moisture and salt storage in the soil, depth of root zone, cation-exchange reactions, and drainage conditions of the soil do not need to be considered, providing that drainage will permit the specified leaching. The leaching requirement (LR) as defined above, is simply the ratio of the equivalent depth of the drainage water to the depth of irrigation water (D_{dw}/D_{iw}) and may be expressed as a fraction or as percent. Under the foregoing assumed conditions, this ratio is equal to the inverse ratio of the corresponding electrical conductivities, that is:

$$LR=\frac{D_{dw}}{D_{iw}}=\frac{EC_{iw}}{EC_{dw}} \qquad (2)$$

For field crops where a value of $EC_{dw}=8$ mmhos/cm. can be tolerated, the formula would be $D_{dw}/D_{iw}=EC_{iw}/8$. For irrigation waters with conductivities of 1, 2, and 3 mmhos/cm., respectively, the leaching requirements will be 13, 25, and 38 percent. These are maximum values, since rainfall, removal of salt by the crop, and precipitation of salts such as calcium carbonate or gypsum in the soil are seldom zero; and, if properly taken into account, these factors all would enter in such a way as to reduce the predicted value of the leaching requirement.

Some care must be exercised in using equation 2, to make sure that the condition of steady-state or longtime average is understood. The equation does not apply if leaching is automatically taken care of by rainfall. Depending on soil texture and depth to water table, this may be the case even in semiarid regions, if the precipitation is confined to a small fraction of the year. Under these conditions, equation 1, which gives the buildup of salinity with depth of irrigation water applied, is useful for predicting salinity increases during an irrigation season or over a period of several seasons when rainfall may be abnormally low.

As an average over a long time, the conductivity of the irrigation water used in equation 2 should be a weighted average for the conductivities of the rainwater (EC_{rw}), and the irrigation water (EC_{iw}), i. e.:

$$EC_{(rw+iw)}=\frac{D_{rw}EC_{rw}+D_{iw}EC_{iw}}{D_{rw}+D_{iw}} \qquad (3)$$

[7] In the report of the U. S. National Resources Committee (1938), C. S. Scofield with the cooperation of R. A. Hill, proposed a formula for what was called "service equivalence," in which the concentration of the drainage water and the concentration of the irrigation water are taken into account. In addition to the salt removed through drainage, it is inherent with this formula that soluble salt is removed from the soil at a rate equal to the consumptive use of water times half the concentration of the irrigation water.

A further contribution to this subject was made at the Irrigation Conference sponsored by the Texas Agricultural Experiment Station at Ysleta, Texas: in July 1951." At this conference, F. M. Eaton proposed what he called a "drainage formula" for calculating the fraction of the irrigation water to be used for leaching. A private communication-to the Laboratory from F. M. Eaton, under date of August 1952, contained a mimeographed paper entitled "Formulas for estimating drainage and gypsum requirements for irrigation waters," in which the bases for the Ysleta formula are presented.

where D_{rw} and D_{iw} are the depths, respectively, of the rainwater and irrigation water entering the soil. Long-time averages may deviate markedly from actual conditions at any one time, as, for example, if the entire root zone is leached through during a short period of extra high rainfall.

Tnformation on the consumptive use of water by the crop is necessary if the leaching-requirement concept is to be used for determining either the depth of irrigation water that must be applied or the minimum depth of water to be drained, in order to keep the soil salinity from exceeding a specified value. The depth of irrigation water (D_{iw}) is related to consumptive use, (D_{cw}) and the equivalent depth of drainage water (D_{dw}) by the equation:

$$D_{iw}=D_{cw}+D_{dw} \tag{4}$$

Using equation 2 to eliminate D_{dw} from equation 4 gives:

$$D_{iw}=D_{cw}/(1-LR) \tag{5}$$

Expressing the leaching requirement (LR) in this equation in terms of the conductivity ratio in equation 2 gives:

$$D_{iw}=\left(\frac{EC_{dw}}{EC_{dw}-EC_{iw}}\right)D_{cw} \tag{6}$$

The depth of irrigation water (D_{iw}) is thus expressed in terms of the electrical conductivity of the irrigation water and other conditions determined by crop and climate; namely, consumptive use and salt tolerance of the crop. The salt tolerance of the crop is taken into account in the selection of permissible values of EC_{dw}. Equations 5 and 6 are subject to the assumptions made in deriving equation 2.

Under actual farming conditions, the depth of water applied per irrigation and the areal uniformity of application are certainly not precisely controlled. Measured water application efficiencies often run as low as 25 percent and seldom exceed 80 percent. Under these conditions, high precision in the determination of the leaching requirement has little significance. A formula like equation 2 would appear to have greatest usefulness in connection with the more saline irrigation waters, and for this case it appears to be justifiable to disregard the salt removed from the soil in the harvested crops. Consider alfalfa growing in the Imperial Valley, California, where 6 tons per acre of sun-cured hay is a common annual yield. The salt added to the soil in the irrigation water consumed by this crop would be about 4 tons. Of this salt, not more than 0.4 ton would be removed in the harvested crop. Under these conditions, therefore, neglecting the salt removed in the crop overrates the salt input to the soil by a factor of about one-tenth. Taking $EC_{dw}=8$ and $EC_{iw}=1$, the calculated steady-state leaching requirement for salt-tolerant crops of the Imperial Valley is 13 percent. A fractional error of one-tenth in this value would not be serious, in view of other uncertainties involved in the practical use of the figure.

The relative significance of the salt removed in the harvested crop will increase as the salt input from irrigation water decreases, but for soils with normal drainage the practical usefulness of a calculated value of the leaching requirement decreases as the salinity of the irrigation water decreases. A special case exists where leaching is severely restricted by low soil permeability and the salt content of the water is also very low. Under these conditions, salt removed from the soil in the harvested crop might conceivably become an important factor determining the permanence of irrigation agriculture.

The steady-state leaching requirement (equation 2), expressed in terms of electrical conductivity, is convenient where soil moisture availability to plants and osmotic pressure relations are the principal concern. Cation exchange is known to effect a change in the relative composition of irrigation and drainage waters, but this process is stoichiometric and does not enter explicitly in the equation. It may happen, however, that with a particular irrigation water and a particular crop, some specific toxic constituent as, for example, the chloride ion or boron, might comprise the most critical problem. A leaching requirement for this constituent could then be calculated, provided some maximum permissible concentration of the toxic ion C_{dw} in the water draining from the soil can be specified and provided also that the other assumptions previously made are tenable. The leaching requirement equation then becomes:

$$\frac{D_{dw}}{D_{iw}}=\frac{C_{iw}}{C_{dw}} \tag{7}$$

where C_{iw} is the concentration of the toxic ion in the irrigation water.

There will be instances, of course, where precipitation of soluble constituents in the soil cannot be neglected when calculating the leaching requirement. Gypsum is deposited in soils from some irrigation waters. Data are being accumulated on the precipitation of calcium and magnesium with bicarbonate in the irrigation water. This latter reaction is considered in chapter 5 on irrigation water quality. Taking precipitation effects into account complicates a leaching requirement equation and will not be included in the present discussion. It should be recalled again that the foregoing equations are based on the assumptions: uniform water application to the soil, no precipitation of soluble salt in the soil, negligible salt removal in the harvested crop, and soil permeability and drainage adequate to permit the required leaching.

Quantitative consideration of the leaching requirement is important when drainage is restricted or when the available irrigation water is efficiently used. If a large fraction of the water diverted for irrigation is wasted in various conveyance, regulatory, and, especially, application losses, then estimates of leaching requirement have little practical significance.

Leaching Methods

Leaching can be accomplished by ponding an appreciable depth of water on the soil surface by means of dikes or ridges and thus establishing downward water movement through the soil. This is the most effective procedure that can be used for removing excess soluble salts from soil. Contour checks can be used for ponding water on the soil where there is considerable slope. Contour borders ranging from **1.5** to 4 ft. or more high are constructed at elevation intervals ranging from 0.2 to 0.5 ft. Overflow gates, placed in the borders connecting adjacent plots, facilitate the control of water and allow a number of contour checks to be kept full simultaneously. Frequent applications of excess irrigation water applied by flooding between border strips while a crop is being grown are sometimes used for leaching. The effectiveness depends upon how uniformly the water is applied and how much water passes through the soil. Either continuous flooding or periodic water applications may be used for leaching. If the soil transmits water slowly, periodic drying may improve infiltration rates.

In cold climates, leaching operations can often be conducted in the fall after the crops mature and before the soil freezes. In warmer climates, leaching operations can be conducted during winter when the land would otherwise be idle. At this time, also. water may be more plentiful and the water table and drainage conditions more favorable than during the regular irrigation season. Unless drainage is adequate, attempts at leaching may not be successful, because leaching requires the free passage of water through and away from the root zone. Where drainage is inadequate, water applied for leaching may cause the water table to rise so that soluble salts can quickly return to the root zone.

Visible crusts of salt on the surface of saline soils have sometimes led to the use of surface flushing for salt removal, i. e., the passing of water over the soil surface and the wasting of the runoff water at the bottom of the field. This method does not appear to be sufficiently effective to be worth while for most field situations. All known tests of the flushing method under controlled conditions confirm this conclusion. Turbulence in the flowing water causes some mixing, but mostly the water at the soil surface that contacts and dissolves the salt moves directly into the dry soil during the initial wetting process when the infiltration rate is highest. In one test the salt added to the soil in the water used for flushing exceeded the amount of salt removed in the waste water.

The depth of water required for irrigation and leaching and the effect of leaching on the depth to water table can be estimated with the aid of the nomograms given in figure 8, chapter 2. The following examples will serve to illustrate the use of the nomograms in connection with irrigation, leaching, and drainage.

(a) For a uniform soil with an initial moisture percentage of 10, an upper limit of field moisture of 20 percent, and a bulk density of 1.6 gm. cm.?, how deeply will a 6-in. irrigation wet the soil? In the left nomogram of figure 8, place a straightedge on 1.6 of the scale B_1 and on 10 of scale A. Scale C_1 then indicates that 1.94 in. of water are required to raise the moisture content of 1 foot of this soil by 10 percent. Therefore, $6/1.94 = 3.09$ ft.=37 in. is the depth of wetting.

(*b*) For a uniform soil with an initial moisture content of 12.5 percent, an upper limit of field moisture of 25 percent, and a bulk density of 1.3 gm. cm.?, what depth of water must be applied to make 3 in. of water pass through the soil at the 4-ft. depth? Evidently the moisture content of the surface 4 ft. of soil must be increased by 12.5 percent before leaching will occur. Place a straightedge on 1.3 of the left nomogram of scale B, (fig. 8), and on 12.5 of scale A. Scale C_1 then indicates that 2 in. of water per foot of soil are required to change the moisture percentage of this soil from 12.5 to 25. Eight inches of water would be required to bring the top 4 ft. of soil to the upper limit of moisture retention, and therefore 11 in. of irrigation water should be applied in order to cause 3 in. of water to pass below the 4-ft. depth.

(c) For a uniform soil with a bulk density of 1.5 gm. cm.? and an average moisture content of 20 percent over a depth interval of 1 foot above the water table, what depth of water in surface inches, when added to the ground water, will make the water table rise 1 foot? Assume the particle density (real density) of the soil is 2.65 gm. $cm.^{-3}$. In the right-hand nomogram of figure 8, place a straightedge on 1.5 of scale A, and on 2.65 of scale B,. Scale C_1 then indicates a porosity of 0.44. Consequently, this soil when completely saturated will hold 0.44 ft. of water per foot of soil. In the left nomogram place a straightedge on 20 of scale A_1 and 1.5 of scale B_1. Scale C_2 then indicates that a moisture content of 20 percent corresponds to 0.3 ft. of water per foot of soil. Subtracting this from 0.44 indicates that 0.14 ft. of water per foot of soil, or (from scales C_1 and C,) 1.7 surface inches of water is sufficient to bring 1-ft. depth of this soil to saturation and hence to cause a rise of approximately 1 foot in the ground-water level.

Field Leaching Trials

Numerous field trials have demonstrated the effectiveness of leaching for salt removal. For example, Reeve and coworkers (1948) found that gypsiferous, saline-alkali soils in the Delta Area, Utah, are reclaimable by leaching with 4 ft. of water. The right-hand curve in figure 12 shows the salt distribution with depth at the beginning of leaching tests. This soil had been idle for many years, with the water table fluctuating between 2 and 5 feet below the soil surface. Leaching treatments of 0, 1, 2, and 4 ft. of water were applied to test plots. The curves in the figure show the resulting change in salt content with depth. Wheat was planted and subsequently irrigated with 18 to 24 in. of water in 3 applications of 6 to 8 in. each. In addition, approximately 12 in. of rain fell during the winter months, making a total of 30 to 36 in. of water applied in addition to the initial differential leaching treatments. The increase in yield of wheat was approximately linear in relation to the depth of water used for leaching (fig. 13).

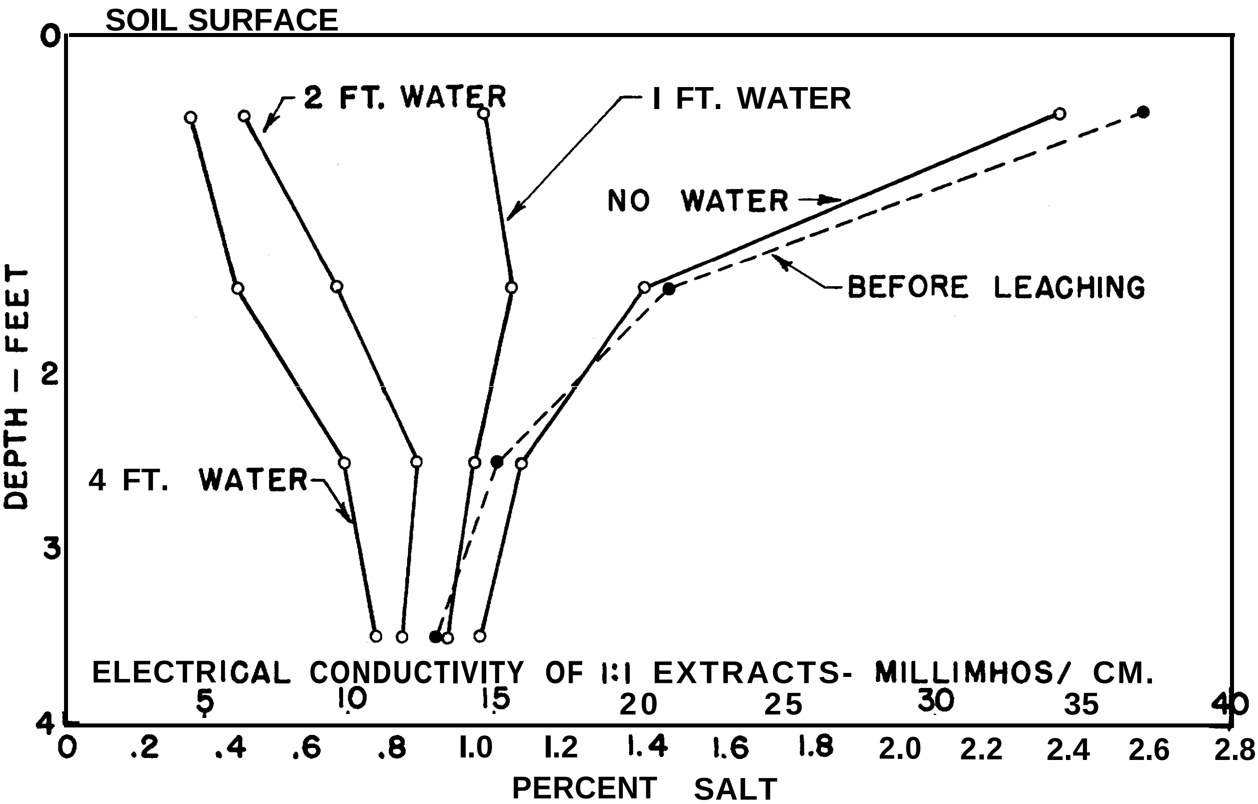

FIGURE 12.-Distribution of salt content with depth as related to depth of water applied for leaching in the Delta Area, Utah (Reeve and others, 1948).

Leaching practices, although basically the same, may vary from one region to another. In the Delta Area tests, the ponding method was used, and water was added in successive increments until the total amount for leaching had been applied. About 10 days were required to leach the plots with 4 ft. of water. In some parts of the Imperial and Central Valleys of California, where infiltration rates are low, water is ponded on the surface by the contour-check method for periods up to 120 days. In such instances, rice is sometimes grown to aid in the reclamation process and also to provide income during leaching. In other areas, rice is included regularly in the crop rotation as an aid in salinity control.

In addition to the removal of excess salts and exchangeable sodium, other practices are usually required for complete reclamation. Plant nutrients that are leached from the soil must be replaced, and fertilizer practices following leaching should compensate for plant nutrient losses. Nitrogen is the principal nutrient subject to leaching loss. Soil structure that may have deteriorated during the salinization or alkalization process must be restored. Unfavorable soil structure after leaching is sometimes a special problem and may be improved by adding manure or other forms of organic matter, by growing crops that are beneficial to structure, or by alternate wetting and drying, as indicated by the field tests of Reitemeier and associates (1948) and Bower and coworkers (1951).

Special Practices for Salinity Control

The failure to recognize that saline and alkali soils require special management practices can result in low production or in complete crop failure. These special practices can be followed over a period of time to improve lands that are partially affected or to prevent reclaimed lands from again becoming unproductive. Where only irrigation water of poor quality is available or where drainage and full-scale reclamation are not economically feasible, it may be possible to carry on successfully what might be referred to as "saline agriculture." Irrigation, leaching, and tillage practices can all be directed toward salinity control. Salt-tolerant crops can be selected and chemical amendments used when necessary.

Many crop failures result from growing crops that have low salt tolerance. Alfalfa, barley, sugar beets, and cotton are tolerant crops that can often be grown where salinity is a problem. Lists of salt-tolerant fruits, vegetables, field, and forage crops are given in chapter 4.

In general, irrigation methods and practices that provide uniformity of application and downward movement of water through soils favor salinity control. Methods that pond or flood water over the soil surface, such as border, check, and basin methods of irrigation, give greater uniformity of application than furrow or corrugation methods. Only part of the surface is covered by water with the furrow and corrugation methods so that movement of water is downward and outward from the furrow and is upward into the ridges. Wadleigh and Fireman (1949) have shown that by furrow irrigation excessive amounts of salts concentrate in the ridges. Salt distribution resulting from furrow irrigation in a test plot that was salinized initially to 0.2 percent is shown in figure 14. They further showed that cotton plants in the ridges extracted moisture mainly from beneath the furrows where leaching occurred and that there was little root activity in the ridges.

Germination and emergence of plants is often a critical factor in over-all production. Ayers (1951) has shown that the germination of seeds is greatly retarded and that the number of seeds germinating may be materially decreased by salinity. If favorable conditions can be maintained during the germination and seedling stages, certain crops may make fair growth even under moderately high salinity conditions. Heald and others (1950) conducted experiments in Washington on the preemergence irrigation of beets. They showed that irrigation next to the seed row caused movement of salts away from the seeds and into the ridges. Thie allowed the seeds to germinate and to become established in essentially nonsaline conditions, thereby increasing yield by increasing stand (fig. 15). Further over-all leaching increased sugar beet yields.

Careful leveling of land makes possible more uniform application of water and better salinity control. Barren spots that appear in otherwise productive fields are often the result of high spots that do not get sufficient water for good crop growth and likewise do not get sufficient water for leaching purposes. Lands that have been irrigated 1 or 2 years after leveling can often be improved by replaning. This removes the surface unevenness caused by the settling of fill material. Annual crops should be grown following land leveling, so that replaning after 1 or 2 years of irrigation can be accomplished without crop disturbance.

Crusting of the soil and failure of seedlings to emerge may indicate an alkali condition that might be corrected by amendments. Irrigating more freqhently, especially during the germination and seedling stage, will tend to soften hard crusts and help to get a better stand.

Drainage of Irrigated Lands in Relation to Salinity Control

Drainage in agriculture is the process of removal of excess water from soil. Excess water discharged by flow over the soil surface is referred to as surface drainage, and flow through the soil is termed internal or subsurface drainage. The terms "artificial drain-

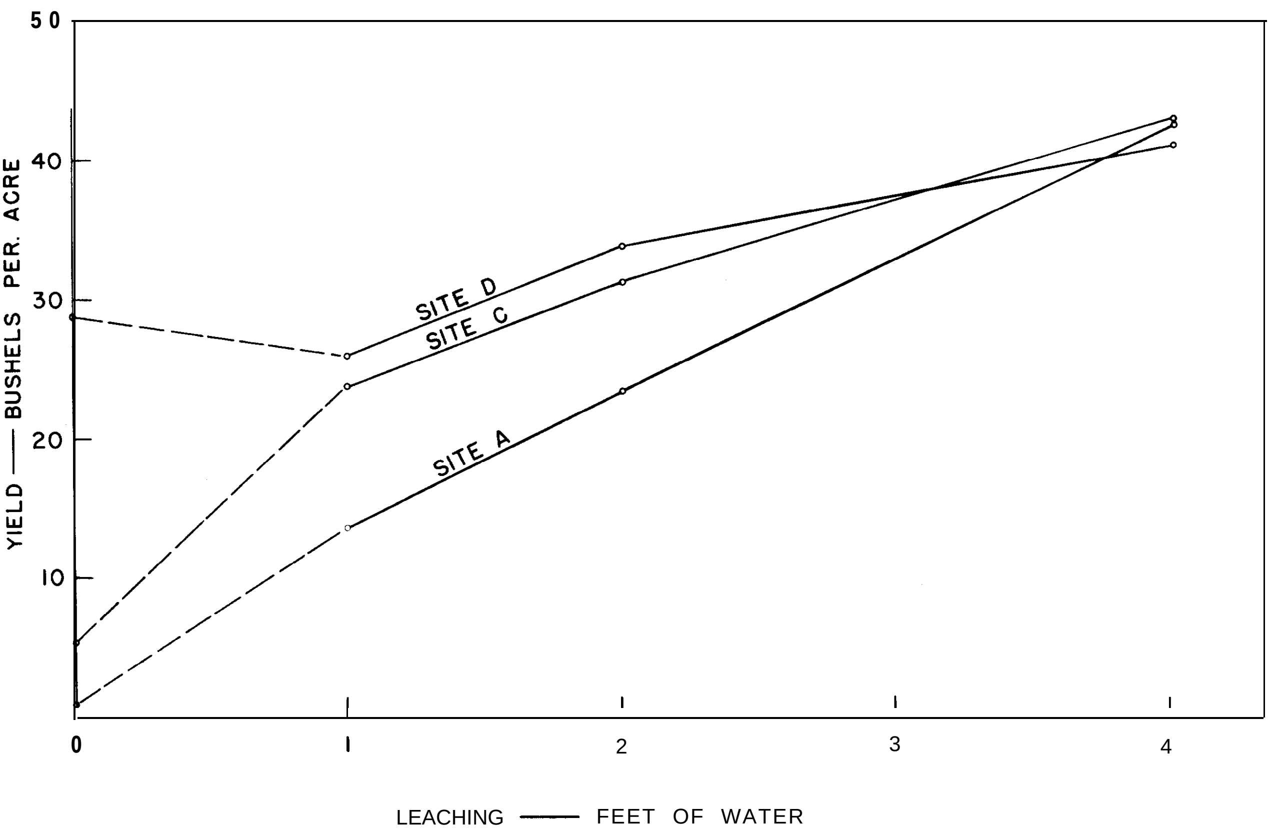

FIGURE 13.-Grain yields as related to the depth of water used for leaching in the Delta Area, Utah (Reeve and coworkers, 1948).

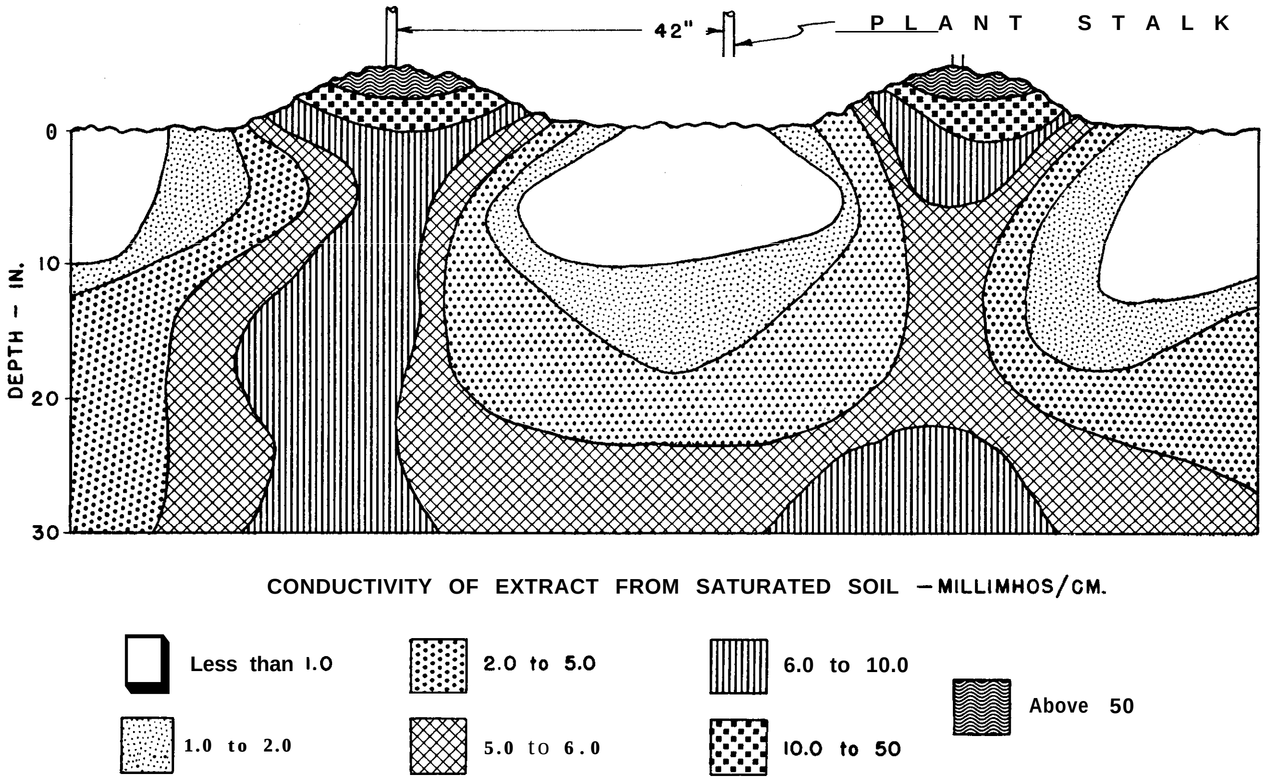

FIGURE 14.-Salt distribution under furrow-irrigated cotton for soil initially salinized to 0.2 percent salt and irrigated with water of medium salinity (Wadleigh and Fireman, 1949).

age" and "natural drainage" indicate whether or not man has changed or influenced the drainage process.

Irrigated land is drained primarily to increase agricultural productivity, but there are other beneficial effects. Areas that are poorly drained require the expenditure of large sums of money annually for construction of highway subgrades and for safeguarding public health, since mosquito control and other disease problems are related to drainage conditions. Drainage improvements serve many public and private interests, and the justification for drainage improvements should be based upon all benefits that may be derived therefrom.

The drainage program for irrigated land should be initiated and continuously integrated with the development of the irrigation system in order to attain an efficient over-all water and salinity control program. The removal of excess water and salts must be considered in every irrigation enterprise. Excess water may be partially discharged or removed from the soil by natural means, but often supplementary drainage facilities are required. Irrigation practices, together with methods of distributing water, are related to drainage, and sometimes the need for artificial drainage facilities may be lessened or avoided altogether by efficient management of irrigation water.

The design of drainage systems is influenced by many factors, and there are no simple rules or formulas by which all of these factors can be taken into consideration. However, the principal factors can be grouped under drainage requirements, water-transmission properties of soil, and boundary conditions.

Drainage Requirements

The permissible depth and mode of variation of the water table with respect to the soil surface and the quantity of water that a drainage system must convey, both surface and subsurface, relate to drainage design and may be referred to as the drainage requirements. The climate, the quality of the irrigation water, the characteristics of the soil, the crops, and the cropping system must all be considered in the determination of drainage requirements for any given locality.

The adequacy of drainage for agricultural purposes depends upon whether or not there is an excess of water on or in the soil for periods of time that are detrimental to crops. Inadequate aeration of the soil may be a direct consequence of inadequate drainage and may result in a limitation of growth of plants or severe damage to root systems through pathological, physiological, or nutritional disturbances, or through limitation of the effective depth of the root zone. The optimum moisture content of the soil for tillage and other farming practices is also involved because farm operations can be seriously delayed by wet soil.

In irrigated regions the adequacy of drainage is related to salinity. Salts in the irrigation water, in the soil, or in shallow ground waters increase the drainage requirements. In addition to aeration effects and soil-moisture requirements for tillage, a minimum allowable water-table depth that will permit adequate leaching and that will prevent concentration of salts in the root zone by upward flow must be established. The depth to the water table must be such that upward flow of saline ground water into the root zone is reduced or eliminated. Thus, irrigation, leaching, and soil-management practices that are involved in the control of salinity are important in establishing drainage requirements.

As a minimum requirement, a drainage system must be adequate to remove from the soil the equivalent depth of water that must be passed through the root zone in order to maintain a favorable salt balance. With a knowledge of the consumptive use, the minimum amount of water required to be drained can be estimated by the use of equations 2 and 4:

$$LR=\frac{D_{dw}}{D_{iw}}=\frac{EC_{iw}}{EC_{dw}} \qquad (2)$$

$$D_{iw}=D_{cw}+D_{dw} \qquad (4)$$

Equation 2 gives the fraction of the water applied as irrigation that must pass through and beyond the root zone to maintain the electrical conductivity of the drainage water below a specified value (EC_{dw}) for the steady-state or long-time average salt-balance conditions. Equation 4 gives the depth of irrigation water (D_{iw}) as a function of consumptive use (D_{cw}) and the equivalent depth of drainage water (D_{dw}). Solving equation 2 for D_{iw}, substituting in equation 4, and rearranging gives:

$$D_{dw}=\frac{D_{cw}}{1-LR}LR \qquad (8)$$

Expressing LR in this equation in terms of the conductivity ratio of equation 2 gives:

$$D_{dw}=\frac{EC_{iw}}{EC_{dw}-EC_{iw}}D_{cw} \qquad (9)$$

The depth of the water to be drained (D_{dw}) is thus expressed in terms of the electrical conductivity of the irrigation water and other conditions determined by the crop and climate; namely, consumptive use and salt tolerance of the crop. The salt tolerance of the crop is taken into account in the selection of permissible values of EC_{dw}. Equations 8 and 9 are subject to the assumptions made in deriving equation 2.

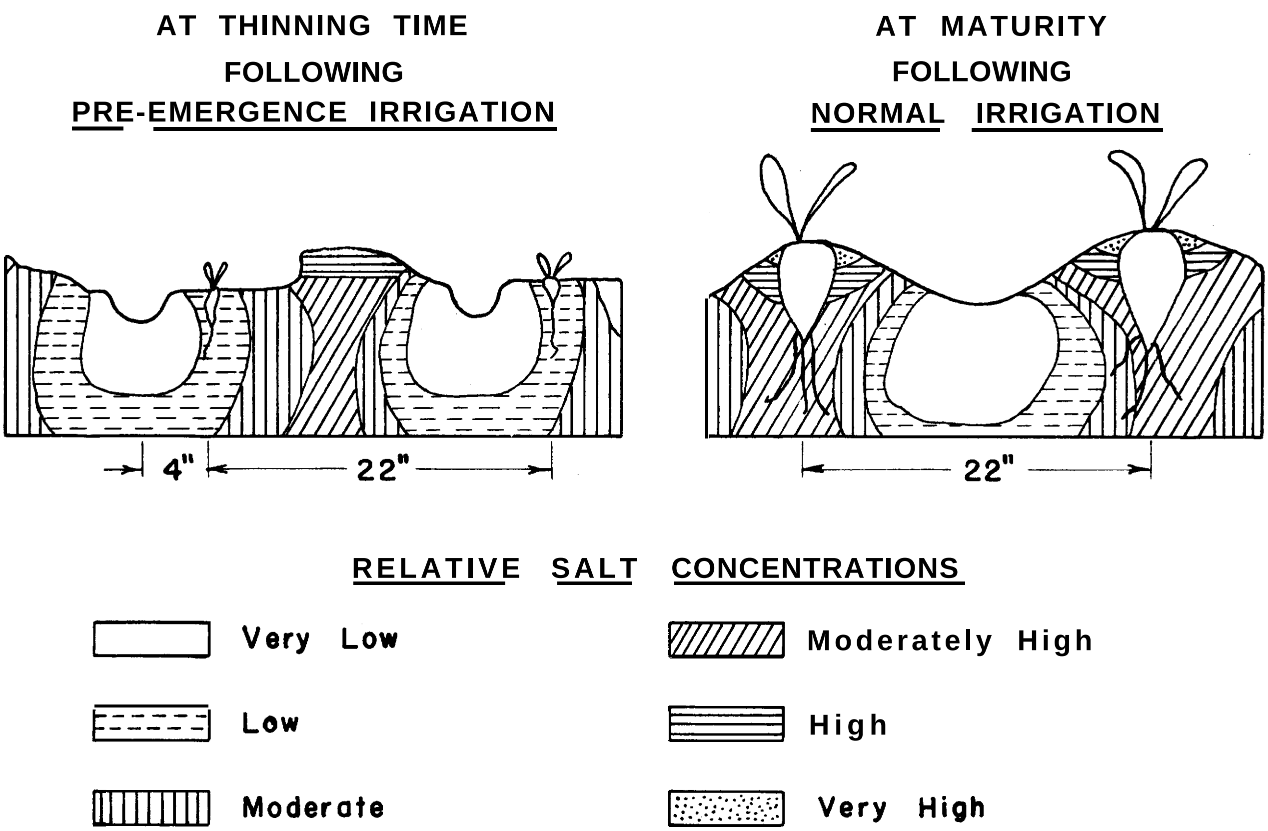

FIGURE 15.-Salt concentration in the vicinity of growing beets as related to position in the furrow (redrawn from Heald and others, 1950).

The term D_{dw} in the equation does not include drainage water that moves in-laterally from adjacent areas and that must pass into and through the drainage system, but represents only the depth by which irrigation water, assumed to be applied uniformly at the soil surface, exceeds the consumptive use. For any specified EC_{dw}, which depends upon the salt tolerance of the crop, the depth of drainage water (D_{dw}) is the minimum depth of water that is required to be drained. This condition is satisfied when the previously defined leaching requirement is just met. For a value of $EC_{dw}=8$, which applies for moderately tolerant crops, and for irrigation waters of $EC_{iw}=0.5$, 1, 2, and 4 mmhos/cm., the depths of drainage water that must pass through the soil are 7, 14, 33, and 100 percent of the consumptive use (D_{cw}), respectively.

The passage of excess water through the root zone is accompanied by a decrease in the electrical conductivity of the drainage water. The equivalent depth of drainage water that is required to be drained (D_{dw}) from soil where irrigation water is applied inefficiently but uniformly may be estimated by substituting in equation 9 the electrical conductivity of the drainage water (EC_{dw}) as sampled and measure-d from the bottom of the root zone.

The depth of water that is drained beyond the root zone may also be expressed in terms of the water-application efficiency- and the total depth of water applied or the consumptive use. The equation $E=D_{cw}/D_{iw}$ is based on the definition of water-application efficiency (Israelson, 1950), where E represents water-application efficiency and the other symbols are as previously defined. Solving this equation for D_{cw} in one case and for D_{dw} in the other, substituting in equation 4 and solving for D_{dw}, we obtain:

$$D_{dw}=D_{iw}(1-E) \tag{10}$$

and

$$D_{dw}=D_{cw}\left(\frac{1}{E}-1\right) \tag{11}$$

Measured application efficiencies often run as low as 25 percent and seldom exceed 80 percent. Correspondingly, the water to be drained that comes directly from irrigation will range from 20 to 75 percent of the irrigation water applied and from 25 to 300 percent of the consumptive use. The total quantity or equivalent depth of water to be drained will be equal to that given by these equations plus that from other sources, such as seepage from canals and artesian aquifers. Seepage from canals is a major source of excess ground water in many areas, and seepage losses of 30 to 50 percent of the water diverted often occur.

Water-Transmission Properties of Soils

The principles and background theory for fluid flow in porous media are well known and are adequately treated in the literature. A discussion of the forces and properties determining the flow and distribution of water in soil, both saturated and unsaturated, and a description of measuring methods are given by Richards (1952). An important part of this background theory is embodied in the well-known Darcy equation, which in its generalized form states that for isotropic media the flow velocity, or specific discharge, is proportional to the hydraulic gradient and is in the direction of the greatest rate of decrease of hydraulic head.

The water-transmission properties of subsoils that cannot be controlled or changed appreciably have a direct bearing upon the design and layout of drainage systems. Soils, generally, are highly variable with respect to water-transmission properties, and it is necessary to assess the nonhomogeneity and to appraise the influence of soil variations on the direction and rate of flow of ground water.

Boundary Conditions

This concept is commonly used in the solution of flow problems and involves a geometric surface defining the boundaries of the problem along with hydraulic conditions over this surface, i. e., hydraulic head, hydraulic gradient, and flow. In other words, the external influences and constraints characterizing any given flow problem are included in the boundary conditions. While the root zone is the region of primary concern for agricultural drainage, a drainage problem may involve a considerably larger and deeper region. The upper and lateral bounding surfaces may be reasonably definite, but the lower boundary will depend on stratigraphy and hydraulic conditions. Many irrigated areas of the West are in alluvial valleys where topography and stratigraphy vary widely and where there may be diverse sources of ground water. The identification and delineation of these sources is especially important in establishing and defining boundary conditions.

Surface drains function mostly to eliminate water from the soil surface that may otherwise contribute to underground flow. Deep gravity drains, tile, and open ditches provide outflow points below the ground surface for controlling water-table depths and hence are a part of the boundary conditions. They are mostly less than 15 ft. deep because of construction limitations. Where conditions are favorable for pumping, water tables can usually be maintained at greater depths and thereby be controlled more effectively by pumping than by any other method. Most wells are installed to obtain water for irrigation, but often they also function to improve drainage conditions.

Layout and Placement of Drains

Drainage systems may consist of intercepting drains or relief-type drains, depending upon their location and function. Intercepting drains collect and divert water before it reaches the land under consideration, and relief drains are placed to remove water from the land being drained. Pumped wells, tile, or open drains may serve either of these purposes. Relief-type drains are used in broad valleys where the land has little slope, whereas intercepting drains more often are used in areas where topography is irregular. In areas of rolling or irregular topography, where lands of appreciable slope are irrigated, water that percolates downward through the surface soil often flows laterally through subsoil materials in the direction of the land slope. In these areas, seeps may be caused by a decrease in grade, a decrease in soil permeability, a thinning out of permeable underlying layers, the occurrence of dikes or water barriers, or the outcropping of relatively impermeable layers or hardpans. If the seepage water cannot be eliminated at its source, the placement of tile or open drains immediately above the seep to intercept such flows is usually the most effective procedure for solving this type of drainage problem.

Proper placement of drains is of considerable importance in the design of a drainage system. In nonuniform soils drainage systems may best be designed by considering the nature and extent of subsoil layers and by locating the drains with respect to these subsoil materials. Generally drains should be oriented perpendicular to the direction of ground-water flow and, where possible, should connect with sand and gravel layers or deposits. In soils of alluvial origin, the orientation of both permeable and impermeable deposits may be such that a few well-placed drains may control ground water over a much larger area than the same length of drain installed with uniform spacing in accordance with some arbitrary pattern. This has been demonstrated in a number of irrigated areas. For example, in the Grand Valley, Colorado, open drains that cut across and intercept sand and gravel deposits provide much more effective drainage than drains dug parallel to these deposits.

In areas where artesian conditions occur, drainage by tile and open drains is often impractical. Although the quantity of upward flow from an artesian source may be small, it usually exerts an important controlling effect on the height of the water table between drains. Artesian aquifers in many cases may be highly permeable and ideally located for drainage purposes, but they may be unavailable for receiving and discharging excess water applied at the soil surface because of the artesian pressure condition. Reduction of the water pressure in these aquifers by pumping or other means should be a first consideration.

The problem of flow into drains under falling water-table conditions has not been solved analytically. However, solutions have been developed for the ponded condition where drains are installed in saturated isotropic soil with a layer of water covering the surface. The falling water-table case typifies the drainage conditions in irrigated soils where it is desired to maintain adequate depth of water table between drains, whereas the ponded area more nearly represents conditions in humid regions where it is desired to remove excess water in short time periods following precipitation. Although the falling water-table condition differs appreciably from the ponded case, some of the important findings with the ponded area may have useful application for the falling water-table condition. For the ponded case, assuming isotropic soil, Kirkham (1949) concluded that "The most important single geometrical factor governing rate of seepage of water from soil into drains is the drain depth. Doubling the depth of drains will nearly double the rate of flow." For the falling water-table case, which is the usual condition in arid regions, the depth to the water table midway between drains is directly dependent upon the depth of the drains. For a given spacing, assuming soil conditions do not change with depth and other conditions remain constant, the depth to water table midway between drains increases directly with drain depth.

Proximity of drains to relatively impermeable layers is also an important consideration. Kirkham (1948, *p. 59)* states: "Drains should not be placed too near, on, or in an impervious layer. ... It is found that lowering the drain onto or into an impervious layer, although increasing the hydraulic head, decreases the flow rate. ..." He further states that "Drain shape (as well as size) appears to be unimportant in governing seepage rate into drains." From this, it is apparent that drain size should be determined primarily upon the basis of flow-velocity requirements. A gravel pack around tile drains is commonly used as a filter to allow free flow of water and at the same time to prevent sediment from entering the tile line.

Techniques for Drainage Investigations

A drainage investigation should provide information regarding the occurrence, flow, and disposition of excess water within a given basin or area. Information regarding hydrology, geology, meteorology, topography, and soils is needed and for some areas is already published and available. Reports of earlier drainage surveys should not be overlooked.

Measurements of Hydraulic Head

Inadequate drainage may be manifest by the presence of ponded water, marshy lands, and the growth of hydrophytic plants; but, in the absence of these obvious signs, depth to ground water is the most common index of the adequacy of drainage. Uncased observation wells are commonly used for determining the depth of the water table. Sometimes ground-water observation wells are lined with perforated casing. If there is a vertical component of flow, the true elevation of the water table is difficult to determine unless piezometers are used.

The water table is the elevation in the profile at which the soil water is at atmospheric pressure. This elevation corresponds to the bottom of the shallowest hole in which free water will collect. In a deeper hole or an observation well with perforated casing, the equilibrium elevation at which the water stands represents a balance between inflow and outflow for all the soil layers penetrated by the hole and may not be a useful hydraulic-head value.

The hydraulic head of ground water at each point in the soil is the elevation at which water stands in a riser connected to the point in question. There should be no leakage externally along such a riser or piezometer in order to insure that the elevation at which water stands in the piezometer is determined by the pressure in the ground water at the bottom end of the tube. This condition of external sealing is readily met under most field conditions for piezometers installed in accordance with Methods 35a and 35b. Measurements of hydraulic head and hydraulic gradient provide basic information on drainage conditions and the source and flow of ground water.

The number and arrangement of sites at which ground-water measurements should be made will depend upon the nature of the area in question and the purpose for which the measurements are made. In typical irrigated valleys information on both the adequacy of drainage and direction of ground-water flow is usually desired. Wells may be located to serve both purposes. Observation wells are often placed in a grid pattern for which spacing is selected to coincide with the land-survey system. In gently sloping areas, points of measurement can be farther apart than in areas of irregular topography. For determining the direction of the horizontal component of flow, water-table readings may be made at any desired spacing. More measurement sites are required in localities where there are abrupt changes in the slope of the water table.

Water-table contour maps and water-table isobath maps are useful in interpreting water-table data (Methods 36a and 36b). Profile flow patterns (Method 36c) may be used to show the nature of flow in cases where vertical as well as horizontal components of flow occur, such as sidehill seeps, seepage from canals, flow into drains, and upward flow from artesian aquifers. Water-table isopleths, which are described in Method 36d, can be used to show time fluctuations of the water table on a profile section.

Convenient methods for installing small-diameter piezometers have been described by Christiansen (1943), Pillsbury and Christiansen (1947), and Reger and others (1950). Piezometers may be installed by either driving or jetting as outlined in Methods 35a and 35b. The jetting technique provides a log of the nature and arrangement of subsoil materials in addition to the installation of a pipe for hydraulic-head readings. Piezometers 150 feet deep have been installed by this method.

Water levels in irrigation and domestic wells are often used for ground-water study. Water levels in such wells may or may not represent the water-table level. Deep-well readings should not be used as a measure of water table unless it can be definitely established by independent water-table measurements that the well reflects the true water-table level. Information regarding wells, such as total depth of well and depth of screens or perforations, is necessary in order to interpret well readings correctly.

Determination of Subsoil Stratigraphy

Hand augers, power augers, driven tubes, standard well-drilling equipment, and jetted piezometers can be used for studying subsoil materials and for locating and characterizing subsurface layers. The development of the jetting method of installing piezometers has made it possible to make subsoil investigations at only a fraction of the cost of augering or the use of well-drilling methods. Piezometers may be jetted for the sole purpose of determining subsoil stratigraphy, or the pipe may be left in place after the soil log is obtained as a permanent installation for hydraulic-head measurements.

Subsoil logs from jetted piezometers are usually made on the basis of texture, since information on texture provides an indication of the water-transmission properties of soils. Depths of strata changes may sometimes be obtained to within ± 0.1 ft. by this method, and soil layers can be distinguished that are too thin to be logged by well-drilling methods. An estimate of the texture and consolidation of the material is made from the vibration or feel of the pipe to the hands during the downward motion, from the rate of downward progress, from the examination of sediments carried by the effluent, and from the observation of color changes that occur in the effluent. (See Method 35b.)

Standard well-drilling equipment may be used for obtaining samples of subsurface materials and for logging underground strata. Logs of irrigation, domestic, or municipal water-supply wells that have been drilled in an area may usually be found in either county or State governmental offices. Some States require well drillers to file with the State engineer a log of each well drilled. Such logs provide useful information regarding the major clay layers and principal water-bearing aquifers. They are often deficient in pertinent details, however, especially concerning subsoil changes at shallow depths. In interpreting well logs the method of drilling should be taken into consideration. Logs of wells drilled by bailing methods, where sediments are actually obtained and examined from within a limited depth range, are usually more reliable than logs obtained by other drilling methods.

Hand augers and driven tubes are generally limited to depths less than 20 ft. They are used mainly for appraising stratigraphy near the surface. Power augers of various types are commercially available that can be used to depths of 60 ft. or more. In sandy soils it is sometimes necessary to case the hole with pipe or tubing as augering progresses in order to get a hole drilled to the desired depth and to obtain samples.

Undisturbed cores, 4 in. in diameter and from depths up to 10 ft., can be obtained by use of the power-driven core-sampling machine, an earlier model of which has been described by Kelley and coworkers (1948). This machine is trailer mounted and is usable over terrain passable to trucks. Soil cores are useful for the observation of structure and for making various physical measurements on undisturbed subsoil materials. Cracks, root holes, and fine sand lenticles may be overlooked with augering and other sampling methods, but these are preserved for examination in an undisturbed core.

Determination of Water-Transmitting Properties of Soils

In addition to determining the position and extent of subsoil materials as outlined above, information on the rates at which soils transmit water is required in planning and designing drainage systems. ***Soils are extremely variable with regard to water transmission.*** The heterogeneous nature in which most alluvial soils are deposited adds materially to the problem of assessing their water-transmitting properties. Soils formed both in place and by alluvial deposition may be extremely variable not only in a lateral direction but with depth as well. The problem of appraising the water-transmitting properties of soils involves measurements by suitable methods at representative sites or on representative samples.

The ratio of the waterflow velocity to the hydraulic gradient is called the hydraulic conductivity. This is the proportionality factor in the Darcy equation. This quantity varies over a range, as much as 100,000 to 1, in earth materials in which drainage operations are conducted. Hydraulic conductivity is often related to texture, coarse soils having high conductivity. Particle-size distribution may also be an important factor. Porous media with uniform particle sizes tend to be more permeable than materials having a more or less continuous range of sizes.

The hydraulic conductivity of soils, although related in a general way to texture, depends also upon soil structure. Soils near the surface that may be dry much of the time and are subject to alternate wetting and drying, freezing and thawing, plant root action, and alteration by other biological processes may exhibit entirely different water-transmitting properties than soils of similar texture below a water table. From the standpoint of drainage the latter are of greater importance, since subsurface drainage is concerned largely with water movement below the water table.

Hydraulic conductivity can be measured for disturbed samples or undisturbed cores in the laboratory or for undisturbed soil in the field. Measurements on disturbed samples of aquifer materials may be satisfactory for drainage investigation purposes, if the samples are packed to field density. Methods for making such measurements are summarized by Wenzel (1942).

Several methods have been developed for measuring the hydraulic conductivity of soil in place in the field below a water table. A procedure developed by Diserens (1934) and Hooghoudt (1936) in Holland makes use of the rate of water seepage into an auger hole below the water table and is described in Method 34d. The mathematical treatment developed by Kirkham and Van Bavel (1949) for this method assumes homogeneous isotropic soil, but hydraulic-conductivity determinations by this method in nonuniform soils may be taken as average or effective values. The auger-hole method is limited to soils below a water table in which the walls of the auger hole are stable. With the use of suitable screens it may also be used in sands or other noncohesive soils.

The piezometer method, based on the analysis by Kirkham (1946), has been adapted for large diameter tubes by Frevert and Kirkham (1949) and for small diameter pipes by Luthin and Kirkham (1949). The latter procedure is particularly suitable for determining the hydraulic conductivity of individual layers of soil. It is essentially a cased auger hole in which an opening or cavity is placed at any desired depth in the soil, following the procedure outlined in Method 34c.

Drainage design may be influenced by the fact that both uniform and nonuniform soils may be anisotropic with respect to hydraulic conductivity, i. e., the conductivity may vary with direction in the soil. Alternate lenses of coarse and fine sediments are commonly found in alluvial soils and usually conduct water more readily in a horizontal than a vertical direction. The above field methods may be useful in obtaining information on the degree to which soils are anisotropic. Reeve and Kirkham (1951) point out that field methods in which long cavities with respect to the diameter are used, such as is usually the case with both the auger-hole and the small-pipe piezometer methods, measure essentially the hydraulic conductivity in a horizontal direction, whereas the large-diameter tube method, which has a horizontal inflow surface, essentially measures conductivity for vertical flow. Hydraulic conductivity in any desired direction can be measured with undisturbed cores.

Since most soils are not uniform, the problem of appraising the water-transmitting properties, as related to depth and spacing of drains, involves not only the method of measurement but also a statistical problem of sampling as well. The number of samples required for soil appraisal is increased if the soil is highly variable or if the samples are small in size. Reeve and Kirkham (1951) showed that the effective sizes of sample associated with a small core (2-in. diam. × 2 in. long), a piezometer (l-in. diam. × 4-in. cavity), a tube (8-in. diam. with a cavity length equal to zero), and an auger hole (4-in. diam. × 30 in. deep), are in the ratio of 1, 35, 270, and 1,400, respectively; the latter three values being based on the region in which 80 percent of the hydraulic-head difference is dissipated. It is apparent that field methods for appraising conductivity on large undisturbed volumes of soil have distinct advantages over laboratory methods.

Information on the water conductance of subsurface aquifers often has application to drainage appraisal and can be obtained from well tests. High specific yield, i. e., high rate of flow per unit drawdown, indicates high aquifer permeability and vice versa. Data from existing wells can be used or new wells can be drilled. Wenzel (1942) has summarized and discussed the equations and methods used by a number of investigators of pumped wells. Theis (1935) presented equations for flow into wells for nonequilibrium conditions, and Jacob (1940, 1947) reviewed the principles of flow in artesian aquifers. Peterson and coworkers (1952) have developed equations and procedures for study of ground-water flow to wells for the steady-state or equilibrium condition.

Chemical Amendments for Replacement of Exchangeable Sodium

The kind and amount of chemical amendment to be used for the replacement of exchangeable sodium in soils depend upon the soil characteristics, the desired rate of replacement, and economic considerations.

Suitability of Various Amendments Under Different Soil Conditions

Chemical amendments that are applied to alkali soils are of three types:

Amendments for alkali soils:	*Chemicals*
Soluble calcium salts	Calcium chloride
	Gypsum
Acids or acid-farmers	Sulfur
	Sulfuric acid
	Iron sulfate
	Aluminum sulfate
	Lime-sulfur
Calcium salts of low solubility	Ground limestone
(May also contain magnesium)	Byproduct lime from sugar factories

While each type of amendment has a place in reclamation, effectiveness under different soil conditions is governed by several factors, the principal ones being the alkaline-earth carbonate content and the pH reading. From the standpoint of their response to the various types of amendments, alkali soils may be divided into three classes: (1) Soils containing alkaline-earth carbonates, (2) soils having a pH reading greater than 7.5 but practically free of alkaline-earth carbonates, and (3) soils having a pH reading of less than 7.5 and containing no alkaline-earth carbonates.

Any of the soluble calcium salts, acids, or acid-formers may be used on soils in class 1, but limestone will be of no value. The addition of acid or acid-forming amendments to soils in classes 2 and 3 tends to make them acid in reaction. When the amount of acid or acid-forming amendment needed for reclamation is sufficient to make the soil excessively acid, the choice of amendment is limited to soluble calcium salts, unless limestone also is applied. In general the acidification of soils of arid regions to a pH reading as low as 6 to 6.5 is usually beneficial to plant growth. To determine if the amount of acid or acid-former needed for reclamation is sufficient to cause excess acidity, the amendment can be applied at the desired rate to a sample of the soil and a pH reading can be obtained after the reaction is complete. If the addition of sulfur, which reacts slowly in the soil, is contemplated, the addition of a chemically equivalent amount of sulfuric acid may be useful to predict the pH reading that may eventually be obtained upon complete oxidation of the sulfur. While the application of limestone alone to soils of classes 2 and 3 will tend to be beneficial, the effectiveness of lime on different soils varies markedly, inasmuch as the solubility of $CaCO_3$ decreases with increasing pH reading. Data on $CaCO_3$ solubility in relation to pH reading are given by De Sigmond (1938) as follows:

pH value of $CaCO_3$ saturated solution:	Solubility of $CaCO_3$ (*Meq./l.*)
6.21	19.3
6.50	14.4
7.12	7.1
7.85	2.7
8.60	1.1
9.20	.82
10.12	.36

Sodium carbonate or carbon dioxide was used to obtain pH readings above or below 7. On the basis of these data it is apparent that the effectiveness of limestone as an amendment is markedly decreased at pH readings above 7.5, whereas it may be quite effective at pH readings below 7. Hence, limestone may be used to advantage on class 3 soils, but its value on class 2 soils is questionable. Some soils that contain excess exchangeable sodium also contain appreciable exchangeable hydrogen and, therefore, have an acid reaction. In Hungary large areas of such soils have been quickly and effectively reclaimed by the addition of chalk ($CaCO_3$).

Chemical Reactions of Various Amendments in Alkali Soils

The following chemical equations illustrate the manner in which various amendments react in the different classes of alkali soils. In these equations the letter X represents the soil exchange complex.

Class 1. Soils Containing Alkaline-Earth Carbonates

GYPSUM.—$2NaX + CaSO_4 \rightleftharpoons CaX_2 + Na_2SO_4$

SULFUR.-

(1) $2S + 30_2 \rightleftharpoons 2SO_3$ (microbiological oxidation)

(2) SO, $+ H_2O \rightleftharpoons H_2SO_4$

(3) $H_2SO_4 + CaCO_3 \rightleftharpoons CaSO_4 + CO_2 + H_2O$ [8]

(4) $2NaX + CaSO_4 \rightleftharpoons CaX_2 + Na_2SO_4$

LIME-SULFUR (CALCIUM POLYSULFIDE).—

(1) $CaS_5 +$ 80, $+ 4H_2O \rightleftharpoons CaSO_4 + 4H_2SO_4$

(2) $H_2SO_4 + CaCO_3 \rightleftharpoons CaSO_4 + CO_2 + H_2O$ [8]

(3) $2NaX + CaSO_4 \rightleftharpoons CaX_2Na_2SO_4$

IRON SULFATE.—

(1) $FeSO_4 + H_2O \rightleftharpoons H_2SO_4 + FeO$

(2) $H_2SO_4 + CaCO_3 \rightleftharpoons CaSO_4 + CO_2 + H_2O$ [8]

(3) $2NaX + CaSO_4 \rightleftharpoons CaX_2 + Na_2SO_4$

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[8] The reaction of H_2SO_4 and $CaCO_3$ may also be written as follows: $H_2SO_4 + 2CaCO_3 \rightleftharpoons CaSO_4 + Ca(HCO_3)_2$. Under these conditions the $Ca(HCO_3)_2$ as well as the $CaSO_4$ would be available for reaction with exchangeable sodium and 1 atom of sulfur when oxidized to H_2SO_4 could theoretically result in the replacement of 4 sodium ions by calcium. Kelley (1951, *p. 135*) found under field conditions that approximately 3 exchangeable sodium ions per atom of sulfur were replaced, whereas a greenhouse-pot experiment conducted at this Laboratory indicated that the reaction takes place without the formation of appre-

Class 2. Soils Containing No Alkaline-Earth Carbonates; pH 7.5 or Higher

GYPSUM.-Same as in class 1.

SULFUR.-Steps (1) and (2) as in class 1.

(3) $2NaX + H_2SO_4 \rightleftharpoons 2HX + Na_2SO_4$

LIME-SULFUR.-Step (1) as in class 1.

(2) $10NaX + 4H_2SO_4 + CaSO_4 \rightleftharpoons 8HX + CaX_2 + 5Na_2SO_4$

IRON SULFATE.-Step (1) as in class 1.

(2) $2NaX + H_2SO_4 \rightleftharpoons 2HX + Na_2SO_4$

LIMESTONE.-Two possibilities suggested by Kelley and Brown (1934) are:

(1) $2NaX + CaCO_3 \rightleftharpoons CaX_2 + Na_2CO_3$

(1) $NaX + HOH \rightleftharpoons NaOH + HX$

(2) $2HX + CaCO_3 \rightleftharpoons CaX + CO_2 + H_2O$

Class 3. Soils Containing No Alkaline-Earth Carbonates; pH Less Than 7.5

GYPSUM.—Same as in class 1 and 2.

SULFUR.--Same as in class 2.

LIME-SULFUR.-Same as in class 2.

IRON SULFATE.-Same as in class 2.

LIMESTONE.-Same as in class 2, and if exchangeable hydrogen is present:

(1) $2HX + CaCO_3 \rightleftharpoons CaX_2 + CO_2 + H_2O$

Estimation of Amounts of Various Amendments Needed for Exchangeable-Sodium Replacement

/Exchangeable sodium and cation-exchange-capacity determinations serve as valuable guides for estimating the amounts of chemical amendments needed to reduce the exchangeable-sodium-percentages of alkali soils to given levels. The procedure for estimating the amount of amendment needed for a given set of conditions can be illustrated by an example. Suppose the 0 to 12-in. layer of an alkali soil contains 4 meq. of exchangeable sodium per 100 gm. and has a cation-exchange-capacity of 10 meq. per 100 gm. The exchangeable-sodium-percentage is therefore 40. It is desired to reduce the exchangeable-sodium-percentage to about 10. This will necessitate the replacement of 3 meq. of exchangeable sodium per 100 gm. Assuming quantitative replacement, it will be necessary to apply the amendment at the rate of 3 meq. per 100 gm. of soil. By referring to table 6, which relates tons of gypsum and sulfur per acre-foot of soil to milliequivalents of sodium per 100 gm. of soil, it is found that 5.2 tons of gypsum or 0.96 ton of sulfur are required. If it is desired to use amendments other than gypsum or sulfur, the supplementary data given below will be helpful in converting the tons of sulfur found to be needed in table 6 to tons of other amendments.

Amendment:	*Tons equivalent to 1 ton of sulfur*
Sulfur	1.00
Lime-sulfur solution, 24 percent sulfur	4.17
Sulfuric acid	3.06
Gypsum ($CaSO_4 \cdot 2H_2O$)	5.38
Iron sulfate ($FeSO_4 \cdot 7H_2O$)	8.69
Aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$)	6.94
Limestone ($CaCO_3$)	3.13

TABLE 6.—*Amounts of gypsum and sulfur required to replace indicated amounts of exchangeable sodium*

Exchangeable sodium (Meq. per 100 gm. of soil)	Gypsum [1] ($CaSO_4 \cdot 2H_2O$)	Gypsum [1] ($CaSO_4 \cdot 2H_2O$)	Sulfur (S)	Sulfur (S)
	Tons/acre-foot [2]	*Tons/acre-6 inches* [3]	*Tons/acre-foot* [2]	*Tons/acre-6 inches* [3]
1	1.7	0.9	0.32	0.16
2	3.4	1.7	.64	.32
3	5.2	2.6	.96	.48
4	6.9	3.4	1.28	.64
5	8.6	4.3	1.60	.80
6	10.3	5.2	1.92	.96
7	12.0	6.0	2.24	1.12
8	13.7	6.9	2.56	1.28
9	15.5	7.7	2.88	1.44
10	17.2	8.6	3.20	1.60

[1] The amounts of gypsum are given to the nearest 0.1 ton.
[2] 1 acre-foot of soil weighs approximately 4,000,000 pounds.
[3] 1 acre-6 inches of soil weighs approximately 2,000,000 pounds.

The reaction between an amendment such as gypsum and exchangeable sodium is an equilibrium reaction and, therefore, does not go entirely to completion. The extent to which the reaction goes to completion is determined by the interaction of several factors, among which are the differences in the replacement energies of calcium and sodium, the exchangeable-sodium-percentage, and the total cation concentration of the soil solution. For the usual case where a quantity of gypsum equivalent to the amount of exchangeable sodium present in the surface 6- or 12-in. layer of soil is applied, some progress has been made in determining the percentage of the applied calcium that reacts with exchangeable sodium. The available data indicate that when the exchangeable-sodium-percentage of the soil exceeds 25, 90 percent or more of the calcium supplied bv the amendment replaces exchangeable sodium as the soil is leached. The percentage of added calcium that replaces exchangeable sodium does not become less than 50 until the exchangeable-sodium-percentage becomes less than 10. It should be pointed out that under the above conditions not all of the replacement of exchangeable sodium takes place in the depth of soil upon which the application is based, although the greater part of it does. As a general rule, it is suggested that

ciable amounts of $Ca(HCO_3)_2$. A high soil-moisture level, low soil temperatures, and the reiease of CO_2 by plant roots would favor the formation of $Ca(HCO_3)_2$ as a product of the reaction.

the rates of gypsum and sulfur application indicated by table 6 be multiplied by the factor 1.25 to compensate for the lack of quantitative replacement.

A simple test based on the work of McGeorge and Breazeale (1951) has been proposed by Schoonover for determining the gypsum requirement' of alkali soils. The test, which is given as Method 22d, involves an arbitrary procedure and does not measure a distinct chemical property of the soil. The relation between the exchangeable-sodium content and the gypsum requirement, as determined by Method 22d, of 29 nongypsiferous soil samples has been studied at the Laboratory. The ranges in various characteristics of the samples were as follows: electrical conductivity of the saturation extract, 0.2 to 30 mmhos/cm.; exchangeable-sodium-percentage, 6.3 to 65.5 ; and exchangeable-potassium-percentage, 2.1 to 27.3. As indicated by a correlation coefficient of 0.96, a good relation was found between exchangeable-sodium content and gypsum requirement. For soil samples having exchangeable-sodium contents ranging from 0.1 to 12 meq./100 gm., the relation between the two variables is expressed by the equation: Exchangeable sodium, milliequivalents/100 gm. $= 0.96 + 0.99 \times$ gypsum requirement, milliequivalents/100 gm.[9] Inasmuch as Method 22d gives a good estimate of the exchangeable-sodium content of these alkali soils, it would appear to be useful for estimating the amount of gypsum needed when information on the exchangeable-sodium content and the cation-exchange-capacity is not otherwise available. Amounts of gypsum can be converted to quantities of other chemical amendments by the use of table 6 and data on page 49.

Speed of Reaction of Amendments and Economic Considerations

The choice of a chemical amendment may be influenced by the time required for its reaction in the soil. In general, the cheaper amendments are slower to react. Consequently, if immediate replacement of exchangeable sodium is desired, one of the quicker acting but more expensive amendments will be needed.

Owing to its high solubility in water, calcium chloride is probably the most readily available source of soluble calcium, but it is seldom used because of its cost. Sulfuric acid and iron and aluminum sulfates that hydrolyze readily in the soil to form sulfuric acid are also quick-acting amendments. Sulfuric acid is often cheap enough for field application, but the use of iron and aluminum sulfates usually is not economically feasible. Because of their relatively low cost, gypsum and sulfur are the most common amendments used for reclamation. The rate of reaction of gypsum in replacing sodium is limited only by its solubility in water; its solubility is about 0.25 percent at ordinary temperatures. The presence of sodium and chloride ions in the water increases the solubility of gypsum, whereas calcium and sulfate ions tend to decrease its solubility. Limited data indicate that the application of 3 to 4 ft. of irrigation water is sufficient to dissolve 4 or 5 tons/acre of agricultural gypsum having a degree of fineness such that 85 percent will pass a 100-mesh sieve.

As sulfur must first be oxidized by microbial action to the sulfate form to be available for reaction, it is usually classed as a slow-acting amendment. McGeorge and Greene (1935) have shown in laboratory studies of Arizona soils that sulfur applications of about 1 ton/acre are rapidly and usually completely oxidized in 2 or 3 weeks under favorable moisture and temperature conditions. Larger applications required more time for complete oxidation. They also found that within the usual particle-size limits of agricultural sulfur, the coarse-grade material was practically as effective as the finer and more expensive grades. In spite of these findings, various agriculturists frequently report incomplete oxidation of sulfur in soils a year or more after application. Often this appears to be caused by the presence of lumps of the sulfur and insufficient mixing of the amendment with the soil following application.

As previously mentioned, the solubility of limestone when applied to alkali soils is markedly influenced by the pH reading and by the presence of exchangeable hydrogen. Unless the soil is decidedly acid, the chemical reaction of limestone is slow. Particle size is also an important factor affecting the rate at which limestone, gypsum, and sulfur react in soils. The finer the particle size the more rapid the reaction.

There is considerable interest at present in the use of lime-sulfur as an amendment. Lime-sulfur is a brown, highly alkaline liquid containing calcium polysulfides and some calcium thiosulfate. The calcium content is ordinarily about one-fourth that of the sulfur content, and its action depends mostly on the sulfur content. Usually the material is applied in irrigation water. Like elemental sulfur, it must first be oxidized to sulfuric acid and then react with alkaline-earth carbonates to produce a soluble form of calcium.

Application of Amendments

From the standpoint of efficiency in replacing exchangeable sodium, it is advantageous to leach most of the soluble salts out of the soil before applying chemical amendments. As a result of the removal of soluble salts, a higher proportion of the calcium supplied by the addition of amendments is adsorbed by the soil-

[9] SCHOONOVER, W. R. EXAMINATION OF SOILS FOR ALKALI. University of California Extension Service, Berkeley, California. 1952. [Mimeographed.]

In a private communication, C. D. Moodie of the Washington Agricultural Experiment Station has reported a study of the relation between the gypsum requirement and the exchangeable-sodium contents of soils from the Yakima Valley, Washington. A relation similar to that obtained by Schoonover was obtained for soils containing low amounts of exchangeable potassium, but for soils containing high amounts of exchangeable potassium the slope of the regression line was considerably lower. Thus, estimates of the exchangeable-sodium content based on the gypsum requirement and the equation given in this handbook may be high if the soil contains large amounts of exchangeable potassium.

exchange complex. The advantage gained through increased efficiency in exchangeable-sodium replacement by leaching prior to the application of amendments may be more than offset by the decrease in soil permeability that usually accompanies the leaching of saline-alkali soil. Whether amendments should be applied before or after removal of soluble salts, therefore, will depend upon permeability relationships.

Such chemical amendments as gypsum, sulfur, and limestone are normally applied broadcast and then incorporated with the soil by means of a disk or plow. Thorough incorporation is especially important when sulfur is used to insure rapid oxidation to the sulfate form. Because of hazards in handling, the application of sulfuric acid is difficult under ordinary field conditions. However, special equipment is now available that sprays the concentrated acid on the soil surface. Although chemical amendments are ordinarily applied to the surface, deeper placement may be advantageous if the exchangeable-sodium accumulation occurs uniformly in the subsoil, or B horizon. While there appears to be no information on the subject, it is possible to obtain deep placement by distributing the amendment behind a plow or subsoiler.

Amendments are sometimes applied in the irrigation water. Special equipment for treating irrigation waters with gypsum has been described by Fullmer (1950). A simple method of treatment consists in placing a bag of gypsum with the side slit open in the irrigation ditch, preferably at a weir where the water has considerable turbulence.

Except where sulfur is used, saline-alkali soils should be leached immediately following the application of amendments. Leaching dissolves and carries the amendment downward, and it also removes the soluble sodium salts that form as a result of cation exchange. Soils receiving sulfur ordinarily should not be leached until sufficient time has been allowed for most of the sulfur to oxidize and form gypsum, but the soils should be kept moist, as moisture is essential to the process of microbial oxidation.

Improvement of the physical condition of alkali soils involves the rearrangement and aggregation of soil particles as well as the replacement of exchangeable sodium. This has been demonstrated and emphasized by Gardner (1945). The rearrangement of soil particles so as to improve physical condition is facilitated by alternate wetting and drying, by alternate freezing and thawing, and by the action of plant roots.

Laboratory and Greenhouse Tests as Aids to Diagnosis

While physical and chemical analyses made on saline and alkali soil samples provide basic data that may be needed to ascertain the cause of low productivity and the treatments required for reclamation, supplementary tests conducted on soil columns or in greenhouse pots are often helpful in obtaining satisfactory answers to soil problems. Such tests may be used to verify conclusions reached on the basis of physical and chemical tests or to check on how the soil responds to indicated treatments for improvement. It should be recognized, however, that plant growth on saline and alkali soils contained in small pots may be at variance with growth obtained under field conditions. Laboratory and greenhouse tests are less costly, less laborious, and less time-consuming than field tests and often provide valuable clues as to the behavior of the soil in the field. Generally, all but the more promising procedures for improving saline and alkali soils can be eliminated by laboratory and greenhouse studies.

Laboratory tests on soil columns may be used to estimate the amount of leaching needed for removal of excess soluble salts; to determine the response of soils to the addition of various kinds and amounts of amendments; and to determine the changes in such soil properties as permeability, pH reading, and exchangeable-sodium-percentage that take place upon leaching. Determinations on soil columns are especially useful in the diagnosis of saline-alkali soils, as the characteristics of these soils usually change markedly upon being leached.

It would be best to conduct tests on undisturbed soil cores. A power-driven soil sampler capable of taking 4-inch diameter cores to a depth of 10 feet has been developed by Kelley and associates (1948). In the absence of a core sampler, disturbed samples representing the various soil layers may be packed in tubes of convenient diameter and length. A technique similar to that used for making hydraulic-conductivity measurements on disturbed soil samples can be used in setting up these soil columns. Leaching and amendment treatments may then be applied to the soil columns, and the effects upon water-movement rates noted. Changes in soluble-salt content, pH reading, and exchangeable-sodium status obtained by various treatments may be determined by removing the treated soil from the tube and making the appropriate analyses.

Greenhouse tests are useful when it is desired to obtain information on plant-growth responses. They may be used for various purposes such as to determine whether the soil contains sufficient soluble salt or exchangeable sodium to affect plant growth adversely, to determine plant response to leaching and the addition of chemical amendments, and to estimate the fertilizer needs of saline and alkali soils (Bower and Turk, 1946).

Greenhouse pot tests may be conducted under various conditions. The procedure to be followed will depend upon the facilities available, the kind of plant to be grown, and the purpose of the tests. A few suggestions for conducting greenhouse tests are:

(*a*) If possible, use the crop or crops to be grown in the field.
(*b*) Use containers of soil as large as feasible. If leaching treatments are to be employed, provision should be made for measuring the volume and salt content of the leachate.
(*c*) An attempt should be made to grow the crop during its normal season and to avoid exces-

sive temperatures that are often obtained under greenhouse conditions.

(*d*) Replicate each treatment at least twice and arrange each set of treatments in randomized blocks.

(*e*) If possible, irrigate with water having the same composition as that to be used in the field.

(*f*) If the soil has been leached or amendments applied, it may be desirable to analyze the soil at the conclusion of the test to determine the changes in the soil properties that have taken place.

Although this handbook is not primarily concerned with soil fertility, it should be recognized that saline and alkali soils, like other soils of arid regions, usually respond markedly to nitrogen and phosphorus fertilization. Adequate fertilization after the removal of excess soluble salts and exchangeable sodium is usually required to obtain maximum productivity. The greenhouse technique devised by Jenny and coworkers (1950) for determining nutrient level and fertilizer response is suggested as a possible method for determining the fertilizer requirements of saline and alkali soils.

Reclamation Tests in the Field

Leaching operations and the application of amendments in the field usually entail considerable expense. Therefore, before attempting the improvement of saline and alkali soils on a large scale, it is frequently desirable to determine whether a proposed treatment will be successful. Often this can be ascertained on an experimental basis by the use of field plots. It is not the purpose of this section to give methods for conducting field-plot experiments of the research type. However, procedures are given that are considered adequate for testing treatments involving leaching, cultural practices, and the application of amendments. Tests in which drainage is a treatment are difficult to conduct on a plot basis and, hence, will not be considered.

Saline and alkali soils usually are extremely variable in nature, their characteristics often changing-markedly over relatively short distances. Therefore, considerable care should be taken to select a test area that is as uniform as possible and yet representative of the soils to be considered. Examination and tests of soil samples from various locations over the proposed test area-are valuable in determining soil uniformity. Sometimes it is difficult to locate a single area of sufficient size and uniformity to conduct the test. Then it is advisable to place individual replications on separate areas within the field.

Selection of the size and shape of plots is influenced by the kinds of treatments to be used, the crop to be grown, the method of applying water, and the amount of space needed for the operation of equipment. Ordinarily, the plots should be as small as possible, as this tends to reduce soil variability within the test area. If at all feasible, a border or dike should be constructed around each plot to control the application of water. This permits the impounding of water for leaching and the estimation of infiltration rates. Tests that involve only the application of amendments such as gypsum **or** manure may be conducted on plots as small as 15 ft. by 15 ft. On such plots, the amendments can be applied by hand. When leaching is a differential treatment, plots of somewhat larger size are needed, as border effects may be of considerable magnitude in small plots. **Leachig** tests have been satisfactorily conducted on **1/50-acre** plots. Cultural treatments, such as subsoiling and deep plowing, may require the use of fairly large plots to permit operation of the machinery. From the standpoint of minimizing border effects, plots should be as nearly square as possible. Square plots are usually convenient to handle when the land is flood-irrigated, but when the slope of the land is such that water must be applied in furrows or corrugations a long narrow plot must be used. Cropping procedure and **tillage** operations must also be considered in selecting the shape of the plot.

The design of field-plot tests is governed primarily by the treatments to be used (fig. 16). The simplest design is that in which the various treatments are arranged in blocks and located at random, each treatment occurring only once in each block. Individual blocks serve as replications. This design is satisfactory for comparing various amendments or cultural practices or for testing the effect of leaching. If the test involves a combination of amendments and leaching or cultural treatments, it is advantageous to employ a split-plot design in which leaching or cultural treatments constitute main plots and the amendment treatments consist of subplots. Owing to the marked variability of saline and alkali soils, it is recommended that treatments be replicated at least four times. All treatments within each replicate block should be located at random.

The improvement of saline and alkali soils may be evaluated by means of plant-growth responses, soil analyses, and determinations such as infiltration rate. When the problem is one of excess salinity only, determinations of crop yields on the various plots often will suffice for the evaluation of the treatments. If facilities are available, it is also advisable to determine by analysis the soluble-salt content of the soil before and after treatment. In alkali soils where poor physical condition is a problem, the effect of the treatments upon the soil as well as upon plant growth should be determined. Changes in the exchangeable-sodium content of the soil upon treatment may be determined by soil analyses, whereas improvement in water-transmission properties may be estimated by means of infiltration measurements. Estimates of infiltration rates are readily obtained when individual plots are flood-irrigated. Infiltration rates on furrow-irrigated plots may be estimated by measuring the amount of water applied to the plot and the amount that runs off.

Applications of chemical amendments influence both the physical and chemical properties of alkali soils. In studying the response of plants on alkali soils to the application of chemical amendments, it may be **desir-**

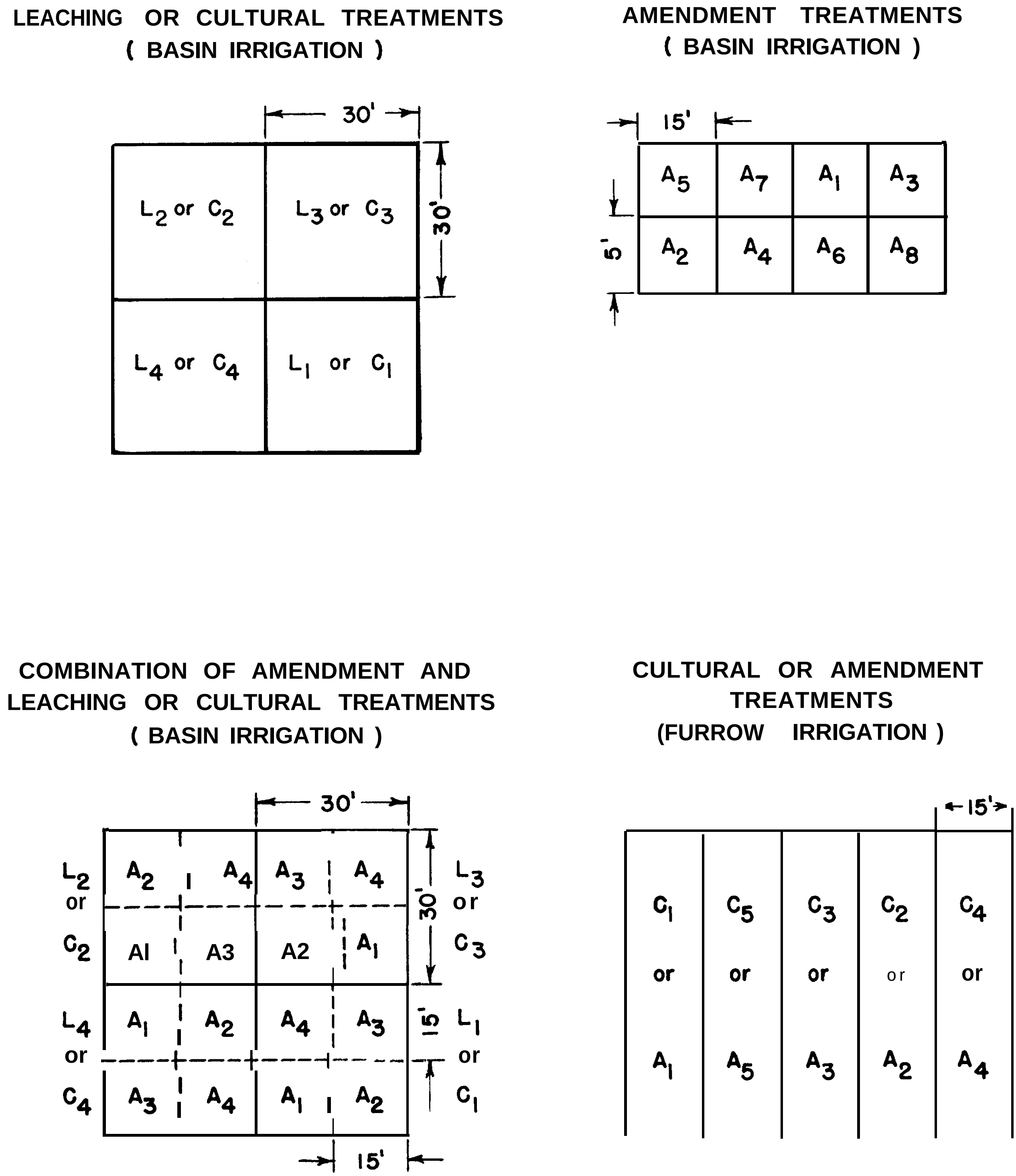

FIGURE 16.-Example showing individual replicates of plot layouts for conducting field tests: C, Cultural treatments; L, leaching treatments; A, amendment treatments; ——— main plot boundary; ______ subplot boundary. The subscripts refer to treatment levels, for example: L_1, control; L_2, 12 surface inches; L_3, 36 surface inches.

able to separate the strictly chemical aspects of 'the response from the physical aspects. Preliminary tests indicate that treatment of alkali soils with the recently developed commercial aggregating agents will largely eliminate poor physical condition without altering the chemical characteristics appreciably. Therefore, reclamation tests that include applications of chemical amendments and commercial aggregating agents singly as well as in combination are suggested as a means for determining the nature of the response.

Reclamation of Saline and Alkali Soils in Humid Regions

This chapter deals primarily with the improvement and management of saline and alkali soils as they occur in the arid and semiarid regions of western United States. Any treatment of the subject would be incomplete, however, without reference to the pioneer research work and the extensive practical experience with the reclamation of saline and alkali soils in the Netherlands and other low countries in humid regions. Underlying principles relating to soil properties and plant responses apply equally well to both cases. The main difference is that in humid climates precipitation exceeds consumptive use, so that if drainage is adequate, i. e., if the water table is maintained at a sufficient depth, excess soluble salts are leached out of the soil by rain water.

It often happens that the rainfall pattern in humid climates during the crop growing season is not ideal and it is profitable to maintain the water table at some elevation that is in or near the root zone. Subirrigation is hazardous in arid regions, but it is a relatively common practice in humid climates. In any climate this practice requires close attention to the concentration of soluble salts in the root zone, and careful coordination between subirrigation, leaching, and drainage requirements. Hooghoudt (1952) has recently reviewed the methods and practices used in the Netherlands for tile drainage and subirrigation.

A special case of salinity in humid as well as arid climates occurs in greenhouse soils. This type of agriculture has considerable economic importance in many countries. Since crop production is directly dependent on irrigation and the leaching action of rainfall is absent, water management to control salinity and exchangeable sodium in the soil is the same as for irrigation agriculture in an arid climate.

Economically, in humid climates the most important consideration of soil salinity and exchangeable sodium has been in connection with the drainage and reclamation of soils underlying salty lakes and shallow coastal waters. In the Netherlands, experience with this process extends over many centuries, and the large areas of fertile agricultural land that have been gained by this means have become a major factor in the national economy. Zuur (1952) has sketched historical and technical aspects and has given an introduction to the extensive literature of the Netherlands on this subject. He states that, to start with, soils reclaimed from the sea contain about 2 percent sodium chloride. In 2 years after ditching, this content is reduced "in the wet Dutch climate" to 0.1 percent or less in the surface 80 cm. of sandy soils. Clay soils require a longer time to leach to this depth, but crops can be grown fairly soon after artificial drainage is established.

Most of the polder soils of the Netherlands, coming both from recent marine deposits and from old sea clays, contain sufficient sulfur and calcium carbonate so that with the oxidation processes which accompany drainage, the soil solution is kept saturated with gypsum for several years. This is a most fortunate circumstance because the removal of exchangeable sodium takes place simultaneously with the reduction of salinity, without the need for the addition of chemical amendments. Zuur (1952) has given the data in table 7 as being typical of changes in the exchangeable-cation status of a polder soil following drainage.

TABLE 7.—*Exchangeable cations in the topsoil of a polder reclaimed from salt water (Zuur, 1952)*

Time	Ca	Mg	K	Na
	Percent	*Percent*	*Percent*	*Percent*
Just after drainage	17	35	9	39
4 years after ditching	73	17	5	5
7 years after ditching	82	10	ii	2
Final situation	87	8	4	1

The reclamation of soils that have been subjected to sea-water inundation is an agricultural problem that has assumed considerable economic importance and has been given a great deal of attention by soil and plant scientists. This is particularly serious when it occurs on older cultivated soils in humid regions, because of the lack of soluble calcium for replacing exchangeable sodium concurrently with the leaching out of the soluble salts. Leaching by rain water changes the soil from the saline-alkali to the nonsaline-alkali condition, with the attendant deterioration of structure. Reclamation then requires soluble calcium for replacing exchangeable sodium and careful management and cultural practices for some time to reestablish a favorable physical status of the soil. Van den Berg (1952) provides an introduction to the literature on this subject.