

Irrigation Water and Saline and Alkali Soils

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If irrigation water is of good quality, the soils to which it is applied may be improved because of the calcium in the water and the beneficial effect derived from leaching or washing any excess salts from the soils. But if the quality of water is unsatisfactory, the soil may deteriorate until it will no longer produce satisfactory crops.

Four major characteristics determine quality of water for irrigation:

The total concentration of soluble salts; the concentration of sodium and the proportion of sodium to calcium plus magnesium; the concentration of bicarbonate; and the occurrence of the minor elements, such as boron, in amounts that are toxic.

The total concentration of soluble salts is an essential consideration in waters that are used for irrigation. The salt content of most irrigation waters ranges from 0.1 to 5 tons of salt to the acre-foot of water (approximately 70 to 3,500 parts per million). The amount of soluble salts in river waters in the Western States varies greatly—70 p. p. m. in the Columbia River at Wenatchee; 1,574 p. p. m. in the Sevier River near Delta, Utah; and 2,380 p. p. m. in the Pecos River at Carlsbad, N. Mex. The Colorado River, an important source of irrigation water in the Southwestern States, contains about 1 ton of soluble salts to an acre-foot of water (740 p. p. m.).

The salt content of a river may change downstream because of return flow from drainage and because of the solution of minerals as water moves along the river bed. The soluble salts in the Rio Grande, for example, increase from about 180 p. p. m. at Otowi Bridge, N. Mex., to 780 p. p. m. at El Paso, Texas, and 1,770 p. p. m. at Fort Quitman, Tex. The concentra-

tion of salt in the lower Rio Grande, however, drops because of the lower concentration of salts in some of the tributaries, so that at Rio Grande City, Tex., more than 900 miles down the river from Fort Quitman, the amount of soluble salts is only about 525 p. p. m.

The range in salt concentration in ground waters pumped from wells may be much greater than that of surface waters. Ground water from wells near each other may be different in salt concentration and composition.

Even the variations in water from different depths at a single location may be large. Analyses of many wells in the Coachella Valley, Calif., indicated a range in soluble salts from 130 p. p. m. to approximately 8,500 p. p. m. Two wells, 565 and 180 feet deep, within a half-mile of each other had salt concentrations of approximately 400 and 8,500 p. p. m., respectively.

The evaporation of moisture from the soil surface does not remove salt from the soil, and relatively little is absorbed by plant roots. Consequently the use of saline irrigation water results in the accumulation of soluble salts in the soil unless it is prevented by leaching and drainage. One can use irrigation water with a moderate degree of salinity, however, if drainage is adequate and enough irrigation water is applied so that some of it goes through the soil profile and out into the drainageways. In that event, the concentration of soluble salts in the water will restrict the crops that can be grown to those with moderate salt tolerance. If saline waters are used so sparingly that there is no excess for drainage, however, there will be an increase in the salinity of the soil.

Because of the potential salinity problem when saline irrigation waters are used, leaching and drainage must be provided to remove dissolved salts that would otherwise accumulate in the root zone or in the subsoil immediately below.

Carl S. Scofield referred to the relationship between the quantity of dis-

solved salts delivered to an area with irrigation water, and the quantity removed from the area by the drainage water as the salt balance of the area. If a favorable salt balance is to be attained, the output of salts must be approximately equal to the input. When the salt balance is adverse, the input of salts exceeds the output. This condition must be avoided in a permanent irrigated agriculture.

THE SALINIZATION of soil affects the growth of crop plants in two ways.

The first is a reduction in the amount of water absorbed by the roots. That occurs because continued irrigation with saline water in the absence of a favorable salt balance results in a gradual but progressive increase in the osmotic pressure of the soil solution. Osmotic pressure is a measure of the soluble salts in solution and provides a method of expressing the concentration of the soil solution on an energy basis. Retardation of growth is virtually linear with increases in the osmotic pressure of the soil solution, and is largely independent of the kind of salts present. In extreme cases, a soil may become so saline that it will not even support the growth of halophytes (salt-tolerant plants), just as soils may become too dry to support the growth of xerophytes (plants adapted to growth under dry conditions).

The effect of a given amount of soluble salts in the soil solution is intensified as the soil moisture content declines between irrigations—as indicated by the increase in the osmotic pressure of the soil solution that accompanies drying out. Furthermore, as a soil gradually dries following an irrigation, the surface attraction of the soil for water, known as soil-moisture tension, increases. Soil-moisture stress is defined as the osmotic pressure of the soil solution plus the soil-moisture tension.

Experiments by C. H. Wadleigh and others in 1946 and 1948 have shown that, if other factors are not limiting, the vegetative growth of crop plants is closely related to the average soil-

moisture stress. Also, it has been shown that the absorption of water from the soil by plant roots depends upon the soil-moisture stress. Thus, one of the main effects of soil salinity is to limit the water supply of the plant. This induces modifications in growth that are usually associated with a lack of water in the plant tissue.

Wide variations among irrigation waters may exist with respect to the kinds of salts present, as well as with the amount of salts in solution. Salts, when dissolved in water, dissociate or separate into chemically equivalent amounts of positively and negatively charged particles—ions. The positive ions are cations. The negative ions are anions.

The major ions in irrigation water are the cations calcium, magnesium, and sodium; and the anions bicarbonate, sulfate, and chloride. Other ions that may be present are potassium, carbonate, nitrate, silica, iron, and boron, but they are usually found in low concentrations. Occasionally waters may be high in bicarbonates and, less frequently, in nitrates. In waters of low total salt concentration, bicarbonates frequently exceed the combined sulfate and chloride content, but in rivers with higher salt content, such as the Arkansas, Colorado, Gila, Pecos, and Rio Grande, the predominant salts are sulfates or chlorides.

Sodium salts are usually present in irrigation waters, and if the proportion of sodium is high, it may be adsorbed on the soil particles and result in an unfavorable physical condition. Such soils, when they are wet, tend to run together and impede the movement of water and air. They form hard clods when dry. Irrigation waters with high sodium percentages therefore may require special management practices.

The use of waters that are low in total salts but high in bicarbonate aggravates the sodium problem. Water that is relatively low in total salts and has a sodium percentage ($\text{Na} \times 100 / \text{total cations}$) that is within safe limits may be questionable if the amount of

bicarbonate is considerably in excess of the calcium and magnesium present. This excess bicarbonate over calcium plus magnesium is referred to as residual sodium carbonate. The occurrence of residual sodium carbonate is fairly common in the Western States. Out of a group of approximately 450 well and stream supplies in the San Joaquin Valley, slightly more than half contained residual sodium carbonate. This condition also occurs in many other places—in the White River, South Dakota; the Sevier River, Utah; the Humboldt River, Nevada; and the Nile River in Egypt.

When an irrigation water containing residual sodium carbonate evaporates in the soil, calcium and magnesium carbonates precipitate, and the sodium percentage of the soil solution increases. Then sodium replaces calcium on the soil particles, the exchangeable-sodium percentage of the soil increases, and the physical condition of the soil, especially the permeability, may be impaired. In addition, the pH may increase and organic matter may be dissolved, giving the dark color typical of a so-called black alkali soil.

Some salts or ions that are harmless in low concentrations may accumulate in the soil solution in sufficient amounts to cause toxic reactions in plants. The ions most likely to cause such reactions are sodium, chloride, bicarbonate, and sulfate. Less frequently, crops grown in soils having excessive amounts of calcium and magnesium may show toxic symptoms. Selenium, lithium, and fluoride are found in a few waters and soils, and may be accumulated in plant tissues. Ordinarily selenium and fluoride do not affect plant growth but may have serious effects on animal life. A fraction of a part per million of lithium in irrigation water produces tip and marginal burning and defoliation of citrus leaves.

Besides the indirect effects of sodium on plant growth resulting from adverse modifications of the physical properties of the soil, there is some evidence of its specific toxicity. If the sodium

content of the soil is high, almonds may develop tipburn and avocados a leaf scorch. Leaf burn in salt-sensitive cotton varieties has been correlated with high sodium content in the leaves. Other common cations affect specific crops. An example is guayule, a rubber-producing shrub native to North America, which grows poorly in the presence of only moderate amounts of soluble magnesium.

The accumulation of the chloride ion in plant tissues frequently results in toxic symptoms. Among the crop plants that are sensitive to the chloride ion are peaches and other stone fruits, pecans, some citrus varieties, avocados, and some grapes. Many species are no more sensitive to chloride than to equal concentrations of sulfate salts. Specific sensitivity to high concentrations of the sulfate ion have been reported for tomato, flax, cotton, and orchardgrass.

The bicarbonate ion is toxic because its accumulation in the soil solution affects mineral nutrition and tends to reduce the availability of iron in many plants. Apple orchards in Washington become chlorotic when irrigated with water high in bicarbonates. Continued use of such a water may seriously affect the mineral nutrition of the tree. Specific toxicity of the bicarbonate ion has also been demonstrated with Dallis grass. A reduction in the growth of beans accompanied by chlorosis becomes more pronounced with increasing concentrations of bicarbonate. On the other hand, garden beets are much more tolerant to bicarbonate.

Boron is a minor constituent of practically all natural waters. Irrigation waters should be analyzed for it if one suspects its presence at toxic levels. Boron is essential to the growth of plants, but it may be toxic at concentrations only slightly in excess of those needed for optimum growth.

Toxicity may develop with boron-sensitive crops when the concentration is as low as one part per million (1 p. p. m.). Water containing 1 p. p. m. or less of boron may be regarded as

excellent. For most crops, however, water that contains 1 to 2 p. p. m. is satisfactory. Water up to 3 p. p. m. may be used with the more boron-tolerant crops. Water containing more than 3 p. p. m. is doubtful or definitely unsuitable for irrigation purposes. Boron is responsible for symptoms of toxicity that have appeared on citrus and walnut trees in southern California and on those and other crops elsewhere.

Irrigation waters are classified on the basis of the more important constituents in solution so that the effect of the water on crops and on soils can be anticipated with some assurance. Such classifications assume that the water will be used under average conditions with respect to climate, amount of water used, drainage, texture and permeability, and salt tolerance of the crop. Under unusual circumstances it may be possible to use a water that under average conditions would be considered unsafe. Conversely, under some conditions, it may not be safe to use a "good" water.

The United States Salinity Laboratory has proposed a scheme for classifying irrigation waters on the basis of two main factors. Waters are divided into four classes with respect to salt concentration, the salinity hazard, and into four other classes with respect to the probable extent to which soil will absorb sodium from the water and the length of time required to adversely affect the soil (the sodium hazard). The characteristics of irrigation water based on these two criteria are determined by chemical measurements and are assigned values that indicate the overall water quality.

A PROBLEM of great economic importance to the farmer arises when salinity or alkali conditions develop in good farmlands. This can occur as a result of natural causes, such as salty ground water and poor drainage, or from manmade causes, such as the application of irrigation water of poor quality, improper soil management,

and lack of drainage facilities, or from some combination of these factors.

Saline and alkali soils contain excessive concentrations of either soluble salts or adsorbed sodium (alkali) or both. The original sources of these salt constituents are the primary minerals found in soils and in the exposed rocks of the earth's crust. As a result of chemical decomposition and physical weathering, the soluble constituents are gradually released from the minerals. These soluble salts in humid areas are carried downward by rain into the ground water and ultimately are transported by streams to the oceans. Leaching usually is local in nature in arid regions, and the soluble salts may not be transported far. This is so because there is less rainfall to leach the soluble salts out of the soil and transport them away and because the high evaporation rates characteristic of arid climates tend to concentrate the salts in ground waters and in soils.

Inadequate drainage is associated with and contributes to the severity of saline and alkali soil conditions. Because of the low rainfall in arid regions, surface drainageways may be poorly developed, and consequently drainage basins may have no outlet to permanent streams. The salt-bearing waters drain from the surrounding high lands of the basin to the lower lands, and may temporarily flood the soil surface or form permanent salty lakes.

Saline and alkali soil problems most often develop as a result of the irrigation of level valley lands, which may be nonsaline and well drained under natural conditions but may have drainage facilities inadequate to take care of the additional ground water resulting from irrigation practices. In that event, the ground-water level may be raised from a considerable depth to within a few feet of the soil surface in a relatively short time. When that occurs, the water moves upward to the soil surface as a result of evaporation and plant use. This increases the salt content of the surface soils and of the

soil water in the root zone, forming problem soils varying from a few acres to hundreds of square miles in area.

Soil deterioration frequently results from the application of either good or poor irrigation water to soils with impaired drainage, since in this case the accumulation of soluble salts cannot be prevented. Saline and alkali problems also arise if drainage facilities are adequate but insufficient irrigation water is applied to provide for the necessary leaching of excess salts.

A SALINE SOIL contains enough soluble salts so distributed in the soil that they interfere with the growth of most crop plants. Ordinarily the soil is only slightly alkaline in reaction (pH 7.0 to 8.5) and contains very little adsorbed sodium. Saline soils are often recognized by the presence of white salt crusts; by damp, oily-looking surfaces devoid of vegetation; by stunted growth of crop plants, with considerable variability in size and with a deep blue-green foliage; and sometimes by tipburn and firing of the margins of leaves. Chemical and electrical-conductivity measurements rather than observations, however, are commonly used for assessing soil salinity. The determination of salinity status in terms of plant response should take into account the moisture-holding capacity of the soil in addition to its salt content.

The water required for the growth processes of plants is absorbed by the roots from the soil solution. Many crop plants absorb and transpire or evaporate 500 pounds of water in a season for each pound of dry matter produced. The soil moisture in arid regions is replenished by irrigation with water containing appreciable amounts of soluble salts, or by upward movement of more or less saline ground waters. In either instance, soluble salts are added to the soil with each application of water. Also, the concentration is increased between each irrigation through loss of water by evaporation from the soil, as well as by plant transpiration. And, as we mentioned earlier, the total con-

centration of the soluble salts, rather than their chemical nature, is mainly responsible for the harmful effects of saline soils on crop growth.

Often it is not economically feasible to maintain a condition of low salinity in a soil. The reason may be the extreme salinity of the irrigation water, the cost of providing adequate drainage, or the inherently low permeability of the soil. Then the farmer has to learn to live with the salt.

He can adopt management practices that minimize the effects of salinity, and he can make a judicious selection of crops or crop varieties that will produce satisfactory yields under moderately saline conditions. In selecting crops for saline soils, particular attention should be given to the salt tolerance of the crop during germination.

Poor crops frequently result from a failure to obtain a satisfactory stand. It is possible to modify planting practices to minimize the accumulation of salt around the seed and to improve the stand of crops under saline conditions. Recommended management practices and the salt tolerance of many species and varieties of crop plants are listed in the Department of Agriculture Handbook 60, *Diagnosis and Improvement of Saline and Alkali Soils*.

The chemical characteristics of saline soils are determined chiefly by the kinds and amounts of salts present.

Soil particles, as a consequence of electrical charges on their surfaces, adsorb and retain cations such as sodium, calcium, and magnesium. The adsorbed ions are combined with the soil particle, but they can interchange freely with other ions in the soil solution. This reaction is called cation exchange. The proportion of the various cations on the exchange complex is related to their concentration in the soil solution. Calcium and magnesium are less easily exchangeable than sodium. Since sodium salts seldom make up more than half of the soluble constituents of saline soils, very little sodium is adsorbed by the clay particles. Therefore the adsorbed ions in

saline soils are principally calcium and magnesium. Such clays are stable in water, are easily worked into granules and crumbs, and help produce a desirable environment for seed germination and plant growth.

Because of the presence of excess salts and the absence of significant amounts of adsorbed sodium, saline soils generally are flocculated; and, as a consequence, their permeability is equal to or higher than that of similar nonsaline soils. Consequently, if adequate drainage is provided, the excess soluble salts may be removed by leaching with ordinary irrigation.

AN ALKALI (or sodium) soil contains sufficient adsorbed (exchangeable) sodium to interfere with the growth of most crop plants. The soil may be highly alkaline in reaction but does not contain excessive amounts of soluble salts. These soils correspond to "black alkali" soils and frequently occur in small irregular areas called "slick spots." Sodium usually becomes the dominant cation in alkali soils either through the accumulation of sodium salts or as a result of the precipitation of calcium and magnesium salts.

As the proportion of exchangeable sodium increases, soils tend to become dispersed and impermeable to water and air. Because the partially sodium saturated clay is highly dispersed, it may be transported downward through the soil and accumulate at lower levels, where the soil may develop into a dense layer with a columnar structure, having a low permeability. It becomes increasingly difficult to replenish the water supply of the root zone by irrigation, and also more difficult to establish a condition of surface tilth favorable for seed germination and seedling growth.

Alkali soils may be improved or reclaimed by the replacement of the harmful exchangeable sodium by beneficial calcium and magnesium. That is generally accomplished by the addition of chemical amendments, the

kind and the amount depending upon the soil characteristics, the desired rate of replacement, and economic considerations. Chemical tests are used to obtain estimates of the amounts of chemical amendments needed to reduce the exchangeable sodium to a given level. Sodium is relatively easy to replace, so the amount of calcium that must be added to insure replacement is only slightly in excess of the sodium present. The sodium released must be removed by leaching with water to insure completion of the reaction.

The choice of an 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. Because of 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 and relatively expensive amendments. Lime-sulfur, sulfur, sulfur-containing gases, and other acids are useful but generally are too expensive. These acids and acid-forming amendments should be used only on calcareous soils because they react with limestone (calcium carbonate) to release soluble calcium, which replaces the adsorbed sodium. Because of its comparatively low cost, gypsum is the most common amendment used for reclamation. The rate of reaction of gypsum is limited only by its relatively low solubility in water.

Except in places where sulfur is used, alkali soils should be leached immediately following the application of the amendments. Leaching dissolves and carries the amendment downward and removes the soluble sodium replaced by calcium-bearing amendments.

The reclamation of alkali soils involves more than replacement of the

adsorbed sodium, however. A good physical condition must be restored. That involves the rearrangement and aggregation of soil particles to form soil granules which produce good tilth. Good soil structure is promoted by alternate wetting and drying, and freezing and thawing, and by the action of plant roots and organic matter.

A SALINE-ALKALI SOIL contains excessive quantities of both soluble salts and adsorbed sodium so distributed that the growth of most crop plants is reduced. The soil is seldom highly alkaline (pH above 8.5) in reaction. The soils form as a result of the combined processes of salinization and the adsorption of sodium. As long as excess salts are present, the appearance and properties of these soils usually are similar to those of saline soils. If the excess soluble salts are leached out, the soil properties may change markedly and become similar to those of alkali soils. They become strongly alkaline, the particles disperse, and the soil becomes unfavorable for the entry and movement of water and gases and for tillage.

The management of saline-alkali soils is then similar to that of alkali soils. That is, the soluble salts and exchangeable sodium must be removed by the addition of amendments followed by leaching. In theory, it is economical to leach out most of the soluble salts before the application of amendments. That is not recommended, however, because the permeability of saline-alkali soils declines markedly upon leaching and the rate of reclamation is retarded. Saline-alkali soils often contain gypsum. When such soils are leached, the gypsum dissolves and the replacement of exchangeable sodium by calcium takes place concurrently with the removal of the excess salts.

THE HISTORY of irrigation development in this country and elsewhere shows that, while some failures may be assigned to unfavorable economic or

social conditions, and a few to lack of adequate engineering, most failures have been due to unfavorable conditions of water, soil, and drainage.



Many people have learned through experience that the productivity of some irrigated land may be relatively short-lived. On the other hand, many irrigated areas are very successful and continue to be highly productive for a long time. It seems clear that long-continued irrigation farming can be practicable where conditions are favorable. Furthermore, if the causes of failure are ascertained and clearly understood, methods of avoiding failure may be devised and used.

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