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REPRINTED FROM
ADVANCES IN AGRONOMY, VOLUME 16

ACADEMIC PRESS INC., NEW YORK

SALINITY IN RELATION TO IRRIGATION

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I. Introduction

History reveals that civilization began in an environment of irrigation agriculture. The Nile Valley in Egypt and much of the land in China have been irrigated for more than 4000 years, and still they produce good yields. These are but two examples of successful long-time irrigation developments. Despite successes in some areas, failures occurred in others, notably in Mesopotamia, where an early great civilization developed in the valley formed by the Tigris and Euphrates Rivers. Although the downfall of this civilization has been attributed to many and varied causes, most authorities agree that finality was determined by waterlogging and salinity.

Salinity is the major and ever-present threat to the permanence of irrigation agriculture. In 1958, about 31 million acres of land were under irrigation in the 17 western States and Hawaii and, according to Hayward (1958), approximately 27 per cent of this land is salt affected to some degree. Unless salinity is controlled, productivity decreases, land values drop, and, in severe cases, the land is completely abandoned. In fact, during the decade 1929 to 1939, over 1 million acres of irrigated land in the 17 western States were abandoned because of the accumulation of salt and sodium. However, most of this abandoned land has been restored to production.

This report is concerned with the technical aspects of the problems of irrigation agriculture on salt-affected land, with emphasis on factors or practices that are important for the development of a permanent irrigation agriculture.

II. Salinity of Irrigation Waters

The salt content of most irrigation waters ranges from 0.1 to 5 tons of salt per acre-foot (70 to 3500 p.p.m.). Therefore, a knowledge of water quality is exceedingly important because it greatly influences irrigation and drainage practices, the choice of crops grown, and to some extent other management practices.

A. Classification of Waters

Significant contributions have been made to our knowledge of water quality by Hilgard (1906), Kelley *et al.* (1939; Kelley and Brown, 1928), Scofield (1936; Scofield and Headley, 1921; Scofield and Wilcox, 1931), Eaton (1935, 1936, 1950), Doneen (1954), Thorne and Thorne (1951), Wilcox (1948, 1955), and U. S. Salinity Laboratory Staff (1954). Although the several proposed methods of classifying irrigation waters differ somewhat, they agree reasonably well with respect to criteria and limits.

Christiansen and Lyerly (1952) believe that probably too much emphasis has been placed on an attempt to answer the question, How good is the water? rather than, What can be done with this water? Somewhat similar views have been expressed by Eaton (1958) and Kelley (1962) to the effect that too rigid a dependence on any classification is questionable. Even so, classification data provide a basis for anticipating with reasonable confidence, the general effect of an irrigation water on the soil and on the plant.

The classification recommended by the U. S. Salinity Laboratory Staff (1954) and Wilcox (1955) incorporates many of the desirable features of the early classifications, together with more recent developments based both on research and on field observations. However, this classification is tentative and should be used for general guidance only. The four generally recognized criteria of irrigation water quality are (1) total salinity, (2) sodium, (3) boron, and (4) bicarbonate.

1. Salinity Hazard

Total salt concentration is probably the most important single criterion of irrigation water quality. On the basis of electrical conductivity (EC) measurements, waters are divided into four classes: low salinity, medium salinity, high salinity, and very high salinity, the dividing points between classes being 250, 750, and 2250 μmho./cm. This range includes waters that can be used for irrigation of most crops on most soils, to waters that are not suitable for irrigation under ordinary conditions. More than half of the irrigation waters in the western United States have conductivity values of less than 750 μmho./cm. (500 p.p.m. dissolved solids) and less than 10 per cent of the waters have conductivities in excess of 2250 μmho./cm. (1500 p.p.m. dissolved solids).

2. Sodium Hazard

The sodium adsorption ratio (SAR), described in Section III, B, 3, for soil extracts, is used to evaluate the sodium, or alkali hazard of irrigation waters. This ratio expresses the relative activity of sodium ions in cation-exchange reactions with the soil. The SAR is more significant than the soluble-sodium percentage (SSP) for use as an index of the sodium, or alkali hazard, of the water because it relates more directly to the adsorption of sodium by the soil. However, because irrigation waters become concentrated in the root zone, the SAR will indicate a minimum, but not necessarily the ultimate effect of a particular water on the sodium status of the soil.

Waters are divided into four classes with respect to the sodium hazard: low, medium, high, and very high, depending upon the values for SAR and EC. At EC values of 100 μmho./cm., the dividing points are at SAR values of 10, 18, and 26, but with increasing salinity, these SAR values decrease progressively until at 2250 μmho./cm., where the corresponding dividing points are at SAR values of approximately 4, 9, and 14. With respect to sodium hazard, waters range from those that can be used for irrigation on almost all soils to those that are generally unsatisfactory for irrigation.

3. Boron Hazard

Boron is very toxic to plants at low concentrations in the soil solution. Because boron tends to accumulate in the soil from low concentrations in the irrigation waters, it is necessary to consider this constituent in assessing the quality of irrigation waters. The classification in Table I uses the limits originally proposed by Scofield (1936).

TABLE I
Permissible Limits of Boron for Several Classes of Irrigation Waters[a]

Boron class	For irrigation of Sensitive crops	Semitolerant crops	Tolerant crops
1	< 0.33	< 0.67	< 1.00
2	0.33 to 0.67	0.67 to 1.33	1.00 to 2.00
3	0.67 to 1.00	1.33 to 2.00	2.00 to 3.00
4	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
5	> 1.25	> 2.50	> 3.75

[a] Values as parts per million.

The specific toxicity of boron to crops is discussed in Section IV, B, 3. Table VI indicates the relative tolerance of some common crops in relation to the boron present in irrigation waters.

4. *Bicarbonate Hazard*

The bicarbonate ion is primarily important because of its tendency to precipitate calcium, and to some extent magnesium, in the soil solution as their normal carbonates. Carbonate ions are seldom present in waters, but bicarbonate ions may represent an appreciable proportion of the total anions present in irrigation waters. In many tropical waters, bicarbonate is often the main anion present.

The effect of the bicarbonate ion concentration on water quality is expressed in terms of the *residual sodium carbonate* (RSC) concept of Eaton (1950), defined in the following equation:

$$RSC = (CO_3^{--} + HCO_3^{-}) - (Ca^{++} + Mg^{++})$$

in which the concentration is expressed in milliequivalents per liter. It is obvious from this equation that as calcium and magnesium are lost from the soil solution by precipitation, the relative proportion of sodium remaining in the water is increased. Thus, the sodium hazard as defined by the SAR (cf. Section III, B, 3) is increased.

Laboratory and field studies (Wilcox *et al.*, 1954) have resulted in the tentative conclusion that waters containing less than 1.25 meq./l. RSC are probably safe for most purposes. Waters containing 1.25 to 2.5 meq./l. are marginal, and those containing more than 2.5 meq./l. of RSC are not suitable for irrigation purposes. However, with good management practices, it should be possible to use some of these marginal waters successfully for irrigation. These practices would be (1) adequate leaching, which would tend to maintain a low level of bicarbonate in the soil solution, and (2) the application of gypsum or any other source of soluble calcium, to maintain a favorable Ca:Na ratio in the soil solution. Either of these practices would tend to retard sodium accumulation in the exchange complex.

5. *Other Hazards*

a. Lithium. Lithium toxicity to citrus has been observed in California (Bradford, 1963). Where the problem occurs, the lithium content of the irrigation water is 0.05 p.p.m. or more. A survey of 400 waters from throughout the State showed that about one-fourth of these waters contained toxic levels of lithium (0.05 to 0.50 p.p.m.) and that this constituent was usually associated with low magnesium, or high sodium, or both. It is significant that the order of tolerance of lithium-sensitive plants closely parallels their sodium tolerance (Bingham *et al.*, 1964).

b. Pollutants. Many substances that are discharged as industrial wastes into surface streams may have phytotoxic properties. Wilcox (1959) reported information on many substances that are known to be toxic to plants. Great caution should be exercised in the use of an irrigation water that is suspected of containing phytotoxic pollutants.

B. Interpretation of Irrigation Water Analyses

The analysis of a water should provide information on its suitability for irrigation and, in addition, suggest the management practices to be followed. The successful use of a particular water may depend not alone on quality, but also on the drainage characteristics of the soil and on management practices. In appraising waters for irrigation, first consideration should be given to (1) the *salinity hazard* and (2) the *sodium hazard*, followed by the independent characteristics (3) *boron*, or other toxic elements, and (4) *bicarbonate*, any of which may change the quality rating.

Table II gives the analysis of several waters that vary widely in their characteristics. The following description of these waters illustrates the management practices required for their successful use for irrigation.

Columbia River water (1) represents a typical mountain water, low in total salts and containing chiefly calcium and bicarbonate ions. It presents no hazard for irrigation.

Colorado River water (2) is a high calcium (gypsiferous) water with a moderately high salinity hazard, but a low sodium hazard (EC = 1130 μmho./cm.; SAR = 2.8). It is used successfully under good management for all but the most salt-sensitive crops on about 600,000 acres of land

TABLE II
Analyses of Some Typical Irrigation Waters[a, b]

Water	Location sampled	EC × 10^6 at 25°C.	Dissolved solids (p.p.m.)	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	B (p.p.m.)	SAR	TAF	RSC
				Milliequivalents per liter											
(1) Columbia River	Grand Coulee, Washington	140	85	1.06	0.35	0.08	0.03	—	1.21	0.26	0.02	0.04	0.1	0.11	0
(2) Colorado River	Yuma, Arizona (below Imperial Dam)	1130	753	4.59	2.14	5.05	0.13	—	2.77	6.25	2.71	0.18	2.8	1.0	0
(3) Pecos River	a. Alamogordo Dam	1000	741	8.48	1.56	1.52	—	—	2.08	8.43	0.99	—	0.7	1.0	0
	b. Artesia, New Mexico	2500	1860	15.60	4.19	9.66	—	—	2.44	17.99	8.97	—	3.1	2.5	0
	c. Red Bluff Dam	8620	5900	24.50	12.09	60.46	—	—	1.97	34.14	60.10	—	14	8.0	0
(4) Gila River	Gillespie Dam, Arizona	8160	5620	14.87	10.94	60.90	0.31	—	3.18	27.90	56.96	2.6	17	7.6	0
(5) Well Water No. 85	Van Horn, Texas	500	476	0.10	0.10	5.90	0.10	—	3.80	1.70	0.50	—	19	0.4	3.60
(6) Well Water No. 55	El Paso, Texas	1950	1210	1.00	1.00	16.00	0.50	—	3.50	3.70	11.20	—	16	1.6	1.50
(7) Well Water No. 49	El Paso, Texas	6000	3775	22.20	4.80	30.90	0.30	—	7.30	18.30	34.50	—	8.4	5.4	0
(8) Ruzizi River	Belgian Congo	—	918	0.45	5.78	4.72	1.87	3.48	7.89	1.00	0.71	—	2.7	1.2	5.14

[a] Analyses were obtained as follows: Waters (1) to (4) from *U. S. G. S. Water Supply Paper* **1575** (1938); Waters (5) to (7) from *Texas Agr. Expt. Sta. Circ.* **132** (1952); and Water (8) by private communication.

[b] EC, electrical conductivity; SAR, sodium adsorption ratio; TAF, tons per acre-foot; RSC, residual sodium carbonate.

in Southern California. Adequate drainage is a first requirement for success with this water.

Pecos River water (3) is moderately saline at its source (EC = 1000 μmho./cm.) in northern New Mexico, but it rapidly gathers calcium, sodium, sulfates, and chlorides and becomes extremely saline as it flows southward toward the Rio Grande (EC = 8620 μmho./cm. at Orla, Texas). This water is gypsiferous, which is a point in its favor for irrigation. Water (3b) is used with moderate success in the Pecos Valley in New Mexico where the soils are permeable and well drained, but it requires high leaching for salinity control.

Gila River water (4) has three major hazards for irrigation—a very high salt content (EC = 8160 μmho./cm.), high sodium (SAR = 17), and high boron (2.6 p.p.m.). The use of this water is obviously limited to the growth of crops having both high-salt, and high-boron tolerance under a high-leaching regime. This water can be used only on very permeable, well-drained land.

Well waters (5), (6), and (7) represent the extreme variations in concentration and composition often observed in pumped waters. Water (5), although low in salt content, is very high in percentage of sodium (SAR = 20) and bicarbonate (RSC = 3.60 meq./l.). The quality of this water for irrigation is questionable in view of its extremely low calcium and magnesium content. Since the chief anion is bicarbonate, gypsum should be added either to the water or to the soil to prevent high-sodium accumulation in the exchange complex with resulting loss of permeability. This water should be applied only to coarse-textured soils with at least moderate leaching for removal of released sodium salts from the root zone.

Water (6) is a high-salt, high-sodium water in which chloride is the chief anion. Owing to its high-sodium hazard (SAR = 16), gypsum should be applied occasionally, followed by adequate leaching to prevent loss of permeability. Water (7) resembles Gila River water (4) except that it presents no boron hazard.

Ruzizi River water (7) of the Belgian Congo is included to illustrate a problem often encountered with tropical waters. This water is high in both bicarbonate and carbonate and is being considered for limited, dry-season irrigation of sugar cane in an area receiving 30 inches of rainfall annually. The soils to be irrigated are coarse-textured latosols. This water has a moderate salinity (EC not given), and a rather low-sodium hazard (SAR = 2.7), but, because of its high content of both carbonate and bicarbonate (RSC = 5.14 meq./l.), the calcium content is extremely low. If used extensively for irrigation, considerable difficulty may arise, especially on medium- or fine-textured soil, owing to rapid sodium accumulation. Moreover, nutritional disturbances may arise due to the extremely low calcium:magnesium ratio of 0.08. In this case, gypsum should be applied in generous amounts to the soil. However, if this water is used only for limited (supplemental) irrigation on coarse-textured soils, under conditions of a moderate to high rainfall, little or no difficulty should be encountered.

III. Effect of Salts on Soils

A. Characteristics of Salt-Affected Soils

Salt-affected soils are characterized by the fact that they contain sufficient soluble salts or exchangeable sodium, or both, to restrict plant growth. Agriculturally, they are regarded as a class of problem soils that require special remedial measures and management practices. A knowledge of the chemical and physical characteristics of the several kinds of salt-affected soils is essential to serve as a basis for their diagnosis, treatment, and management (Richards and Hayward, 1957).

1. Source and Composition of Salts

The ultimate source of all the salt constituents found in soils is the primary minerals in the exposed rocks of the earth's crust. The processes of chemical weathering, which include hydrolysis, hydration, solution, oxidation, and carbonation, gradually release these salt constituents to the surrounding water. The ocean may be the source of salts, as where marine deposits have been uplifted and drainage therefrom affects sources of irrigation water. The Mancos shales in Colorado, Wyoming, and Utah are examples of saline marine deposits. The ocean may be a direct source of so-called cyclic salt along the seashore through wind-blown sprays (Teakle, 1937). However, the main source of salt affecting irrigation agriculture is from surface and ground waters.

The soluble salts that effectively contribute to soil salinity consist mostly of various proportions of the cations calcium, magnesium, and sodium and of the anions chloride, sulfate, bicarbonate, and sometimes carbonate. Potassium occurs to a lesser extent than any of the other three cations. Among the anions, bicarbonate and carbonate are usually present in minor amounts as compared to chloride and sulfate. Bicarbonate ions form as a result of the solution of carbon dioxide in water, which may be of atmospheric or biological origin. Bicarbonate and carbonate ions are interrelated, the relative amounts of each being a function of the pH value of the soil solution. Appreciable amounts of carbonate ions occur in soils only at pH values of 9 or higher.

Boron, owing to its marked toxicity to plants at concentrations of only a few parts per million, deserves mention, even though its salts make no important contribution to total soil salinity. The reclamation of boron-rich soils is discussed in Section V, B, and the toxic effect of boron on plant growth is discussed in Section IV, B, 3.

2. *Salination and Alkalization*

a. Salination. Salination is the process whereby soluble salts accumulate in the root zone of the soil.

Irrigation waters contain soluble salts varying from 0.1 to 5 tons/acre-foot and the annual application may range from 3 to 5 feet. In the absence of leaching, the salt contained in the applied irrigation water is deposited in the root zone of the soil due to evapotranspiration, or consumptive use.

Restricted drainage is a factor that contributes to the salination of irrigated soils. This may involve the presence of a high ground water table, or low permeability of the soil, or both. Where a high water table exists within 4 or 5 feet of the soil surface, upward movement of saline ground water, combined with the evaporation of applied irrigation water, may result in the formation of a saline soil. In severe cases, salts may accumulate at the soil surface, as shown in Fig. 1, with total loss of production.

Low permeability of the soil, causing waterlogging, may be due to an extremely fine-textured condition of the soil to well below the root zone, or to the presence of an impermeable barrier below the root zone. The latter may consist of a clay lens (clay pan), caliche layer, or a silica hardpan. De Sigmond (1924) considered the presence of an impermeable layer essential for the formation of the saline soils in Hungary. Many thousands of acres of irrigated lands in the United States are affected by high water table conditions and require an effective drainage system for economic crop production.

b. Alkalization. This is the process whereby the exchangeable-sodium content of a soil is increased, leading to the formation of a sodic soil. It involves both salination and change in composition of the accumulated salts.

Calcium and magnesium are the dominant cations found in normal soils in arid regions. However, as soluble salts accumulate from irrigation waters and become more concentrated in the soil, owing to consumptive use and to the lack of leaching, certain composition changes occur. The solubility limits of calcium sulfate, calcium carbonate, and magnesium carbonate are exceeded, causing calcium and magnesium to

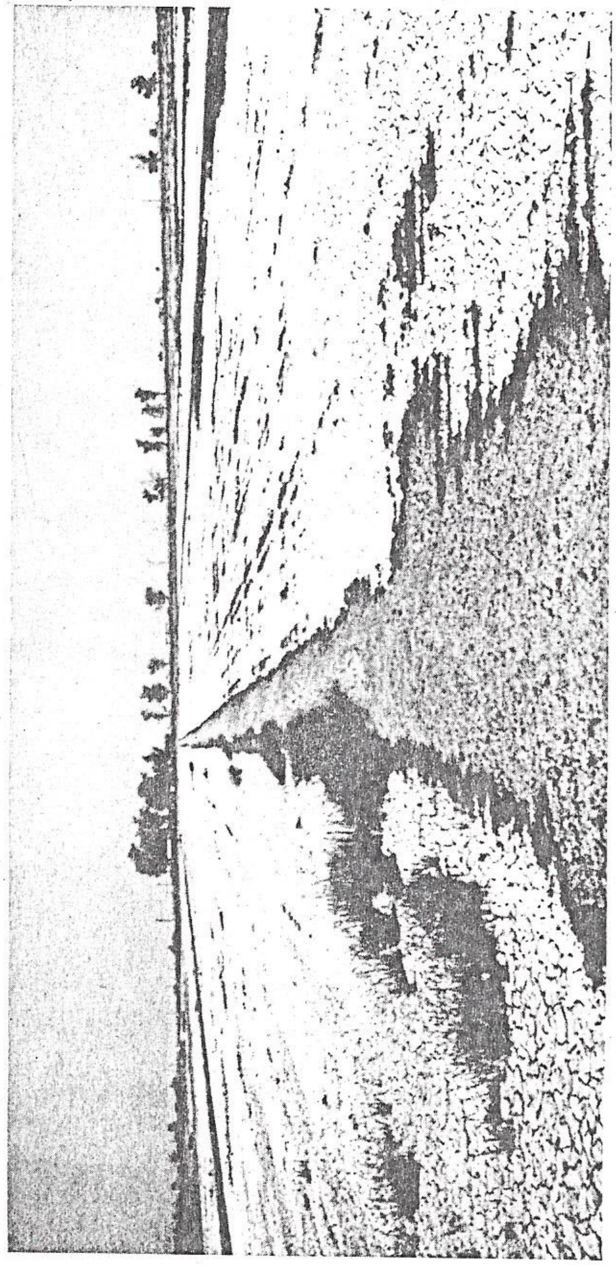


Fig. 1. Border-irrigated alfalfa field that became highly salinized as a result of poor management, i.e., lack of adequate drainage for salinity control.

precipitate. This causes a corresponding increase in the relative proportion of sodium in the soil solution, i.e., the soluble-sodium percentage (SSP) increases. Due to the dynamic equilibrium between soluble and adsorbed ions, sodium replaces some of the calcium and magnesium originally present on the exchange complex of the soil (Kelley, 1951). In general, half or more of the soluble cations must be sodium (SSP > 50) before appreciable amounts of this ion are absorbed by the cation-exchange complex. In some saline soils, practically all the soluble cations are sodium and, therefore, sodium is the predominant adsorbed cation.

As long as soluble salts are present in the soil solution in appreciable quantities, the soil (saline-sodic) remains flocculated and permeable, and the pH is less than 8.5. If the soluble salts are removed by leaching, the soil (sodic) may become very impermeable because of the dispersing effect of the adsorbed sodium ion on the exchange complex. Some of the sodium hydrolyzes off the exchange complex, forming traces of sodium hydroxide, and the pH increases, often as high as 10.

Arany (1956) pointed out the importance of the anions associated with sodium in the formation of sodic soils. The alkaline sodium salts (bicarbonate, carbonate, silicate) favor nearly complete displacement of calcium by sodium because of the low solubility of the corresponding calcium salts. Conversely, the neutral sulfate and chloride salts of sodium produce only partial replacement of calcium by sodium. Therefore, the rate of alkalization is more rapid for the basic than for the neutral salts.

3. *Saline Soils*

Saline soils contain soluble salts in such quantity that they interfere with the growth of most crop plants. By definition, the electrical conductivity of a saturation extract (EC_e) of a saline soil is greater than 4 mmho./cm. and the exchangeable-sodium percentage (ESP) is less than 15. The pH of the saturated soil is usually less than 8.5, but if the soil is gypsiferous the pH seldom exceeds 8.2. Saline soils correspond to Hilgard's "white alkali" and to "solonchak" as defined by Russian scientists.

The salts present in saline soils consist mainly of neutral salts, such as the chlorides and sulfates of sodium, calcium, and magnesium. Sodium seldom comprises more than half of the soluble cations and, therefore, it is not adsorbed to any significant extent in the soil exchange complex.

Because saline soils are generally flocculated, their tillage properties and permeability to water are often equal to or better than those of similar nonsaline soils. Restricted plant growth is almost directly related to the total salt concentration of the soil solution and is largely independhad various and somewhat indefinite meanings. Some scientists have used the term alkali to include soils affected both by salts and by exchangeable sodium (Hilgard, 1906), and in this respect its meaning is similar to the term salt-affected. Others have used "alkali" to indicate soils affected mainly by exchangeable sodium (U. S. Salinity Laboratory Staff, 1954). In Iraq, farmers use the term alkali to describe any soil having the appearance of ashes in the surface, regardless of the chemical condition (Buringh, 1960). Thus, the term sodic describes the soil condition in terms of its cause, that of exchangeable sodium.

The soil solution of sodic soils is relatively low in soluble salts and the ionic composition differs considerably from that of saline soils. The predominant cation is sodium because, at high pH and in the presence of the carbonate ion, calcium and magnesium are largely precipitated as calcium and magnesium carbonate. The anions present consist mostly of chloride, sulfate, and bicarbonate, with small to moderate amounts of carbonate, depending on the pH of the soil. If carbonates are present in detectable amounts in the saturation extract, then the pH must be above 9.

The exchangeable sodium present has a marked influence on the chemical and physical properties of sodic soils. As the proportion of exchangeable sodium increases, the soil tends to become dispersed, less permeable to water, and exhibits poor tilth. Sodic soils are usually plastic and sticky when wet and form large clods or crusts on drying. Their crusting tendency is a serious hazard to seedling emergence, and it often accounts for a poor stand of crops, causing reduced yield. A special method of reclaiming high-sodium soils is discussed in Section V, C, 5.

6. *Salination Due to Evaporation*

Considerable salt may accumulate at the soil surface by evaporation from a shallow, saline water table during the fallow period between crops. This is especially significant if the intercrop period is long and the climate is arid. Donnan *et al.* (1954) and Bradshaw and Donnan (1953) recommended that newly reclaimed, fine-textured land having a water table near the root zone should be kept under production (irrigated) continuously to prevent salt from returning to the surface by capillary rise from the water table.

Recent studies of evaporation losses in the Imperial Valley by Doering (1963) provide data to illustrate salination of land during a fallow period. For this purpose, the following revised formula (U. S. Salinity Laboratory, 1954, p. 36) is used in which groundwater (gw) is substituted for irrigation water (iw).

ent of the kind of salts present. If drainage is adequate and the excess salts are removed by leaching, saline soils become normal soils.

Saline soils may be recognized by the presence of a white inflorescence on the surface (Fig. 1) or by an oily looking surface devoid of vegetation. Plants indicate the presence of salinity by stunted growth and sometimes by considerable variability in size within the field. The foliage is often a deep green color with occasional tipburn or marginal burn on the leaves.

4. *Saline-Sodic Soils*

Saline-sodic soils contain sufficient quantities of both soluble salts and adsorbed sodium to reduce the yield of most plants. For the purpose of definition, the exchangeable-sodium percentage is greater than 15, and the electrical conductivity of the saturation extract is greater than 4 mmho./cm. The pH reading of the saturated soil is usually less than 8.5, but if gypsum is present in appreciable quantities, the pH may be as low as 8.2.

These soils form as the result of the combined processes of salination and alkalization (accumulation of exchangeable sodium). As long as excess salts are present, the appearance (Fig. 1) and properties of these soils are generally similar to those of saline soils. If gypsum is present, leaching converts these soils to the nonsaline condition due to the replacement of exchangeable sodium by calcium resulting from the solution of gypsum during the leaching process. However, if gypsum is neither present nor supplied as an amendment, leaching causes the soil to become strongly alkaline (pH above 8.5), the colloids disperse, and the soil becomes unfavorable for the entry and movement of water and for tillage. Although the return of soluble salts may restore the soil to a flocculated condition, the management of saline-sodic soils continues to be a problem until the excess salts and exchangeable sodium are removed from the root zone and a favorable physical condition of the soil is reestablished.

5. *Sodic Soils*

Sodic soils contain sufficient exchangeable sodium to interfere with the growth of most crop plants, but do not contain appreciable quantities of soluble salts. By definition, the ESP is greater than 15 and the EC_e is less than 4 mmho./cm. The pH reading of the saturated soil is usually greater than 8.5 and sometimes as high as 10. Sodic soils correspond to Hilgard's "black alkali" and in some cases to "solonetz," as the latter term is used by Russian scientists.

The term sodic us used here instead of alkali because the latter has

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

D_{gw} = depth of groundwater evaporated
D_s = depth of soil in which salts accumulate
EC_{gw} = EC of groundwater evaporated
d_w = density of water
d_s = bulk density of soil
SP = saturation percentage of soil

The soil studied was a silty clay to a depth of 60 cm. over silt loam, with a water table at 150 cm. The bulk density of this silty clay soil was 1.4 g./cm.^{3} and the SP was 63. Water loss determined by the chloride accumulation method, which agreed favorably with evaporation from a special evaporimeter, was about 0.09 cm./day, or 33 cm./year. For a summer-fallow period of 4 months between regular crops in the rotation, the corresponding water loss was 11 cm. Based on a groundwater salinity of EC = 10 mmho./cm., which is not uncommon, the increase in EC_e of the surface 30 cm. of silty clay soil was calculated to be 4.1 mmho./cm. for the 4-month period. Hence, the salinity of the surface soil might increase twofold as the result of capillary rise of salt from a shallow water table during a 4-month fallow period. The assumption has been made that all the salts remain in solution. If gypsum and/or carbonates precipitate from solution, the change in EC_e is reduced accordingly. The application of a few irrigations during a prolonged intercrop period might prove profitable in terms of maintaining a more favorable salt balance for salt-sensitive crops to follow.

B. Diagnosis of Saline and Sodic Soils

An effective diagnostic system for appraising the salinity and sodium status of soils must take into consideration field moisture conditions because plants are responsive to the salt concentration of the soil solution, which reflects osmotic pressure conditions. Ideally, salinity and sodium measurements would be most reliable if made on extracts of the soil solutions within field moisture range. With pressure-membrane equipment, this is possible but the difficulty of obtaining such extracts makes this system prohibitive for routine use (U. S. Salinity Laboratory Staff, 1954). A test kit for making salinity and sodium tests on soils and waters has been described (Richards *et al.*, 1956) and is commercially available.

Several systems, presently in use, classify soils on the basis of total salt content. In Russia, soils are considered slightly saline at 0.3 per cent salt, moderately saline at 0.7 per cent, and strongly saline at 1.0 per cent, etc. These systems, while providing a measure of total salts in the soil, do not evaluate salinity in terms of the force to which plants are responsive—that of the osmotic pressure of the soil solution.

1. Soil Sampling

Generally, the major root activity occurs in the less saline parts of the soil, and this fact should be borne in mind in determining the salt and sodium status of the soil with reference to plant response. For instance, samples collected from the surface soil around the base (ridge) of row-planted crops at later stages of growth may contain 5 per cent salt or more, representing an EC_e of 50 mmho./cm. or higher. This condition represents an accumulation of salt due to moisture movement into the ridge where it evaporates, not the salt concentration in the active root zone under the irrigation furrow. Therefore, in correlating crop growth with salinity, soil samples should be taken from the active root zone (furrow), which is uncontaminated by surface encrustations of salt.

The larger the number of surface samples and the more carefully they are selected, the more accurate will be the appraisal; but with experience a satisfactory appraisal may be made on the analyses of relatively few samples. Because often the salt content varies with depth, it is advisable to take a few profile samples by genetic horizons or by depositional layers, if present. However, it is recognized that salt does not necessarily accumulate according to genetic horizons. In the absence of layering in the profile, a sample should be taken to plow depth, usually to 6 or 7 inches, and succeeding samples may be taken at intervals of 6 to 18, 18 to 36, and 36 to 72 inches, or at other convenient depths, depending on depth of the root zone, the nature of the problem, and the detail required. The size of sample will depend on the number of measurements to be made, but usually 1000 g. of soil per sample is adequate.

2. Determination of Salinity Hazard

a. Saturation-extract method. The electrical conductivity of the saturation extract (EC_e) expressed in millimhos per centimeter at 25°C. is recommended for appraising the salinity hazard in relation to plant growth (U. S. Salinity Laboratory Staff, 1954).

The unique feature of this method is that the salt concentration in the saturation extract is about one-half the concentration of the soil solution at the upper end (field capacity), and about one-fourth the concentration at the lower end (permanent-wilting percentage) of the field moisture range for plant growth. This relationship makes it possible to interpret salinity measurements (at saturation) directly in terms of field moisture conditions, which is not possible when dilution extracts are used.

The procedure involves making a saturated-soil paste by stirring the soil, during the addition of distilled water, until a characteristic end point is reached. The end point is reasonably definite, and with a little training good agreement can be obtained among various operators. A suction filter is used to obtain a sufficient quantity of extract for making the conductivity measurement and for the determination of soluble cations and anions, if desired. EC_e values may be related to plant growth by reference to Table III.

b. Dilution-extract method. The estimation of salinity hazard from EC measurements made on dilution extracts at 1:1, 1:5, or 1:10 soil:water ratios may have certain advantages, but the limitations of the method should be clearly understood. For rapid salinity determinations, these higher dilutions are often convenient where repeated samplings are to be made on the same textural soil (as in plot experiments) to determine the change in salinity with time or treatment. However, salinity measurements made on dilutions higher than saturation do not relate satisfactorily with salt-tolerance data given in Table IV.

For determination of ESP, dilution extracts are definitely unsatisfactory because, with increase in dilution, calcium replaces sodium in the exchange complex in accordance with the valence-dilution principle. Therefore, the soluble-sodium percentage (SSP) increases with dilution, resulting in lower values for exchangeable sodium. This gives ESP values that are much farther out of line with the actual sodium status of the soil under growing plants than is provided when determinations are made at the SP.

3. *Determination of Sodium Hazard*

The exchangeable-sodium percentage (ESP) has long been used to indicate the sodium status or hazard of salt-affected soils. In fact, the definition of sodic soils is based on the ESP determination. The determination of ESP by conventional chemical methods requires the following separate determinations: (1) soluble sodium on a saturation extract of the soil, (2) total sodium on an ammonium acetate extract of the soil, and (3) the cation-exchange capacity of the soil. When so determined, much time is required and appreciable errors may occur, owing to the indirect nature of its determination as indicated by the formula: ESP = (total sodium — soluble sodium) × 100/cation-exchange capacity.

Recent research (U. S. Salinity Laboratory Staff, 1954) demonstrated that the most reliable index of sodium status is the sodium adsorption ratio (SAR). It is a calculated value and is defined as

$$SAR = \frac{Na^+}{\sqrt{Ca^{++} + Mg^{++}/2}} \quad (2)$$

where concentrations are expressed in milliequivalents per liter. This ratio is based on cation-exchange equations of the mass-action type (Gapon, 1933).

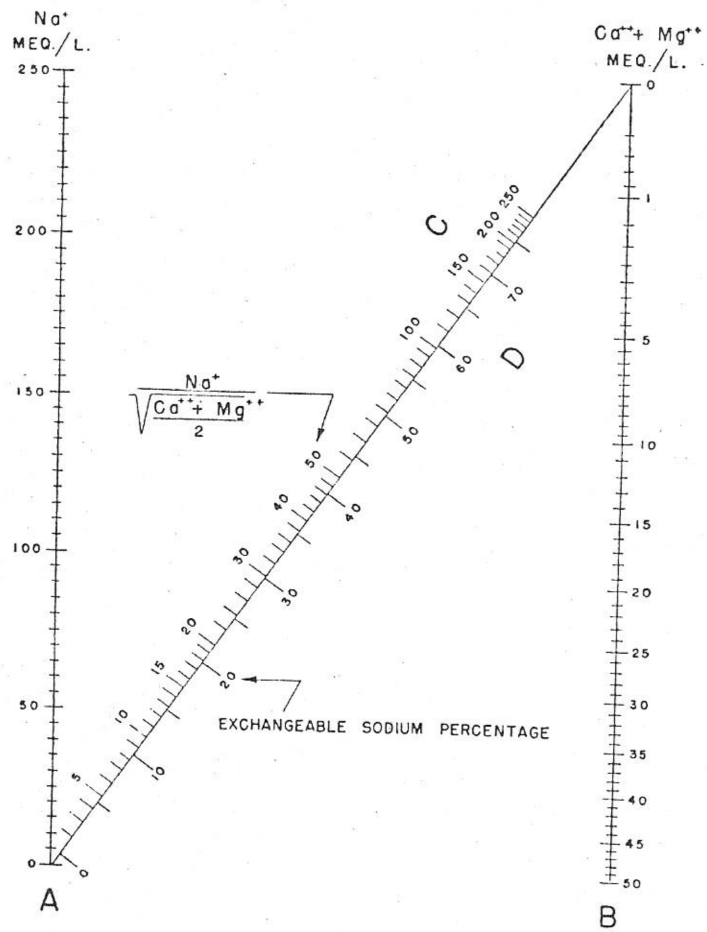


FIG. 2. Nomogram for determining the sodium adsorption ratio (SAR) value of a saturation extract and for estimating the corresponding exchangeable-sodium percentage (ESP) value of soil in equilibrium with the extract.

The unique feature of the SAR is that it takes into consideration changes in both concentration and composition of the salts present in the soil solution that are in equilibrium with the soil. Previously, no formula or equation made this possible. Moreover, the results of a recent study involving 218 soil samples from 24 countries (Bower, 1962), indicated that the SAR can be used with confidence in all arid countries of the world to determine the sodium status of salt-affected soils.

To determine the SAR, it is necessary merely to prepare a saturation extract of the soil, determine the concentration in milliequivalents per liter of the calcium, magnesium (EDTA titration), and sodium (flame photometer) ions in the extract, and substitute these concentrations in the nomogram shown in Fig. 2. The ESP is then interpreted from the SAR line of this nomogram.

Besides flame photometry, sodium may be determined by means of a special glass electrode (Bower, 1960).

IV. Effect of Salts on Crops

A. General and Specific Effects

Salts affect plant growth directly (1) by increasing the osmotic pressure of the soil solution, (2) by accumulating certain ions in toxic concentrations in plant tissue, and (3) by altering the plant's mineral nutrition. Plant growth responses to salinity have been discussed by Hayward and Wadleigh (1949), Grillot (1956), Bernstein and Hayward (1958), and Bernstein (1962).

1. *Kind and Function of Ions*

The principal ions in the soil solution of salt-affected soils are calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate. Some ions (calcium, magnesium, potassium, and sulfate) provide major essential elements for growth, and still others (boron and lithium) may be toxic at very low concentrations.

Soviet scientists attach considerable importance to the composition of the salts in soils in relation to plant growth, but the emphasis is on the anionic composition (Bower *et al.*, 1962). Thus, chloride salinity and sulfate salinity are frequently used terms in their soil science literature. American scientists, in contrast, emphasize the cationic composition of the salts, because the cations are known to undergo exchange reactions with the soil and thereby control its chemical and physical properties.

2. *Osmotic Pressure and Plant Growth*

Gauch and Wadleigh (1944) demonstrated progressive growth reduction of beans in solution culture with increasing salinity, and the equivalent effects of sodium and calcium salts regardless of the anion (Cl or SO_4) present. This indicates that the total concentration of solute particles in the solution, rather than their chemical nature, is mainly responsible for the inhibitory effects of saline solutions on the growth of crop plants.

The cause of growth reduction, associated with increasing osmotic pressure (OP) of the rooting medium, has been attributed to decreased water entry or availability, based on observations of Hayward and Spurr (1943, 1944). However, recent evidence by Bernstein (1961) indicates that water-absorption capacity is relatively unaffected by salinity. The reduced growth associated with osmotic stress is attributed to the process of building up the OP of developing cells (which is contingent upon accumulation of solutes) to meet the increasing OP of the rooting medium and still maintain turgor. This theory suggests that salt tolerance may be defined as the degree to which osmotic adjustment can be made without sacrifice in growth.

3. *Specific Ion and Other Effects*

Certain ions exert specific effects that depress growth and yields independent of osmotic effects. These specific ion effects may be toxic or nutritional in nature. A toxic effect is considered to be due to the presence of an ion in the solution which causes direct damage to the plant. Injury is usually associated with the accumulation of harmful concentrations of the toxic ion in the plant tissue, which may show no other significant change in mineral composition.

a. Sodium and chloride. The toxicity of sodium and chloride ions may be the major factor in salt damage to specifically sensitive fruit crops (Bernstein and Hayward, 1958). Direct toxicities by these two ions have been demonstrated in stone fruits for such crops as peaches, plums, apricots, and also for other crops, for example, citrus, avocados, grapes, strawberries, and blackberries. These toxic effects may occur at osmotic concentrations in the substrate which are below the level that normally restrict yield for these crops.

Chloride may accumulate in the leaves to about 1 or 2 per cent of the dry weight when this anion occurs in the root medium in only moderate concentrations (700 p.p.m. to 1500 p.p.m. in the soil moisture, or nutrient solution). At these concentrations in the leaves, marginal burn develops, leading ultimately to leaf drop, twig dieback, and even death of the plant. The selection of rootstocks for characteristics of low chloride, and also low boron accumulation, offers considerable promise for fruit-crop improvement.

Sodium accumulation in leaves ~~less~~ > than ~~0.05~~ 0.5 per cent of the dry leaf weight produces similar leaf-burn symptoms and extensive injury. Lilleland *et al.* (1945) observed sodium injury in almond trees growing in essentially nonsaline soil containing less than 5 per cent of exchangeable sodium.

b. Boron. The specific effects of boron on plant growth are discussed in Section IV, B, 3.

c. Bicarbonate. The bicarbonate ion in excess may be toxic to plants, although sensitivity varies with different species. As an example, beans and Dallisgrass are very sensitive to the presence of bicarbonate ions in the substrate, whereas Rhodesgrass and beets are relatively tolerant (Wadleigh and Brown, 1952; Brown and Wadleigh, 1955; Gauch and Wadleigh, 1951). Bicarbonate excess may give rise to ion chlorosis, a problem that has been reviewed by Brown (1956). The bicarbonate ion does not frequently occur in sufficient concentration in irrigation waters to produce direct toxic effects, although bicarbonate-induced chlorosis in apple orchards has been observed in Washington (Harley and Lindner, 1945).

d. Nutritional effects. Salinity may inhibit growth in plants because of effects on plant nutrition. Because plants vary widely in their nutrient requirements and in their ability to absorb specific nutrients, the effects of salinity on nutrition differ markedly from species to species.

High concentrations of sulfate generally decrease the uptake of calcium while promoting the uptake of sodium (Hayward and Wadleigh, 1949). Some lettuce varieties are known to develop calcium-deficiency symptoms in the presence of high sulfate concentrations (Doneen and Grogan, 1954). By promoting the uptake of the sodium ion, sulfate may induce sodium toxicity in susceptible species (Brown *et al.*, 1953). Salinity also tends to increase the incidence of blossom-end rot of tomatoes (Geraldson, 1960), a disease likewise attributed to calcium deficiency. On the other hand, high concentrations of calcium may restrict the uptake of essential potassium by beans and some carrot varieties (Bernstein and Hayward, 1958).

B. Salt, Sodium, and Boron Tolerance of Crops

1. *Relative Tolerance of Crops to Salts*

Salt tolerance refers to the ability of plants to tolerate concentrations of soluble salts in the root medium. Information on the salt tolerance of crops is important in diagnosing suspected salt injury in the field, in selecting tolerant crops for saline lands, and in determining irrigation and drainage requirements and management practices for salt-affected land. Table III indicates the response of crops to increasing salinity, expressed as EC_e values.

The salt tolerance of many crops has been appraised, and the data were initially reported in terms of the salinity level (EC_e) that would be expected to give a 50 per cent decrease in yield (U. S. Salinity Laboratory Staff, 1954, p. 67). More recently, these data representing field, vegetable, and forage crops have been revised and published in popular bulletin form (Bernstein, 1958, 1959, 1960).

TABLE III

Crop Response at Different Salinity Levels

Salinity effects mostly negligible	Yields of very sensitive crops may be restricted	Yields of many crops restricted	Only tolerant crops yield satisfactorily	Only a few very tolerant crops yield satisfactorily
0	2	4	8	16

Electrical conductivity of saturation extract in millimhos per centimeter ($EC_e \times 10^3$) at 25°C.

Table IV gives data from these publications for the salinity levels that would permit yields equivalent to 85 or 90 per cent of the yields obtained on comparable nonsaline soil. The position of each crop in this table reflects its relative salt tolerance under management practices that are customarily employed when this crop is grown under irrigation agriculture. Crops are listed within each group in the order of decreasing salt tolerance, but a difference of two or three places in the column may not be significant in some cases. Significant varietal differences were found for Bermudagrass, barley, and smooth brome, whereas for truck crops, such as green beans, lettuce, onions, and carrots, varietal differences were of little or no practical significance.

In applying the information in Table IV, it is important to remember that climatic conditions may influence the sensitivity of plants to salinity. Onions, for example, are more sensitive to a given level of salinity in hot, dry areas than in cooler, more humid areas (Magistad *et al.*, 1943). Consequently, information on salt-tolerant crops should be evaluated with reference to the condition under which they are to be grown.

a. Stage of development. The listing of crops according to salt tolerance (Table IV) fails to reveal certain specific problems because some plants are especially sensitive to salinity during certain stages of development and tolerant at other stages (Bernstein and Hayward, 1958; Bernstein, 1961). For example, rice is quite tolerant during germination but becomes very sensitive during the seedling stage, and again somewhat so during the fertilization of the florets (Pearson and Bernstein, 1959). Corn appears to be appreciably more tolerant during germination than at later stages of growth. Sugar beets, on the other hand, can tolerate salinity levels of only about 4 mmho./cm. in the saturation extract during germination but can easily tolerate three times this salt level once the young seedlings are well established.

TABLE IV
Relative Tolerance of Crops to Salinity Arranged According to Decreasing Tolerance within Groups

Crop	Tolerant	Moderately tolerant		Sensitive
Field	12-8 mmho./cm.	8-4 mmho./cm.		3-2 mmho./cm.
	Barley	Rye	Broadbean	Field beans
	Sugar beet	Wheat	Corn	
	Rape	Oats	Rice	
	Cotton	Sorghum	Flax	
		Sorgo	Sunflower	
		Soybeans	Castorbean	
		Sesbania		
Truck	8-5 mmho./cm.	5-3 mmho./cm.		3-2 mmho./cm.
	Garden beets	Tomato	Yam	Radish
	Kale	Broccoli	Bell pepper	Celery
	Asparagus	Cabbage	Carrot	Green beans
	Spinach	Cauliflower	Onion	
		Lettuce	Peas	
		Sweet corn	Cantaloupe	
		Potatoes	Squash	
		Sweet potato	Cucumber	
Forage	12-6 mmho./cm.	6-3 mmho./cm.		3-2 mmho./cm.
	Saltgrass	Sweetclover	Oats (hay)	White dutch clover
	Bermudagrass	Perennial ryegrass	Orchardgrass	Meadow foxtail
	Tall wheatgrass	Mountain brome	Blue grama	Alsike clover
	Rhodesgrass	Harding grass	Meadow fescue	Red clover
	Canada wildrye	Beardless wildrye	Reed canary	Ladino clover
	Western wheatgrass	Strawberry clover	Big trefoil	Burnet
	Tall fescue	Dallisgrass	Smooth brome	
	Barley (hay)	Sudangrass	Tall meadow oatgrass	
	Birdsfoot trefoil	Hubam clover	Milkvetch	
		Alfalfa	Sourclover	
		Rye (hay)		
		Wheat (hay)		
Fruit	8 mmho./cm.	6-3 mmho./cm.	3-1.5 mmho./cm.	
	Date palm	Pomegranate	Orange	Peach
		Fig	Grapefruit	Apricot
		Olive	Lemon	Boysenberries
		Grape	Apple	Blackberries
			Pear	Raspberries
			Plum	Avocado
			Prune	Strawberry
			Almond	

Many crops are more sensitive during the seedling stage than at later stages of growth. Rice can germinate at salinities up to 10 or 15 mmho./cm., but the plants usually die if the salinity is in excess of 5 or 6 mmho./cm. during the seedling stage (Pearson and Ayers, 1958). Barley is like rice in being more sensitive to salinity during the seedling stage than at earlier or later growth stages.

Occasionally, special practices may be required to permit a crop to survive during phases of minimum salt tolerance. For example, the paddy field is sometimes drained and refilled with fresh water to lower the salinity during the critical, sensitive flowering stage of rice. Special bedding practices have been developed to minimize salt accumulation around the germinating seeds, the condition responsible for poor stands of furrow-irrigated row crops. These practices are discussed in Section VI, C.

2. *Relative Tolerance of Crops to Sodium*

The chemical and physical characteristics of sodic soils were described in Section III, A, 2–5, and the literature on the factors affecting plant growth on such soils has been reviewed (Bernstein and Hayward, 1958). The sodium-tolerance data recently reported by Pearson (1960) for several important agricultural crops are shown in Table V.

The response of plants to exchangeable sodium is complicated by a number of factors, such as direct toxic effects in the case of sodium-sensitive species, indirect effects due to structural deterioration in sodic soils, and nutritional effects. Ratner (1935, 1944) pointed out that decreased absorption of calcium by plants is often due to the presence of increasing levels of exchangeable sodium in the soil.

Sodium-sensitive plants, such as avocado, almond, citrus and stone fruits, exhibit characteristic leaf-burn symptoms when sodium accumulation in leaves becomes excessive (Martin and Bingham, 1954; Jones *et al.*, 1957). They may become injured at ESP levels too low to give unfavorable soil physical conditions. Sodium appears to be directly toxic for these species, since no evidence was detected of the calcium deficiency or any other nutrient unbalance.

Plants normally tolerant to sodium may be inhibited in their growth primarily by the adverse physical conditions in sodic soils, which restricts moisture transmission and aeration, and may physically impede root elongation and seedling emergence. Those sodium-tolerant crops that may be primarily affected by poor soil structure include beets, Rhodesgrass, cotton, tomatoes, and some of the other grain crops. Moderately tolerant crops, alfalfa, clover, Dallisgrass and certain others, may exhibit a nutritional component in the overall growth reduction, as well as effects due to poor soil structure.

From their studies in the Kanpur District of India, Agarwal and Yadav (1956) suggested an additive effect of exchangeable sodium and salinity on crop growth. More recently, Bernstein (1962) found that when a good physical condition of the root zone of the soil is maintained by synthetic soil conditioners, the ESP exerts a pronounced effect on growth at low salt concentrations but not at higher salt concentrations in the root medium. Lagerwerff and Holland (1960) found

TABLE V
Tolerance of Various Crops to Exchangeable-Sodium Percentage (ESP)

Range of ESP values affecting growth		Crop	Growth response under field conditions
Extremely sensitive	2–10	Deciduous fruits Nuts Citrus Avocado	Sodium toxicity symptoms at low ESP
Sensitive	10–20	Beans	Stunted growth at low ESP, despite favorable soil structure
Moderately tolerant	20–40	Clover Oats Tall fescue Rice Dallisgrass	Stunted growth due to nutritional factors and poor soil structure
Tolerant	40–60	Wheat Cotton Alfalfa Barley Tomatoes Beets	Stunted growth, usually due to poor soil structure
Most tolerant	> 60	Crested wheatgrass Fairway wheatgrass Tall wheatgrass Rhodesgrass	Stunted growth, usually due to poor soil structure

similar effects in sand cultures containing exchange resins to simulate the adsorption properties of the soil. Thus, an additive effect does not occur and, under saline conditions where the physical condition of the soil is not too bad, the ESP within limits becomes less critical than under nonsaline conditions. However, yields under such saline-sodic conditions are restricted eventually by the salinity level.

3. *Relative Tolerance of Crops to Boron*

Boron is essential for plant growth at very low concentrations, but it becomes toxic at only a few parts per million in the soil solution. Its presence in both waters and soils has been extensively studied (Eaton, 1935; Wilcox, 1955, 1960; Kelley and Brown, 1928). Table VI gives the relative boron tolerance of several crops, as determined by Eaton (1935) and modified by Wilcox (1958, 1960) based on more recent field observations.

The chief source of boron in agriculture is from irrigation water since all natural waters contain some boron. Only a few surface streams are contaminated, but a large number of well waters are high in boron. When used for irrigation, these waters produce toxic concentrations of

TABLE VI
Relative Tolerance of Crops to Boron

Tolerant	Semitolerant	Sensitive
4 p.p.m.[a]	*2 p.p.m.*	*1 p.p.m.*
Asparagus	Potato	Pecan
Date palm	Cotton	Walnut
Sugar beet	Tomato	Navy bean
Mangel	Radish	Plum
Garden beet	Field pea	Pear
Alfalfa	Olive	Apple
Broadbean	Barley	Grape
Onion	Wheat	Kadota fig
Turnip	Corn	Cherry
Cabbage	Milo	Peach
Lettuce	Oat	Apricot
Carrot	Pumpkin	Blackberry
	Bell pepper	Orange
	Sweet potato	Avocado
	Lima bean	Grapefruit
		Lemon
2 p.p.m.[a]	*1 p.p.m.*	*0.3 p.p.m.*

[a] Indicates limits of tolerance for boron in irrigation waters.

boron in the soil, especially under conditions of poor drainage. Boron has been found in toxic concentrations in the soils of many arid regions of the world. In the United States, it is confined almost exclusively to the irrigated areas of the arid West. The total area in which boron toxicity is a problem is not large, but the injury sometimes is very severe. The classification of waters on the basis of the boron hazard is given in Table I.

Boron is translocated to the leaves where it accumulates in the tip and in the margin. Injury can be recognized by the very characteristic patterns developed on leaves of many crops (Wilcox, 1960). Tip burn, which starts with yellowing followed by browning and death of the leaf tip, affects such plants as lemon, orange, grapefruit, and black walnut. Both tip and marginal burn are characteristic symptoms on cereals and grasses, such as oats, milo, corn, wheat, and barley. Marginal burn occurs on the leaves of many broadleaf plants, including bush berries, alfalfa, and cotton. However, many crops show no characteristic pattern of boron injury. This includes grapes, figs, beans, bell peppers, tomatoes, potatoes, avocados, pumpkin, peas, radish, sunflower, turnips, and beets, among others.

Foliar analysis of leaf tissue is preferred over leaf symptoms as a basis for diagnosing boron injury, and often it provides a more reliable basis for diagnosis than the analysis of soil or water. The boron content of normal mature leaves is about 50 to 100 p.p.m. Boron contents of 20 p.p.m., or less, indicate deficiency, while values above 250 p.p.m. are usually associated with boron toxicity.

If a boron toxicity is indicated, its source should be determined whether from irrigation water, from soil or from fertilizer. If the irrigation water is contaminated, it may be possible to mix it with enough low-boron irrigation water so that the mixed water is safe for use. If this is not possible, then the only aternative is to plant boron-tolerant crops, as listed in the left-hand column of Table VI. If the soil is found to be contaminated with boron, reclamation will be necessary, entailing leaching with a large quantity of water, as described in Section V, B.

V. Reclamation of Salt-Affected Lands

Many studies have contributed to our understanding of the methods and principles of the reclamation of saline and sodic soils (Hilgard, 1906; Harris, 1920; Kelley and Thomas, 1928; Burgess, 1928; Wursten and Powers, 1934; Snyder *et al.*, 1940; Reeve *et al.*, 1948, 1955; Kelley, 1937, 1951; Bower *et al.*, 1951; Overstreet *et al.*, 1951, 1955).

A. Leaching to Remove Soluble Salts

The reclamation by prolonged leaching of salt-affected land in new project areas, and also of previously irrigated but abandoned land in older projects, is an essential part of the overall program of irrigated agriculture. For instance, about one-third of a possible 100,000 acres of irrigable land in the Coachella Valley, California, requires extensive leaching before good production is possible, and most of the nearly one-half million acres now under irrigation in the Imperial Valley required intensive leaching at one time or another. Approximately 1,000,000 acres went out of production in the United States during the period 1930 to 1940, but much of this land has since been reclaimed. Large acreages in the Delta area, Utah, previously irrigated for many years, also have been reclaimed.

The amount of water required to reclaim salty land has been determined on the basis of leaching experiments conducted in Utah (Reeve *et al.*, 1948) and in California (Reeve *et al.*, 1955). The basic findings from these two experiments are expressed in a salt-leaching curve given in Fig. 3. This curve indicates that to reduce the salt content of the soil to about 20 per cent of the initial high value, 1 foot of water is required for each foot of soil considered. Thus, to effectively reclaim a highly

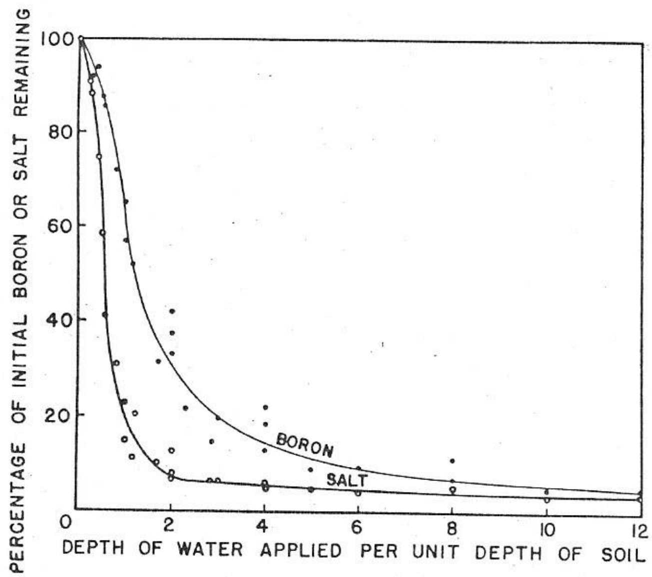


FIG. 3. Percentage of initial salt and boron remaining in the soil in relation to depth of leaching water applied per unit depth of soil. (After Reeve *et al.*, 1955.)

saline soil to a depth of 4 feet, at least 4 feet of water should be applied as a continuous application.

The results of these two leaching experiments are in good general agreement with a recent theoretical analysis of the leaching problem (Gardner and Brooks, 1957); hence, the data should find useful application in other areas.

B. Leaching to Remove Boron

Boron salts are found in toxic concentrations in many arid soils of the world, including the Coachella Valley, California (Kelley and Brown, 1928; Reeve *et al.*, 1955). Where the boron content is only slightly above crop tolerance, it and the accompanying soluble salts may be removed by leaching with about 4 feet of water, the usual reclamation procedure in this valley. However, in a leaching experiment (Reeve *et al.*, 1955) where the soil contained 54 p.p.m. of boron in the saturation extract, at least 3 times as much water was required to reduce the boron to a safe

TABLE VII
Rate of Leaching of Soluble Salts and Boron[a]

Leaching treatment	In saturation extract $EC_e \times 10^3$	Boron (p.p.m.)
None (initial)	64.0	54.0
4 feet of water	4.2	6.9
8 feet of water	3.4	2.4
12 feet of water	3.3	1.8

[a] After U. S. Salinity Laboratory Staff (1954).

level (1.8 p.p.m.) for moderately boron-tolerant crops as was required to remove the soluble salts. These data, shown in Table VII, are in agreement with the results expressed in the boron-leaching curve in Fig. 3.

C. Reclamation Procedures

1. *Flushing*

Rapid flushing of water over the soil surface is practiced in some parts of the world to remove surface accumulations of salt, often referred to as salt crusts. Reeve *et al.* (1955) conducted experiments to determine the reclaiming value of a series of surface flushings with Colorado River water on a highly saline (EC_e = 75 mmho./cm.), silty-clay loam soil in the Coachella Valley. Since the quantity of salt removed was equal to only 1 per cent of the salt present in the surface 2 feet of soil, it was concluded that surface flushing appears to have no essential reclamation value for soils that have sufficient permeability to permit leaching in the usual manner.

2. *Basin Method*

This method, which resembles the border method of irrigation, is extensively used for leaching highly saline land of low permeability. However, it requires heavy machinery for construction of the large borders needed for safely ponding water for long periods of time. Some irrigation districts require official inspection of the borders for proper construction before water is allocated for leaching purposes. This practice resulted from past experience with improperly constructed borders, which resulted in washouts and severe damage to District drainage facilities and often to farmers' crops in adjacent fields.

If the land is properly leveled, parallel borders may be used; otherwise, contour borders are required. Ponded waters on highly saline soils of very low permeability, especially in regions of high aridity and high temperatures, may increase two- or threefold in salinity on prolonged standing in the basins for up to 90 days or longer in some cases. For that reason, a certain amount of the impounded waters may be allowed to waste away at the lower end of the basins to maintain a favorable salt balance in the leaching water. When prolonged leaching is required, it is common practice to dry the basins after 90 to 120 days of ponding and test samples of the leached soil for completeness of salt removal, as a basis for determining the need for additional leaching.

The basin method of leaching has at least two disadvantages. The construction of large borders, often 3 feet high and from 6 to 8 feet wide at the base, requires large costly machinery and much labor. A serious difficulty sometimes results from the accumulation of large quantities of salts within the borders. When the borders are broken down in the finish-leveling process, this salt is scattered over the reclaimed surface, which often results in spotted stands of the initial crop. Moreover, the soil below the borders is not always effectively leached of salts and this may cause a series of sterile strips in the first few crops grown following reclamation. Because of the high cost of border construction, leaching operations seldom are interrupted to change the position of the borders to prevent the occurrence of sterile strips. Obviously, only the more salt-tolerant crops (Table IV) should be grown on land difficult to reclaim.

3. *Furrow-Basin Method*

This method combines the furrow and the basin, or border, methods used for irrigation. It has been used effectively in the Coachella Valley, California, where the soils on the nearly level valley floor vary in texture from loamy sand to loam, and are stratified with discontinuous clay lens in the subsoil, which retard downward movement of water. As for the basin method, the land should be properly leveled (level in one direction with not more than 0.1 per cent slope in the other direction) and provided with adequate underdrainage.

The land is first plowed 18 inches deep to turn under any salt crust present, then it is smoothed with an appropriate implement and furrowed in the level direction. Small narrow borders, approximately twice the height of the furrow ridges, are constructed downslope about 40 feet apart. The borders are alternately cross-diked at about every sixth furrow so that the water applied at the high end of the field meanders slowly back and forth between the main borders as it moves slowly downslope. The water should at no time submerge the ridges of the furrows, and movement should be slow, up to one week being required for the water to reach the far end of a 40-acre block. After a 4-foot depth of water has been applied in this manner, with no runoff, the basins are allowed to dry. After drying, the field is harrowed to level the borders and ridges, smoothed, and plowed again 18 inches deep. This second plowing turns under any salt that accumulated in the ridges and borders from the first leaching. After a smoothing operation, the furrows and borders are again reestablished, as before, but with the borders in offset position. The land is again leached with from 2 to 4 feet of water, as may be required, to effectively remove salts from the root zone into the drains below.

The unique feature of the furrow-basin method of improving land difficult to reclaim is that it provides more effective reclamation, at lower costs and in much less time, than does the standard basin method of leaching using large permanent borders. Moreover, no sterile strips occur due to incomplete leaching under the borders. The small borders can be constructed with a small farm tractor, normally found on most farms.

The furrow-basin method of leaching appears to be highly successful in the Coachella Valley where the soils are coarse to medium textured, but it is doubtful that this method would be equally successful on the deep, fine-textured and less permeable soils of the Imperial Valley.

4. *Trenching*

A trenching procedure, shown in Fig. 4, is used successfully in the Coachella Valley for "spot" reclamation of small areas in otherwise reclaimed fields, which resist improvement after leaching with 4 feet of water in the usual manner. These unreclaimed areas are caused by the presence of clay lens in the subsoil, usually too deep to be broken up by chiseling or subsoiling. They are irregularly shaped and generally vary in size from less than 1 to more than 3 acres.

These resistant areas are trenched about 5 feet deep at 8-foot intervals and in a direction parallel to the tile drains. The tile are usually at about 7 feet below the surface. These 8-inch wide trenches are constructed with a chain-bucket trenching device attached to the rear of a small farm tractor. The trenches are allowed to remain open for several days, or long enough to facilitate drying and cracking of the walls, after which they are backfilled by subsoiling the affected area in a direction perpendicular to the trenches. The loose fill is settled by running water down the trench. After a drying period to permit drainage and settling of the fill, the trenched area is finish-leveled, diked, and heavily leached, as before. Where the clay lens is less than 5 feet below the surface, i.e., above the bottom of the trench, and the space between bottom of trench

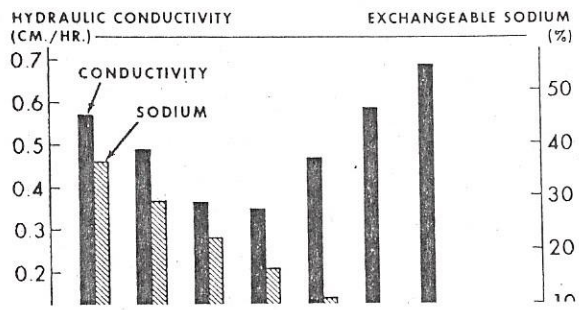
FIG. 4. Trenches for establishing drainage through impermeable clay lens in the subsoil overlying tile drains.

and tile is free draining, this method has proved very successful in completing the job of reclamation.

5. *Use of High-Salt Waters*

Sodic soils are difficult, often impossible, to reclaim because of their extremely low permeability. Complete reclamation depends upon the movement of water through the soil (1) to bring about the exchange of calcium for sodium on the exchange complex and (2) to remove the released sodium salts from the root zone.

Recent studies by Reeve and Bower (1960), including both laboratory and field experiments, have demonstrated that high-sodium soils can be



Available evidence indicates that satisfactory yields are obtained if the salinity at the bottom of the root zone does not exceed the salinity associated with a 50 percent yield-reduction (50 YR). Under these conditions the salinity in the upper root zone will not be greater than one-fourth to one-third that at the bottom of the root zone and, therefore, yields will be at least 90 percent of the maximum obtainable under otherwise comparable nonsaline conditions.

The LR for a particular crop may be obtained by substituting the appropriate 50 YR value for EC_{dw} in Eq. 3. The 50 YR values[1/] for most crops are approximately twice the EC_e values given in Table IV, which represent yield reductions of approximately 10 percent. For alfalfa, a 50-percent reduction in yield occurs when the salinity (EC_e) throughout the root zone is about 8 mmhos./cm. Substituting this value in Eq. 3, $LR = EC_{iw}/8 \times 100$. Thus, for irrigation waters. . .

1/ More accurate YR values for various crops may be obtained from a recent paper: Bernstein, L. 1964. U. S. Dept. Agr. Inform. Bul. 283.

water. If the dilutions are too wide, then loss of permeability may result and the reclamation operation ceases. This indicates that very careful technical control over this type of reclamation is essential for success.

Figure 5 shows the trend in permeability resulting from successive leachings with diluted seawater and also the sodium removal from the exchange complex by a series of dilutions. It should be noted that Colorado River water used alone did not increase the permeability of this highly sodic soil sufficiently to make reclamation possible.

VI. Management Practices for Salt-Affected Land

A. Leaching Requirement for Salinity Control

The relationship between the quantity of salt brought into an area (a farm or an irrigation project) with the irrigation water and the quantity of salt removed in the drainage water has been referred to by Scofield (1940) as the "salt balance" of the area. If a favorable salt balance occurs, the output of salt must equal or exceed the input. Studies of salt balance in large irrigated areas, initially begun by Scofield, have been extended by Wilcox (1963). Other contributions to the subject of "salt balance" and leaching requirement have been made by Hill (1961), Klintworth (1952), and Eaton (1954).

The fraction of the irrigation water that must be leached through the root zone to control salinity at any specified level has been defined by the U. S. Salinity Laboratory Staff (1954) as the leaching requirement, which may be calculated by Eq. (3).

$$LR = \frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}} \tag{3}$$

The LR is expressed in the second part of this formula as the ratio of the conductivity of the applied irrigation water (EC_{iw}), to the conductivity of the drainage water (EC_{dw}) required to maintain salinity at a specified level (favorable salt balance) at the bottom of the root zone. It may be expressed as a fraction or as a percentage. This concept has greatest usefulness when applied to steady state water-flow rates. ~~Values for EC_{iw} represent the maximum salinity tolerated by the crop species grown. The leaching requirement for any particular crop may be illustrated by use of the salt tolerance data in Table IV. For cotton, where a value of EC_{dw} = 8 mmho./cm. can be tolerated, LR = EC_{iw}/8. Thus, for~~ irrigation waters with conductivities of 1, 2, and 3 mmho./cm., respectively, the leaching requirement will be 12, 25, and 38 per cent. These are maximal values, since removal of salt by rainfall, by the crop, and by precipitation of salts such as calcium carbonate or gypsum in the soil, are seldom zero. If properly taken into account, these factors would tend to reduce the predicted value of the leaching requirement.

Kelley *et al.* (1949) stated that as the precipitation decreases below 15 inches, increasing amounts of irrigation water must be applied to provide adequate leaching. In many arid regions, the rainfall effective from the standpoint of leaching (total rainfall — runoff and evaporation) is generally less than 10 inches, and often less than 5 inches. This amount of rainfall is insufficient to appreciably affect the leaching requirement (Eaton, 1954). Failure of the LR formula to consider removal of salts by rainfall, by the crop, or by chemical precipitation, provides a justifiable margin of safety, which is necessary to ensure a productive irrigation agriculture.

If possible, LR values of more than 25 per cent should be avoided because they are wasteful of water, giving rise to low irrigation efficiency and increasing the drainage requirement. Low subsoil permeability may, and often does, determine whether high LR values for salt-sensitive crops can be met. Other factors that may be decisive in this matter are the cost of water and its availability for irrigation. The alternative to high LR requirements is to grow salt-tolerant crops that have lower leaching requirements, and thus conserve irrigation water.

B. Drainage Requirements for Salinity Control

Drainage problems often arise in irrigated areas due to low efficiencies in the conveyance and application of irrigation water, or they may arise from subsurface flows out of overirrigated higher areas (Israelson and Hansen, 1962). Many saline and sodic soils have developed as the result of restricted drainage due to low permeability of the subsoil, or as the result of a high water table in an otherwise permeable subsoil (Thorne and Peterson, 1954; Kelley, 1951; Magistad and Christianson, 1944; Fireman *et al.*, 1950; Fireman and Hayward, 1955; U. S. Salinity Laboratory Staff, 1954).

1. *Drainage Requirements*

In arid regions, drainage is primarily for salinity control. The requirements for drainage include both the adequacy of drainage and the quantity of water to be drained (Reeve, 1957; Edminister and Reeve, 1957).

The adequacy of drainage for irrigated land is primarily related to the control of the water table (at 5 feet or deeper) to maintain a favorable salt balance within the rooting zone of growing crops. If the water table is allowed to rise to within 3 or 4 feet of the soil surface, lands irrigated with saline water often go out of production because of rapid accumulation of salts in the root zone. The depth to the water table must be such that upward flow of saline ground water, by capillary movement into the root zone, is prevented or greatly reduced.

In irrigated land, both high salts and high fluctuating water-table conditions often occur together. Roots that extend and flourish during a period of receding water table may be badly damaged, or often are killed, if the water table rises and inundates the roots. Under saline conditions, the detrimental effects of a high water table are even more severe because of salts in the root zone and the resultant moisture stress to which the plant is subjected. A fluctuating, saline water table at some depth below the root zone is of little consequence except as it may affect the upward movements of salts into the vicinity of actively growing roots.

Pearson and Goss (1953) demonstrated the deleterious effect of both high salt and a high water table on grapefruit trees that were grown in lysimeters equipped for water-table adjustment (Allison and Reeve, 1955). At high salinity, a water table 2 feet below the soil surface caused distinct mottling of the leaves, followed by yellowing and progressive deterioration. High salt (EC_e = 9 to 11 mmho./cm.) caused bronzing and burning of the leaves, followed by defoliation. However, the high-salt treatment combined with a high, fluctuating water table caused dieback as well as defoliation.

Where clay lens or hardpan formations have created perched water tables, often it becomes necessary to break up these impervious layers by subsoiling, deep plowing, or other means. Deep plowing has proved helpful in some, but not all, cases in the Imperial Valley of California, where the soils are fine textured, deep, and stratified, with sand lens. A trenching procedure for establishing drainage through clay lens that has proved successful in medium-textured soils of the Coachella Valley, is described in Section V, C, 4.

2. *Quantity of Water To Be Drained*

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. In this regard, the leaching-requirement equation (3) given in Section VI, A serves to establish a lower limit for drainage. However, the total quantity of water that actually must be drained will be increased by the inefficiencies in water conveyance and application, and by other sources of excess water, which tend to maintain a high water table.

The minimum depth of water required to be drained from the root zone, when expressed in terms of the consumptive use and the leaching requirement, is as follows:

$$D_{dw}\ (\text{min.}) = \frac{EC_{iw}}{EC_{dw} - EC_{iw}} D_{cw} \qquad (4)$$

This gives a lower limit for the quantity of water to be drained, D_{dw}(min.), which is expressed in terms of the salt content of the irrigation water, EC_{iw}, and other conditions determined by the crop and climate, namely, consumptive use, D_{cw}, and the salt tolerance of the crop. The salt tolerance of the crop (Table IV) is taken into account in the selection of permissible salinity values of drainage water, EC_{dw}.

Using this formula, the minimum drainage requirement for alfalfa grown in an arid region, such as the Imperial Valley of California for example, may be calculated. Colorado River irrigation water has an electrical conductivity of 1.1 mmho./cm. and alfalfa has a consumptive use requirement of about 56 inches, with a salt tolerance of 8 mmho./cm. (see Table IV). By substituting these values in Eq. (4), the minimum quantity of water to be moved beyond the bottom of the root zone (drainage requirement) is approximately 9 inches per year. Hence, the applied irrigation water should be 65 inches per year, of which 56 inches is for consumptive use and 9 inches is for drainage or leaching requirement.

C. Special Planting Procedures

Furrow-irrigated row crops often fail to produce satisfactory stands owing to the accumulation of salt in the seed row, which prevents germination. However, properly shaped planting beds minimize salt accumulation around the seed, as shown in Fig. 6 (Bernstein and Fireman, 1957).

In flat-topped beds, the salt initially present in the soil is transported in the wetting front and accumulates in a thin layer along the top of the bed and under the bed center where opposing wetting fronts meet. Salinities 5 to 10 times greater than the initial salinity of the soil are developed in the center of such beds, which precludes the possibility of a good stand for center plantings. However, good emergence is obtained for plantings along the edges of the bed where salinity is at a minimum. Rounded beds are much less suitable for double-row plantings than the flat-topped beds. For success, it is essential that uniform water infiltration occurs from alternate furrows into double-row beds; otherwise, salt moves near to one edge or the other, depending on the differential in infiltration rate, and prevents germination.

With sloping beds, the wetting front effectively sweeps salt along, leaving nonsaline soil at the planting position, despite initial salinities in excess of 25 mmho./cm. in the saturation extract. The sloping bed is, therefore, very effective in limiting salt damage to the seed, and in

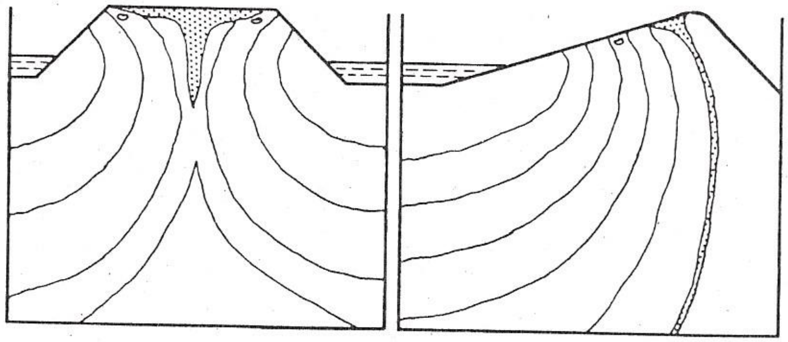


FIG. 6. Wetting and salt accumulation (stippled area) patterns for flat-topped and sloping seed beds. (Diagram modified after Bernstein and Fireman, 1957.)

obviating the need for a thorough leaching prior to planting on soils of limiting salinity.

D. Improving Irrigation Water Quality

The quality of certain waters that have a high alkalizing effect (high SAR) but are low in total salts (such as water No. 5 in Table II) can be improved by increasing the content of calcium. This may be accomplished by the use of a simple machine (Doneen, 1947) that drops powdered gypsum into running water in a standpipe or head ditch. Such machines are commercially available. Turbulence of the moving water keeps the gypsum in suspension until dissolved. This results in a high-calcium water (lowers the SAR, or sodium hazard). The use of such treated waters has improved the permeability of soils previously injured by irrigation with untreated, high-sodium waters. Machines for metering dry fertilizers and soil amendments into irrigation waters have been described (Fullmer, 1950).

Mixing of high-salt waters with low-salt waters is another means of improving water quality for irrigation. This is especially feasible in areas where pumping is practiced primarily for drainage. Occasionally, a pumped water may contain nitrate in excess of crop requirements for fertilization, with resulting injury to yields. Blending of such waters with low-nitrate waters is a corrective measure.

Research on desalting of ocean water is in progress by both government and private agencies. Several different processes (electrolysis, distillation, etc.) for desalinating waters are under study but, to date, no economically feasible method has been discovered.

E. Method and Frequency of Irrigation

The method of applying irrigation water and the quantity of water applied are important from the standpoint of salinity control. At very low salinity levels, furrow irrigation can be used effectively. With increasing salinity, however, the shape of the ridge or planting bed, and the position of the seed with respect to the water line in the furrow, require greater attention, as mentioned in Section VI, C. For still higher salinity conditions, irrigation is best accomplished by the border method of flooding, as for alfalfa. This method gives uniform areal application of water and affords the most effective method for minimizing salt accumulation in the root zone. In any case, the application of irrigation water in excess of consumptive-use requirement, and in accordance with plant tolerance, is essential if salinity is to be controlled at a satisfactory level for maximum crop production.

Sprinkler irrigation provides uniform application and penetration and, therefore, offers greater efficiency in water use and salinity control through elimination of much of the waste associated with surface methods of irrigation. Uniform application of sprinkler-applied water also prevents the surface accumulation of salts in raised planting beds, ridges, or borders. However, the wetting of foliage poses a serious problem for those plants that absorb sodium and chloride in harmful quantities, as mentioned in Section IV, A, 3. In this connection, some crops, such as stone fruits and citrus, are very sensitive to foliar-absorption injury, whereas others, such as strawberries and avocados, are resistant to injury by sprinkler irrigation.

The frequency of irrigation profoundly affects response of plants under saline conditions (Ayers *et al.*, 1943), primarily because it controls the osmotic pressure of the soil solution. The relation of osmotic pressure to the salt concentration of the soil solution and its effect on plant growth was mentioned under Section IV, A, 2. After an irrigation, the soil-moisture content is at a maximum and the salt concentration (OP) is at a minimum, favorable for growth. As the soil dries out because of evapotranspiration, the salt concentration (OP) increases progressively, the dryer the soil is allowed to become before reirrigation. Thus, infrequent irrigation aggravates salinity effects on growth. Conversely, more frequent irrigations, by keeping the soil at a higher moisture content, prevents high salt concentrations in the soil solution and tends to minimize the harmful effects of a given level of salinity. For most plants, therefore, saline soils should be irrigated when the moisture content is considerably above the permanent-wilting percentage.

VII. Conclusions

The permanence of irrigation agriculture has often been questioned, especially in view of historic failures in many parts of the world. The survival of irrigation in Egypt and China for over 4000 years, however, provides convincing evidence that irrigation, under proper conditions, can be permanent.

Based on lessons of the past, it is obvious that the development of a sound irrigated agriculture depends upon a catena, or chain of related factors, involving soils, waters, crops, and man. Failure of any one of these links can bring hardship, or even disaster to an irrigation enterprise. In the past, man was primarily responsible for many of the historic irrigation (civilization) failures.

Regarding soil conditions, relatively few sizable land areas of the world are known where, owing to physical limitations alone, irrigation cannot be practiced successfully. This presupposes that an adequate supply of reasonably good quality water is available for irrigation and that good management practices are followed. Such management practices may include the establishment of an effective drainage system for deep, fine-textured soils of low permeability.

Sufficient data are available to provide a sound basis for reclaiming highly saline, and also highly sodic, soils. Success in either case depends, of course, upon adequate subsoil drainage for removing salt from the root zone.

Irrigation waters vary greatly in quality with respect to salt content (concentration factor), sodium percentage (composition factor), and boron content (phytotoxic factor). Despite quality limitations in some cases, nearly all surface waters of the western United States and many ground waters of adequate supply are being used successfully for irrigation. The increase in salinity of some surface water supplies, owing to fuller utilization and reuse, is a matter of increasing concern to downstream irrigated areas, where ultimately changes in management with respect to leaching, drainage, and kind of crops grown may be required.

Most economic crops have been classified with regard to their response to salinity on the basis of measurements of the EC of a saturation extract of the soil. These data provide an excellent basis for determining the leaching requirement for maintaining a favorable salt balance in the root zone and maximal crop yields. The leaching requirement relates the capacity of a particular crop to tolerate salinity in the root zone to the salinity of the applied irrigation water and, thus, serves to determine irrigation practice.

Within the past few decades, research and education have provided a better understanding of the physical and chemical problems involved in irrigation agriculture in the United States and other developed countries. This knowledge is being extended to newly developed countries throughout the world and should contribute significantly in meeting the need for food and fiber for expanding populations.

Based on our present scientific knowledge of soil and water problems and management practices, there appears to be no valid reason why irrigation agriculture, once established, should not remain permanently successful.

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