A PART OF THE TEXAS A&M COLLEGE SYSTEM

Miscellaneous Publication 111 June 1954

LIBRARY
A. & M. COLLEGE OF TEXAS

• Formulas for Estimating Leaching • and Gypsum Requirements of • Irrigation Waters

in cooperation with the
UNITED STATES DEPARTMENT OF AGRICULTURE

TEXAS AGRICULTURAL EXPERIMENT STATION
R. D. LEWIS, DIRECTOR, COLLEGE STATION, TEXAS

630.72
T35m
#111

SUMMARY

Formulas are presented and discussed for characterizing and interpreting analyses of irrigation waters in the following terms: 1. The percentage of applied irrigation water which should pass through the root zone as drainage to insure reasonable yields (70 to 80 percent of yields on non-saline land) of rotation crops of intermediate salt tolerance in a semi-arid climate. 2. The amount of calcium which should be added to irrigation waters to insure that the sodium percentage of the soil water leaving the root zone will not contain more than about 70 percent of sodium. The latter derivation, by formulas, takes account of: a, calcium required to adjust the sodium percent of the initial water to 70 (a plus or minus value); b, calcium required to offset the precipitation of calcium as calcium and magnesium carbonate; and, c, calcium required to replace calcium and magnesium removed from soil by plants that are taken from the land. The sum of a, b and c represents total calcium requirement; total required calcium is expressed in terms of pounds of gypsum per acre-foot of irrigation water.

The possible need of substituting magnesium for a part of the total calcium in irrigation waters especially low in magnesium is discussed.

Application of the formulas to a series of irrigation waters with varied characteristics indicates that the calcium and magnesium supplied by irrigation waters falls short of requirements in a large proportion of the waters examined.

No material advantage is gained by taking rainfall into account in estimating the leaching requirements of irrigation waters. Rainfall serves in effect to dilute irrigation waters and, therefore, to reduce the required percentage of the total water which should be passed through the root zone, but the acre inches of required leaching per acre foot of applied irrigation water remains essentially unchanged.

The development of the formulas is based on an extensive review and discussion of the salinity literature as it deals with irrigation agriculture.

CONTENTS

Page

Summary 2

Introduction 3

Formulas 4

Derivation of Leaching Percentage 4
  Mean Soil-solution Concentration (Mss) and the Salts of Irrigation Waters 4
  Relative Tolerances and Mean Soil-solution Concentrations 7

Evaluation of Calcium Requirements 10
  Calcium for Adjusting Irrigation Waters to 70 Percent Sodium 11
  Calcium to Offset Bicarbonate Precipitation 11
  Calcium to Offset that Removed from the Land by Plants 12
  Summation of Calcium Requirements 14

Final Calculation of Leaching 14
  Soil Sampling to Determine Existing Leaching Rates 14

Example Waters 14

References 17

Formulas for Estimating Leaching and Gypsum Requirements of Irrigation Waters

FRANK M. EATON*

INTRODUCTION

WHETHER DERIVED FROM STREAMS, WELLS OR SPRINGS, all irrigation waters carry salt in solution. The amounts and kinds present vary between sources and, to a lesser degree, from time to time. Although chemical analyses set forth the concentrations of the various salt constituents of irrigation waters, the problem of interpreting these analyses in terms of crop production and most effective water use remains peculiarly difficult. Often a water analysis represents something rather imponderable not only to water engineers and farmers but also to people engaged in various lines of agricultural research and extension. In this paper formulas are presented for calculating, and for designating as water quality interpretations, the percentage of leaching that should prevail and the amount of calcium (as gypsum) which should be added to insure reasonable yields and prevent deterioration in soil permeability.

As a consequence of evaporation, transpiration and variations in the percentage of water passed beyond the rootzone as drainage, a soil solution may be a few or many times as concentrated as its irrigation water. Plants usually take up only a small part of the total salt added to the soil by irrigation waters; if only the seed or fruit is harvested, much of this accumulated salt is returned to the soil in the vegetative parts. In the process of evaporation, water is lost from the soil but the salt remains. If an irrigation agriculture is to remain productive, the accumulating salt residues of irrigation waters must recurrently be carried beyond the rootzone by leaching. The leaching process should be rapid enough to be compatible with good yields. On the other hand, if excessive quantities of water are passed through the rootzone, water is wasted, soluble plant nutrients are carried away and serious land drainage problems may result. The proportion of the irrigation water leached through the rootzone accordingly must be greater as the salinity of the water increases. For these reasons the salinity of irrigation waters should be interpreted, among other things, in terms of leaching requirements.

The difficulties of decision and practice in water use are enhanced by the fact that a substantial difference exists in the tolerances of crop plants to the various salt constituents of irrigation waters. A further complication is that some soils are poorly permeable to water movement and remain so, irrespective of the quality of the irrigation water. Also, the ionic proportions of some waters impair soil permeability, making it necessary to add amendments to the water for its most successful use. The compositions of some waters induce unfavorable soil alkalinity. The concentrations of sodium and bicarbonate relative to calcium and magnesium (21) are especially significant with respect to soil permeability and alkalinity. The amount of calcium needed to offset the foregoing effects requires estimation which also must include the excess of calcium and magnesium over sodium that is taken from the soil by plants.

Generalized formulas designed to characterize the leaching and calcium requirements of irrigation waters are presented first. The derivation and background for the formulas, with the necessary assumptions and generalizations, are then discussed and, where possible, means are outlined for altering the formulas to more nearly fit particular crops and conditions. In the discussion, consideration is given to the downward movement of the soil solution and its increasing concentration as it passes through the rootzone, to a derivation of the mean effective concentration of the soil solution, to the toxicity of various salt constituents to various crops and to calcium requirements: (1) to adjust the sodium percentage of the water to 70, (2) to offset bicarbonate precipitation and (3) to supply the calcium needs of plants. The sulfate added to waters as calcium sulfate to supply calcium is as toxic as the initial sulfate in the water; this sulfate, therefore, must be added in calculating the final required percentage of leaching.

Others have presented formulas for relating drainage to the salinity of irrigation waters. Scofield (49) prepared what he designated a "service equivalence" formula which assumed that the solution taken up by plants was half as concentrated as the irrigation water. The 1953 edition of "Diagnosis and Improvement of Saline and Alkali Soils" (50) contains mathematical

---

*Principal plant physiologist, U. S. Department of Agriculture, in cooperation with the Texas Agricultural Experiment Station. This manuscript was prepared in part while the writer was serving as salinity consultant with the Food and Agricultural Organization of the United Nations.

expressions for inter-relating the concentrations of irrigation and drainage waters and soil extracts. In both of these treatises, electrical conductance is the measure of salinity. Klintworth (33) presented tables designating required acre inches of application and seepage for waters of serial total salinity in Pretoria, South Africa. An earlier form of the leaching formula of this paper has been applied by Christensen and Lyerly (13) to well waters of the Trans-Pecos area of Texas.

Tables and charts have been presented in the literature at various times (18, 48, 50, 55) for classifying irrigation waters on the basis of salinity and sodium percentages. These classifications do not indicate leaching requirements nor do they take account of the marked changes that occur in composition as irrigation waters enter the soil to become more concentrated and to lose calcium and magnesium by carbonate precipitation.

Ratings of the quality of irrigation waters in terms of leaching and gypsum needs provide water users with knowledge of the limitations and requirements for the successful use of a water. The ratings also provide an index to the relative merits of different water supplies. The cost of the extra water, the greater loss of nitrate with the extra leaching and the possible need for tile drains to prevent water-logging the land are associated with substantial or high leaching percentages. These considerations, added to the costs of the water and gypsum, enable the water user to appraise the feasibility, if the project is a new one, of developing for irrigation both the water supply and the land on which it is to be used. However, statements of the extra water for leaching and of gypsum for the maintenance of soil permeability that are requisite for suitable yields do not inform the water user of the amount of water he may actually pass through the rootzone under any circumstances. Leaching rates can be determined only by measuring the salinity of the soil. Variations in soil permeability, in the amount of growth and in the water requirements of various crops, as well as in climatic factors that influence transpiration rates, are such that the situation could not be otherwise.

Most plants will withstand with about equal injury twice as much sulfate as they will of chloride when the concentrations of these ions are expressed in milligram equivalents per liter (meq/l). For this reason, use is made in the formulas of the expression: $Cl + \frac{1}{2}SO_4$, meq/l. This summarization of chloride and sulfate concentrations in equivalents, with sulfate given a half value, is the same as expressing the two ions in gram molecules, i.e., $Cl + SO_4$, mm/l.

Electrical conductances and osmotic pressures, like total inorganic solids in solution, provide measures of total salinity. But all of these physical measures have the characteristic in common in that they include carbonate and bicarbonate ions. These ions are in part precipitated from solution as the irrigation water enters the soil and becomes more concentrated in the presence of calcium and magnesium. It is for this reason that the leaching formulas, which are based on the concentration relation between the irrigation water and the soil solution, employ the sum of chloride and sulfate.

FORMULAS[1]

The designations used in the formulas are:

Sw—Salinity of irrigation waters expressed as meq/l of Cl plus $\frac{1}{2}SO_4$.

d% and D%—Tentative (d) and final (D) percentage of irrigation water entering soil passed through the rootzone.

Mss—Salinity of mean soil solution measured as Cl plus $\frac{1}{2}SO_4$, meq/l. The value 40 is taken as a Mss concentration that is expected to produce reasonable yields (70 to 80 percent) of crops of intermediate salt tolerance grown in a semi-arid climate such as Riverside, California.

Required leaching—tentative

$$\frac{Sw \times 100}{2 \times Mss - Sw} = d\% \quad \text{or} \quad \frac{Sw \times 100}{2 \times 40 - Sw} = d\%$$

Calcium requirements—Ca in meq/l

Ca *a*: To adjust water to 70 percent sodium:

$$Na \times .429 - (Ca + Mg) = Ca$$

retain plus or minus sign

Ca *b*: To offset HCO_3 precipitation:

$$\frac{HCO_3 \times (100 - d\%)}{100} = Ca$$

Ca *c*: To supply Ca plus Mg taken by plants in excess of Na:

$$\frac{0.30 \times (100 - d\%)}{100} = Ca$$

$$\text{Total Ca} = a + b + c$$

Multiply total Ca by 234 to get pounds of gypsum per acre foot of irrigation water

Required leaching—final

$$\frac{Sw + \frac{1}{2}\text{ total Ca}}{2 \times Mss - (Sw + \frac{1}{2}\text{ total Ca})} = D\%$$

DERIVATION OF LEACHING PERCENTAGE

Mean Soil-solution Concentration (Mss) and the Salts of Irrigation Waters

This section discusses the problem of deriving for purposes of leaching requirement an acceptable method of summarizing in single values the concentrations of salt found in the soil solutions of a soil profile. Not only are various salt constituents found in soil solutions but their concen-

---

[1] Examples of the computations followed in applying these formulas to irrigation waters are shown in Table 3.

trations vary substantially with the depth in the soil from which samples are drawn. The end result desired is a formula for estimating the percentage of a given irrigation water which must be passed through the rootzone so that selected mean concentrations of the soil solution will not be exceeded.

Universally, soil solutions are more concentrated than the irrigation waters from which they are derived; both surface evaporation and the water uptake by plants, in excess of their uptake of salts, contribute to this effect. Various studies (12, 22, 41, 46) indicate that well-drained soils show step-by-step increases in salt concentrations with depth but the gradient is usually reversed in soils with high water tables. Sandy soils that are flood irrigated may show similar concentrations in the upper feet because a great part of the soil solution is displaced from the rootzone with each irrigation.

The following tabulation (20) illustrates these and other points that will be useful in later discussions. The concentrations of bicarbonate, chloride and sulfate in milligram equivalents per liter (meq/l) are those found in displaced solutions from soil samples wetted to the moisture equivalent (m.eq.) before being packed in cylinders for displacement by the method of Burd and Martin (11).

Soil	Superstition sand				Holtville silty clay			
	m.eq.	HCO_3	$Cl+\frac{1}{2}SO_4$	Na%	m.eq.	HCO_3	$Cl+\frac{1}{2}SO_4$	Na%
Colo. R., av.	—	3.2	7.5	43	—	3.2	7.5	43
First ft.	11.4	5.4	13.3	42	22.7	4.1	54.3	45
Second ft.	3.4	3.9	13.5	42	18.1	4.3	91.9	51
Third ft.	4.6	3.3	11.8	44	25.9	2.0	146.5	55
Fourth ft.	5.4	2.1	12.9	44	45.7	1.5	126.7	54
Fifth ft.	3.8	2.3	15.1	46	45.3	.9	109.2	58
Sixth ft.	3.9	1.8	21.9	44	37.4	.8	70.0	60

The two series of displaced soil solutions are from 13-year old grapefruit groves irrigated with Colorado River water. The yield of the grove on Superstition sand was five times as great as the grove on the Holtville silty clay. The soil solution of the Superstition sand remaining from previous irrigations evidently had been displaced by the last irrigation throughout the upper 5 feet, but older soil solution is represented in the sixth foot. The soil solution in the upper 5 feet is about twice as concentrated ($CL + \frac{1}{2}SO_4$, meq/l) as the irrigation water, which indicates that the field capacity of this sandy soil was about double the moisture equivalent to which the samples were wetted for displacement.

The Holtville soil, contrasted with Superstition, is fine textured. The fourth foot of the Superstition sand had a moisture equivalent of 5.4, whereas the moisture equivalent of the fourth foot of the Holtville silty loam was 45.7. The concentration of salt in the soil solution of the third foot of the Holtville soil was 20 times as great as in the irrigation water. Lesser concentrations of salt found in the fourth, fifth and sixth feet of this soil indicate that for some time there had been little movement of water through the third or into the fourth foot, i.e., the residual salts of the irrigation water were only being carried down that far. There were few roots below this level. Had the owner of the Holtville soil known in advance what percent of the water he applied would have to be passed through this soil for reasonable yields and how impermeable his lower soil was, it seems probable that a lighter soil would have been selected for his grove.

On an ideal basis, the residual portions of the water from each of a succession of antecedent irrigations may be regarded as being stacked one above another through the depth of the rootzone. The upper soil zone is occupied by the water of the most recent irrigation and the zone is quite deep. Going downward, the successions of zones, corresponding to the succession of previous irrigations, become progressively narrower. Each irrigation, if ample, displaces the entire series of moisture residues further downward. Between irrigations, plant roots withdraw some of the water from each zone, lessening the volumes of their water and producing, thereby, corresponding increases in the concentrations of the salt. In practice the process of displacement does not quite follow this ideal pattern. The multiplicity of lighter and heavier-textured lenses of which soils are composed, and differences between nearby surfaces in rate of water intake, cause differences in the rates of water penetration. These factors together with inequalities in root distribution cause lateral as well as vertical differences in soil salinity. Nevertheless, the salinity of the water penetrating beyond the rootzone is greater than the water applied to the surface of the land. How much more saline is dependent, primarily, on the percentage of the water applied that is moved downward beyond the plant roots, i.e., on the percentage of leaching in relation to the water applied.

The tabulation shows that the concentrations of chloride and sulfate increased with depth but that there was a loss, rather than a gain, in the concentration of bicarbonate. There also was a gain in the percentage of sodium in the Holtville soil. These losses in bicarbonate and the gain in sodium percentage are due to the precipitation of bicarbonate as calcium and magnesium carbonates.

Several investigators (19, 28, 29, 34) have shown that when the roots of plants were divided between solutions of varied salt concentration, proportionately less water is withdrawn from the more saline solutions than from those of low salinity; but within limits some water always was taken from the most saline solutions. Presumably the uptake of salt and the growth of the plant are influenced by all of the solutions which bathe its roots but the relative effects of the unequal concentrations, versus uniform concentrations, on salt accumulation and on growth have not been estimated.

In another type of experiment (51), containers were packed with soil to which successively greater amounts of sodium chloride previously had been added. The moisture content of the containers was held at relatively high levels by frequent irrigation, but unavoidably each irrigation leached the added salt farther toward the bottoms of the containers. Notwithstanding this downward leaching, each increment in total salt resulted in a further sharp reduction in plant growth. The salt content of the plant tissues was not reported but successive reductions in growth make it evident that the accumulations in the plants must have been somewhat in proportion to the original additions, irrespective of the final position of the salt in the containers.

The foregoing evidence indicates that the entire soil profile occupied by roots must be taken into account in an equation that undertakes to characterize the salinity of irrigation waters in terms of the percentage of the water that must be leached through the rootzone for the maintenance of reasonable crop yields.

Before appraising mean soil solution relations, a somewhat simpler relation will be evaluated, i.e., the relation between the salinity of irrigation waters (Sw), the percentage of leaching (d%) and the salinity of the drainage effluent (Sd). Assuming no precipitation of salt and no salt uptake by plants, the equation for this relation can be written:

$$\text{formula a: } \frac{d\%}{Sw \times 100} = Sd$$

The next section considers the mean soil solution concentration (Mss) that can be expected to produce reasonable yields—70 to 80 percent of the yields on non-saline soils—of plants with intermediate salt tolerances. The equation for percentage of leaching required with various irrigation waters for the maintenance of a desired mean soil solution concentration can be written:

$$\text{formula b: } \frac{Sw \times 100}{2 \times Mss - Sw} = d\%$$

The derivation of the two formulas can be illustrated most clearly by examples. If under formula a one starts with a liter of water containing 5 milliequivalents of Cl and reduces the volume to 100 ml, this residue—corresponding to a drainage of 10 percent (d%)—will contain 50 meq/l of Cl (Sd). The mean concentration (Mss) of the chloride solution, formula b, i.e., before and after evaporation, is 5 plus 50 divided by 2, or 27.5 meq/l. If 27.5 is substituted for Mss in the formula, the value 10 is obtained for d%. If the d% obtained by formula b, is substituted in formula a, the concentration of the drainage effluent (Sd) for any selected Mss value is obtained.

Formula b, with appropriate values substituted for Mss and using the Sw of the irrigation water, is used to characterize irrigation waters in terms of their required leaching for the maintenance of reasonable yields.

It might seem necessary to consider rainfall; rainfall, in effect, serves as a diluent for the irrigation water. But actually a formula for summarizing the salts of irrigation waters in terms of their leaching requirements should characterize the irrigation water rather than conditions of its use. This is not to say that abundant rainfall does not promote leaching. The justification for omitting rainfall is apparent by the examples of the preceding paragraph. Suppose that during the process of reducing the volume of the water by evaporation, a few hundred milliliters of distilled water is added. This addition does not change the concentration of the final volume nor would it change the percentage of the original *irrigation* water which must be wasted from the rootzone; the addition only serves to lengthen the period of volume reduction. From the standpoint of salinity, rain water falling on the land requires no leaching. If, for example, 12-acre inches of an irrigation water containing 2 meq/l of Cl plus $\frac{1}{2}SO_4$ are applied to land, the formula for reasonable yields would show that there should be *0.57 inches of drainage* (4.76 percent). But if with the 12 acre-inches of irrigation there were 12 inches of rain, the rain would, in effect, reduce the salinity of the irrigation water from 2 meq/l down to 1 meq/l. For a 1 meq/l water, the required leaching by the formula is 2.44 percent; 2.44 percent of the total 24 inches of water shows a need for *0.59 inches of drainage.* In other words, the *acre-inches* of drainage needed *per acre foot of irrigation water* remains essentially unchanged, irrespective of the amount of rainfall. The required percentage of leaching in terms of irrigation water applied is thus not altered by rainfall.

If a uniform percentage of drainage is established and maintained in a piece of land, eventually as much chloride will be leached from the soil as is applied annually, irrespective of the leaching percentage. In other words, a salt balance (45) will be achieved. But the salinity of the soil solution and the productivity of the agriculture will be high or low depending on the leaching percentage. It seems to the writer that the salt balance concept can have useful meaning only when considered in this respect.

Assuming that the leaching of a body of land is reasonably uniform and that canal losses and other wastages are negligible, the leaching percentage that has existed can be determined approximately by formula a on the basis of the chloride concentrations in irrigation water and in drainage. Knowing d% and Sw, these values can be substituted in formula b to obtain Mss. Knowing Mss, the productivity of the agriculture can be estimated. Measurements of soil solution concentrations at the bottom of the rootzone provide more reliable information than measurements on drainage wastes. Due to canal seepage and surface wastes, drainage waters always are more dilute than soil solutions at the bottom of the rootzone.

Relative Tolerances and Mean Soil-solution Concentrations

Before undertaking to derive a value for mean soil solution concentration (Mss) with which reasonable yields of crops of intermediate salt tolerances can be expected, several examples are given of the complexities in the depressed growth of plants on saline soils. In this depression of growth two categories of factors are involved:

1. The water-uptake relations of plants are largely encompassed in the idea of a water-moving differential between the forces in the plant for water accumulation versus the forces of water retention in the soil. Both components of the net force determining the magnitude and direction of water movement are subject to wide, and in part independent, variation; particularly is this the case since each of the two opposed forces comprise a number of sub-components. Not all of the antecedents of the forces involved are purely physical.

2. The chemistry of salt toxicity to plants involves many interactions both as to the quantity and kind of ions presented to the roots and those accumulated in the plant. A suppression in the accumulation of desired ions often accompanies the extra uptake of ions that are toxic or, at least, of little nutritional importance. Environments influence salt accumulation and the effects upon growth of the accumulations. Of significance, also, are the pronounced contrasts between species in the concentrations of the various ions which they accumulate and their capacity to tolerate and continue the normal course of metabolic processes with the accumulations. With the extra ionic accumulations in the plant tissues, as a result of the extra salt in the soil, there may be an improvement or a loss or little change in the differential between the osmotic forces of water uptake in the plant versus the opposed osmotic water-retaining forces in the soil.

Through the physiological processes of adaptation to salt, as well as in the choice and natural selection of strains or species having characteristics which provide adaptation, there are many crop and native plants capable of making a creditable growth on relatively saline soils. From the standpoint of the derivation of the present formulas, there is sufficient similarity in the net yield reactions between many of the crop plants to the mixtures of salts in soils to permit classifying them in salt-tolerance groups. Recognition of major chemical and physical features involved in salt tolerance came many years ago.

More facts gradually have been supplied until examples now can be given of the various points in the outline although usually there is little actual understanding of the biological steps in the chain of events between cause and effect.

Kearney (31) in 1913 found no effect of excess soluble salts in soil on the ability of young wheat plants to reduce ultimately the water content of the soil to the wilting coefficient, unless the quantity of salt was sufficient to induce marked pathological symptoms in the plants. In his most saline soil at the moisture equivalent the soil solution had a salt concentration of 3.17 percent (approximately 2.3 atmospheres at planting), and, he notes, at the wilting coefficient it was nearly double this. At the wilting coefficient, the indicated osmotic pressure of the soil solution would have been close to 4.0 atms. This value added to a soil-moisture tension at the wilting of coefficient of 15 atms. would represent a total of 19 atms. against which the final moisture was taken by the wheat plants. Botanists who have made cryoscopic and plasmolytic measurements on plants growing in diverse environments have found the osmotic concentrations in plant cells always are higher than in the supporting substrate. Cryoscopic values as high as 100 atms. have been found in desert leaves, 40 atms. in the nodes of grasses and 25 atms. in cambium tissues. These pressures result both from accumulated ions and from the labile products of photosynthesis.

Van den Berg (6) found his salt-sensitive crops—horse beans, peas and kidney beans—accumulated more salt and showed less water stress in field plantings than the salt-tolerant crops—sugar beets, spring wheat and flax. Specific ionic effects also were noted: spring barley, horse beans, peas and kidney beans were deficient in potassium when grown on saline soils, whereas sugar beets, spring wheat and flax were deficient in calcium. The general proportions of cations were most markedly disturbed in peas and kidney beans.

The accumulation of potassium in bean leaves (24) was sharply depressed when the substrate was high in $CaCl_2$ but increased when high in Na_2SO_4. In the same study, NaCl increased calcium accumulation, whereas Na_2SO_4 depressed its accumulation.

Another experiment is of interest with respect to accumulation and growth (53). Beans, corn, alfalfa and cotton were planted in separate containers which were packed in layers with moist soil containing successively higher concentrations, with depth, of sodium chloride; the moisture content of the soil was high at the start of the experiment and water was not added during the growth of the plants. When the growth of the four crop plants stopped, the roots had penetrated downward further, and had reduced the moisture content of the soil further, in the order of the relative tolerances: beans<corn<alfalfa<cotton. At the end, the corn leaves were rolled

and the alfalfa leaves were wilted but beans and cotton stopped growing without wilting; yet the latter two plants wilt readily when soil moisture is limiting. By one interpretation of the foregoing, each of the four plants grew until the concentration of salt in their leaves, corresponding with the increasing concentrations in the soil solution as the soil dried, approached the respective concentrations compatible with their further growth. On the basis of a good many observations, plant growth becomes inappreciable at moisture levels higher than those at which transpiration becomes inappreciable.

Wadleigh and Ayers (51)—green weight of bean plants—and Wadleigh and Gauch (54)—elongation of cotton leaves—plotted growth at successive moisture and salinity levels against the "integrated soil moisture stress" (sum of osmotic pressure of the soil solution and the soil moisture tension) and obtained points that fitted well on parabolic curves. They concluded that their representation of the total moisture retaining power of the soil constituted one function of growth. They were concerned, however, over the fact that the relation was parabolic and pointed to other growth factors that were possibly involved, such as the accumulation of toxic substances in the plant and the finding of nitrate-N accumulations at the higher tensions in the bean plants. Consideration was not given to the osmotic pressures developed in the plant tissues. The increase in the elongation of the cotton leaves was marked immediately following irrigations with new additions of saline solutions, which reduced both the salinity and the moisture tensions in the previous soil solutions. The elongation of the cotton leaves stopped at about 15 atms. of computed total external force. But at this tension, the soil still was supplying water for transpiration (wilting was not mentioned). They cite tissue expansion as being a function of turgescence.

Mention was made of extra salt accumulations in the plants that result from and tend to balance in their osmotic forces the extra salt in the soils on which the plants are grown. The data (20) illustrating this point are from sand cultures. Measurements were made of the osmotic concentrations in the expressed sap from the leaves of six of the eight crop plants grown together in large outdoor sand cultures for comparison with the osmotic concentrations in the nutrient solutions. There was a control nutrient (0.07 atms.) and cultures with 50 (2.53 atms.) and 150 meq/l (6.0 atms.) of added Cl and cultures with 50 (0.18 atms.), 150 (3.5 atms.) and 250 (5.1 atms.) of added SO_4; in each case Na constituted 50 percent of total bases. The average sap concentration in the leaves of the six crops was higher than in the control solution by 11.2 atms.; in the 50 and 150 meq/l Cl solutions, by 11.6 and 11.5 atms., respectively; and in the three SO_4 solutions, by 12.3, 11.2 and 10.8 atms., respectively. These results indicate that crops in general should not be at a disadvantage in their water relations when grown on saline substrates, i.e., the higher osmotic pressures in leaves would be transmitted as suction forces through the xylem vessel, thereby tending to balance the higher osmotic forces in the soil. This tensional force of osmosis is additive to that produced by transpiration which is similarly transmitted to the roots. Some of the crops growing on the saline substrates gained in osmotic differential (osmotic pressure of sap minus osmotic pressure of substrate) and others lost. Grain sorghum had an osmotic differential on the control solution of 10.3 atms., and on the 150 Cl solution of 11.1, for tomatoes, the corresponding values were 8.8 and 8.2; for cotton, 13.1 and 9.7; for barley, 9.2 and 16.2; and for sugar beets, 12.8 and 15.0. In terms of the accumulation of chloride ion in the leaf saps, the concentrations for grain sorghum, cotton, tomatoes, barley and beets were, respectively, 26, 18, 25, 63 and 44 meq/l, on the control solution, and on the 150-Cl solution, 267, 178, 155, 374 and 175 meq/l. The yield data for these and other crops are summarized in Table 1. Van den Berg noted some plants are much more capable of accumulating salt and withstanding the salt accumulations than are others. The literature on water relations, as reviewed by Hayward and Wadleigh (30), shows that saline substrates may increase or decrease succulence.

Rootstalks have a notable influence on salt accumulations in plants. The chloride accumulations in the leaves and the leaf burning of avocados, grapefruit and oranges were sharply influenced by the rootstalks on which the plants were grown by Cooper and associates (15, 16, 17). Hayward *et al* (27) found no difference between two peach rootstalks in sulfate accumulations in the leaves, but there was an effect on chloride; peaches were more sensitive to chloride than to sulfate salts.

When the roots of plants are transferred suddenly to saline or sugar solutions and when salt crusts are washed into the soil by a shower, wilting may follow promptly. In terms of osmotic relations, this phenomenon is rather apart from the water relations of plants continuously cultured on saline substrates. With a sudden increase in salinity, the time opportunity is lacking for the accumulation of salts by the plant. To accomodate this salt uptake adjustment, investigators either germinate the seeds in the saline soil or add the total desired final salt concentrations as small increments over a number of days.

The number of species showing special sensitivities, or high tolerances, to particular ions is continuously being extended by salinity investigators, particularly those of the U. S. Salinity Laboratory at Riverside, California. Differences in sensitivities and tolerances are not confined to such ions as chloride and sulfate but include calcium, magnesium, sodium and bicarbonate. Solutions high in magnesium are especially toxic when calcium is low. Climatic factors influence salt tolerance (3) but the effects on different species (37) evidently are somewhat diverse and involve differential effects on ionic accumulations and the consequences of the accumulations. In view of the foregoing, formulas for characterizing the salinity of irrigation waters in terms of leaching percentages for reasonable yields or good growth must involve generalizations. Irrigation agriculture usually is not based on the continuous production of a single crop but involves a rotation of crops; the salt tolerances of the crops in a rotation may be somewhat diverse and there are marked changes in climatic conditions between seasons. Kelley, Laurance and Chapman (32) show that major alterations in the chemical properties of soil solutions take place rather slowly except when reclamation practices are used.

The substantial body of data on the salt tolerances of plants has been variously related to soil salinity on the basis of measurements of: (1) the electrical conductivity of soil pastes, which are not well related to the conductivity of saturation extracts (42); (2) the salinity of saturation extracts (49,50), which represent moisture contents twice or more as high as the moisture equivalent; and (3) analyses of high-moisture soil extracts; these latter, because of textural differences and solubilities, usually cannot be converted to soil-solution concentrations. Data on salt tolerances also have been obtained from sand and water cultures; these provide direct information on the concentrations of the salts in which the plant roots are bathed. Some justification for regarding culture-solution concentrations as the equivalent of soil-solution concentrations (at the moisture equivalent) in terms of toxicity is indicated by the fact that immediately following irrigation, the moisture percentages in soils are higher than at the moisture equivalent, whereas, as soils dry, the moisture content falls below the moisture equivalent. At the wilting coefficient it is much below. As irrigation is customarily practiced it appears that concentrations used in sand and water cultures approach in their salt effects the concentration of the rootzone soil solution as represented at the moisture equivalent.

The now extensively-used saturation-extract procedure provides a useful index to soil solution concentrations but it should be regarded as an approximate index rather than as a measure. A soil paste contains about twice as much moisture at saturation as at field capacity (50); at field capacity there is somewhat more moisture than at the moisture equivalent. Briggs and Shantz (9) related moisture-holding capacity (soil voids *nearly* filled in freely drained columns 1 cm. tall) to the moisture equivalent by the relation: (moisture equivalent x 1.57) + 21. In other words, saturation-extract concentrations need to be doubled, or more, to be representative of soil solution concentrations. Results with sandy soils are less reliable in this respect than those for medium and heavy textured soils.

The present need is for values for soil solution concentrations that can be associated with yield reductions of various plants to 90 percent and less of the yield under comparable conditions on non-saline soils. Comprehensive lists of plant tolerances have been worked out by the U. S. Salinity Laboratory (50) on the basis of relative tolerances; the order in which the plants are placed is associated with the range by plant groups of the electrical conductances of saturation-percentage extracts expected to produce yield reductions of 50 percent. In his studies of the salt injury in polders of Holland inundated with sea water, Van den Berg (5) estimated the concentrations of salt in the soil water that resulted in 75 percent yields of 14 crop plants. He designated this level of production as a "reasonable yield." The term "reasonable yield" has been adopted in the present paper. But inasmuch as it is desired that the selected mean soil-solution concentrations for reasonable yields should apply to a group of plants with intermediate tolerances, the present meaning of "reasonable yield" has been broadened to designate yields that are 70 to 80 percent of those on non-saline substrates. In a similar sense, the term "good yields" will be applied to yields of 85 to 90 percent.

A little of the body of experimental data which would have been most useful in the association of measured yield reductions with known substrate concentrations of chloride and sulfate was published (37) in a paper featuring osmotic concentrations in relation to climate. Further data derived from soil plots irrigated with waters high in chloride salts and from greenhouse studies in sand and solution cultures have been presented in original papers from the U. S. Salinity Laboratory and summarized in the relative tolerance lists (50). Van den Berg's (5) data on chloride toxicity in inundated polders also provide valuable orientation data. Insofar as it has been possible to collate the foregoing material, recognizing climatic and other variables, a general justification is indicated for the use made here of the data (20) summarized in Table 1; grain sorghum, tomato, alfalfa and cotton of this table have moderate to good salt tolerance (intermediate tolerance). The averages of the data for these four crops were used in the extrapolations to reasonable and good yields. All of the plants represented were grown together in large outdoor sand cultures during the summer of 1934 at Riverside, California. As here summarized, the percentage yields of plants at the 100 meq/l concentrations are the means of cultures with 50 to 150 meq/l, and at the 200 meq/l concentration they are the means of cultures with 150 and 250 meq/l. In all substrates, sodium constituted 50 percent of the sum of calcium, magnesium and sodium.

Table 1. Relative growths of several crops on sand culture nutrient solutions with added concentrations of chloride and sulfate salts as 50 percent sodium.

Crops		Control nutrient[1]	Control nutrient plus			
			Medium salt		High salt	
	Meq/l ——	—[1]	50 Cl	100 SO_4	100 Cl	200 SO_4
	Mm/l ——	—	50	50	100	100
	O.P. atms -	0.7	2.5	2.6	4.3	4.3
	EC × 10^3 —	1.7	6.6	8.1	11.4	13.5
1. Lemon plants		100	28	59	—	24
2. Navy beans (seed)		100	39	45	—	—
3. Dwarf sorghum (grain)		100	54	60	30	24
4. Stone tomato (entire tops)		100	78	64	49	40
5. Alfalfa (3 cuttings)		100	73	75	59	63
6. Acala cotton (seed cotton)		100	75	77	61	57
Averages, nos. 3, 4, 5, 6		100	70	69	50	46
7. Barley (grain)[2]		100[2]	138	91	93	49
8. Sugar beets (fresh roots)		100	98	80	93	71

[1] Contained 0.6 and 2.7 meq./l. of Cl and SO_4, respectively.

[2] Barley data are problematical on relative basis since the control plants were attacked badly by mildew, whereas there was little or none in the salt cultures.

With substrate concentrations expressed as millimoles (rather than milliequivalents) per liter, it is found by curvilinear extrapolation to a concentration of 5 mm/l that a mean yield of 75 percent for the four species (reasonable yield) is represented at a concentration of about 40 mm/l, and a mean yield of 85 to 90 percent (good yield) at a concentration of 20 mm/l. The concentration values expressed in millimoles per liter are the same as is represented by the summation Cl + ½SO_4, meq/l.

The summer climatic conditions at Riverside are probably representatively intermediate of the irrigated regions of western United States. The salt tolerances of the four crops used for the extrapolations to reasonable and good yields are representative of those with moderate to good tolerances, i.e., intermediate tolerances, and each of the four crops showed similar tolerances to chloride and sulfate salts when these were expressed in terms of molar concentrations. For plants of this category, considered in terms of various rotations and an intermediate climate, the value 40 meq/l for Cl + ½SO_4 for reasonable yields seems suitably representative. Using the value 40 for mean soil solution (Mss) in the general drainage formula, Sw for Cl + ½SO_4 in the water and d% for the leaching percentage:

$$\frac{\text{Sw} \times 100}{2 \times \text{Mss} - \text{Sw}} = \text{d}\% \text{ becomes: } \frac{\text{Sw} \times 100}{80 - \text{Sw}} = \text{d}\%$$

Substitution of other Mss values permits much leeway in the formula's application to particular crops and conditions. It was derived with the intention that other Mss values should be substituted, when appropriate ones are known, to fit special needs on a crop-to-crop, rotation-to-rotation or regional basis. Also, if crops are especially tolerant or sensitive to chloride versus sulfate salts, the two ions can be given other relative weights. The percent-leaching formula in itself does not anticipate a need for evaluating unusual proportions of calcium, magnesium and sodium; with soil solutions adjusted to a limiting value of 70 percent sodium, it may not be necessary to modify the formula for bases unless magnesium constitutes an unusual proportion of total bases in the water supply (see later discussion).

EVALUATION OF CALCIUM REQUIREMENTS

The possible need for supplemental calcium in irrigation waters can be understood best by resolving calcium requirements into three categories. Each of these will be considered in terms of the composition of irrigation waters and each will be directed toward the provision of about 70 percent of sodium in the drainage effluent; the sodium percentage in the upper soil usually will be maintained by the formulas at substantially less than 70 percent. Adapted to formulary determination, the three calcium requirements are as follows: *a* is an adjustment of the initial irrigation water to 70 percent sodium. Depending on the sodium percentage of the water, this formula yields either a calcium-requirement value or a calcium-excess value. If there is an excess it is carried over to apply to the needs under *b* and *c*. *b* is the calcium required to replace the calcium and magnesium precipitated as relatively inert calcium and magnesium carbonates; this calcium requirement is estimated on the basis of the bicarbonate concentration in the water. *c* is the calcium required to replace the calcium and magnesium taken up by plants and actually removed from the land. *a* and *b* are peculiar to irrigation agriculture; *c* applies to agriculture generally. As a result of calcium removals by plants and insufficient soluble calcium supply to replace calcium lost by HCO_3 precipitation, irrigated soils become alkaline, whereas rain-supplied soils become acid. Supplemental irrigation introduces special sodium and soil pH considerations.

The selection of 70 percent sodium for the rootzone effluent is somewhat empiric. Soils that are otherwise permeable will probably remain reasonably so in the presence of 50 to 100 meq/l of salt when the soil water contains no more than 70 percent sodium. With a soil solution containing 80 meq/l of bases and 70 percent sodium, the exchangeable sodium of most soils would probably fall in the range of 15 to 20 percent. Richards (43) has proposed defining soils that contain more than 15 percent of exchange sodium as *nonsaline alkali soils* if the electrical conductance of the saturation extract is less than 4 millimhos/cm at 25° C., and as *saline alkali soils* if the conductance is greater than this amount. An electrical conductance of 4 millimhos/cm in many saturation extracts would correspond roughly with 80 meq/l of salt in the soil solution. By Richard's definition, any *sodium soil* (more than 15 percent exchange sodium) is an *alkali soil.*

Data are somewhat meager on the effects on plant growth of various sodium percentages in nutrient solutions. Bean plants grown by Gauch and Wadleigh (24) on nutrient solutions, with $CaCl_2$, NaCl and Na_2SO_4 added to give a series of similar osmotic concentrations, showed similar reductions in yield. On the other hand, using a mixture of sand and exchange amberlites, Bower and Wadleigh (8) showed beans had a marked reduction in growth when sodium constituted as much as 15 percent of the exchangeable bases; at this level, the growths of beets, Rhodesgrass and Dallisgrass were not affected. In both experiments, the beans accumulated much sodium in their roots, but not in their leaves. Thorne (47) found that the growth and calcium content of tomato plants were depressed only as the exchange sodium in a sand-bentonite mixture exceeded 40 percent. The exchange behavior of amberlites is not wholly comparable (2) with that of bentonite, a common soil mineral. Martin, Harding and Murphy (38) showed sharp reductions in the growth of orange seedlings with 14 percent of exchange Na or K. But the growth of neither barley nor tomatoes was influenced by as much as 28 percent of either ion. Both Na and K depressed Ca accumulation.

McGeorge (36) found that plants grown on calcareous soils with high pH are notably low in calcium, nothwithstanding the mass of calcium carbonate in the soil. Bower and Turk (7) with a further review of the literature, showed that an appreciable growth of alfalfa did not occur on a calcareous soil ($CaCO_3$ 7.5 percent) with a pH of 9.6 until $CaCl_2$ (12 meq/100 gms) was added and the soil leached with water. This addition and leaching provided a fair growth (soil pH reduced to 8.6) and a threefold increase in the percentage of calcium in the plants. They also found an additional great increase in growth when $MgCl_2$ was substituted for a part of the added $CaCl_2$; this substitution did not result in any additional lowering of the pH of the soil but it did increase the magnesium content of the plants. A question is raised by the preceding results as to whether the additions of calcium by the formulas take care of magnesium requirements. Magnesium is almost always present in waters but numerous instances of well waters with only a trace of magnesium have been noted (18) in the southern part of the San Joaquin Valley of California. Sometimes it may be desirable to substitute magnesium for a part of the calcium designated by the formulas for calcium requirements. Irrigation waters with little magnesium should be regarded as suspect. Soils high in replaceable Mg have caused permeability difficulties and gypsum was not very effective in replacing the exchangeable Mg (correspondence with Dr. W. T. McGeorge). Decrease in the percent of exchangeable magnesium improved the permeability of an Hawaiian Islands soil (26).

Calcium for Adjusting Irrigation Waters to 70 Percent Sodium

The amount of calcium, meq/l, required to establish a sodium percentage of 70 in an irrigation water may be derived from the formula:

$$\text{Na} \times .429 = \text{Ca plus Mg needed for } 70\% \text{ Na}$$

or

$$\text{Ca } a\text{: Na} \times .429 - (\text{Ca} + \text{Mg}) = \text{Ca requirement: } \textit{plus or minus}$$

If the sign is positive, the indicated amount of calcium should be added to the water. If the sign in negative, the amount is above the need and is carried over (minus sign) to apply against HCO_3 precipitation (Ca *b*) and to the calcium requirements of plants (Ca *c*) when *a*, *b* and *c* are totaled.

Some investigators may feel that a greater assurance of suitable soil permeability, flocculation and aeration would be provided if the adjustment was made to 60 or 65 percent sodium. The adjustment to 60 percent would be made by substituting the factor 0.666 for the factor 0.429, or to 65 with the factor 0.538. These and other factors are obtained by the relation: 100 divided by desired %Na equals 1 plus factor, i.e., 100/70 equals 1.429.

There are several reasons for not including potassium in the calculation of sodium percentages: 1) for uniformity in water reports K should be omitted because it oftentimes is not determined; 2) K deflocculates soils to a less extent than does Na; and 3) in many soils, the small amount of K supplied by irrigation waters often will be used nutritionally and taken from the land; the K in seed commonly is quite high. These conclusions do not overlook the fact that K is sometimes found in drainage waters.

Calcium to Offset Bicarbonate Precipitation

The tabulation (page 5) of the displaced soil solutions from the Superstition sand and Holtville silty clay shows that the concentrations of chloride and sulfate in the soil solutions exceeded those of the water and increased with depth, whereas there was a loss with depth in bicarbonate concentration. The irrigation water in this case contained 3.19 meq/l of HCO_3, the sixth-foot soil solution of the Superstition soil (pH 6.6 and Na percent 44) contained 1.75 meq/l of HCO_3, and that of the Holtville soil (pH 7.6 and Na percent 60) contained 0.85 meq/l.

In pure solutions at the CO_2 content of the air, calcium carbonate has a solubility of about 1 meq/l; under the same conditions, the solubility of magnesium carbonate is about 15 times greater. But in soil solutions and soil extracts, as well as in lakes and ground waters, it is usual to find somewhat less Mg than Ca. It is largely unknown whether the Mg is precipitated with Ca as dolomite—$CaMg(CO_3)_2$—or whether the conditions that prevail in soils cause $MgCO_3$ to be precipitated out of proportion to its solubility relative to $CaCO_3$. Clark (14), in his data on geochemistry, provided an extensive discussion of this subject. Irrespective of the cause, Mg does disappear from solution along with Ca during the passage of irrigation waters through the soil. In the Colorado River water (see previous tabulation), there were 5.41 meq/l of Ca and 3.01 meq/l of Mg. The sixth-foot soil solution of the Superstition sand contained 11.79 and 6.6 meq/l of the respective ions; the increase in Cl concentration between the water and soil solution was 3.3-fold. The solution of the sixth foot of the Holtville silty clay contained 18.69 meq/l of Ca and 18.14 of Mg; the increase in Cl concentration was 12.4 fold. An irrigation water used in the Emmett Valley of Utah (22) contained 0.51 meq/l of Ca and 0.06 of Mg; in another analysis the values were Ca 0.40 and Mg 0.23. The mean of four ground water samples in irrigated fields served by this water contained 0.44 meq/l of Ca and 0.21 of Mg; there was a 10-fold increase in Cl. An irrigation water used in the Delta area of Utah (41) contained 4.3 meq/l of Ca and 7.3 of Mg; the mean of two drainage waters was 32 meq/l of Ca and 54 meq/l of Mg; the increase in Cl was 20 fold.

From the foregoing and other literature, it appears that HCO_3 concentrations in the lower rootzone of only moderately saline irrigated soils containing 60 or 70 percent sodium ordinarily can be expected to be as low as the irrigation water at CO_2 equilibriums with the air. Assuming that the change in HCO_3 concentration between irrigation water and soil solution is only nominal, it is possible to predict the loss in calcium and magnesium resulting from bicarbonate precipitation on the basis of the percentage of the applied irrigation water passed beyond the rootzone, i.e., on the basis of leaching percentages. The leaching percentages used in the HCO_3 formula will be taken as those derived for leaching by the formula for reasonable yields of crops of intermediate tolerance. To illustrate: with leaching at 1 percent, 99 percent of HCO_3 precipitated; with leaching at 10 percent, 90 percent of HCO_3 precipitated; and with leaching at 50 percent, 50 percent of HCO_3 precipitated. Expressing the HCO_3 of the irrigation water, and the Ca required to offset the HCO_3 precipitation of Ca, in meq/l, this relation becomes:

$$\text{Ca } b: \frac{HCO_3 \times (100 - d\%)}{100} = HCO_3 \text{ prec. or Ca required}$$

The foregoing conclusions with respect to nominal concentrations of bicarbonate expected in soil solutions with upwards from 30 or 35 percent of calcium and magnesium would appear to make unnecessary a consideration of bicarbonate toxicity (25,52). But this conclusion cannot be extended to soil conditions where the calcium is not in excess of HCO_3; under such conditions high sodium percentages and high pH values in the soil are to be expected. An appreciable accumulation of bicarbonate ions by plant roots has never been demonstrated (40).

Under some conditions at least, plant roots can accumulate calcium from solid phase calcium carbonate, but in so doing the associated carbonate ion would be released to the soil solution. Since the present evidence indicates that plant roots do not accumulate carbonate ion, the liberated carbonate ion would result in the precipitation of another molecule of calcium carbonate. It thus becomes immaterial in the instance of calcium requirements in calareous soils whether the plants take their calcium from the liquid or from the solid phase.

Calcium to Offset that Removed from the Land by Plants

A representation is needed of the amounts of calcium and magnesium removed from irrigated land by plants in terms of applied irrigation water. To supply this need, water requirement data by Briggs and Shantz (see Shantz and Piemeisel 44) have been combined with mineral analyses assembled by Morrison (39) for expression of removals of various minerals by various crops in terms of meq/l per acre foot of irrigation water. Insofar as data from the two sources could be paired for representative crops, the results are presented in Table 2. The water requirement data, recomputed here to pounds of produce per acre-foot, are for Akron, Colorado and thus represent the semi-arid climate of the Western Plains; they are higher than those which would pertain in cool coastal climates and lower

Table 2. Estimates of minerals removed from the soil per acre-foot of water transpired by plants (rain plus irrigation), meq./l. per acre-foot of water[1]

Crop	Produce lbs./ac.ft. net water	Ca	Mg	Na	SO_4	Cl	Net Ca+Mg req.
Alfalfa hay	2930	0.68	0.20	0.07	0.18	.10	0.84
Brome grass hay	2530	.09	.14	.23	.05	.10[2]	.11
Clover hay	3260	.80	.33	.09	.07	.24	1.09
Sudan grass hay	6510	.43	.61	.07[2]	.07	.03[2]	1.00
Cowpea hay	4780	.87	.54	.15	.35	.07	1.35
Cowpea seed	1670	.03	.13	.07	.10	.01	.12
Soybean hay	4210	.73	.56	.06	.25	.07[2]	1.26
Soybean seed	1400	.06	.11	.05	.07	.01	.14
Barley hay	5250	.20	.16	.08	.16	.05	.33
Barley grain	1990	.04	.07	.03	.07	.03	.09
Corn fodder	7080	.31	.32	.04	.21	.12	.61
Corn grain	1760	.01	.09	.03	.05	.01	.08
Oat hay	4240	.16	.21	.10	.20	.20	.33
Oat grain	1520	.03	.06	.02	.07	.02	.08
Wheat hay	4880	.14	.16	.09	.19	.12	.26
Wheat grain	1560	.01	.02	.01	.07	.01	.02
Cotton, seed cotton[2]	1800	.07	.09	.03	.01	.01	.14
Navel orange[2]	1100	.03	.02	.01	.01	.01	.04
Sugar beets, fresh roots	22480	.16	.20	.29	.05	.19	.24
Beef steers (or sheep)	130[3]	.01	.00	.00	.00	.00	.01
Means		.24	.20	.08	.11	.07	.41

[1] Unless marked with a footnote, the chemical data are from Morrison (39) and the water requirements at Akron, Colorado, by Briggs and Shantz (42).

[2] Data from other publications or by approximation.

[3] Assumes a gain of 500 pounds on alfalfa-bromegrass pasture that would produce 5 tons of hay.

than those which would be found under hot desert conditions.

With variations in climate and in soils, marked differences are found in mineral compositions within species. The subject cannot be discussed at length but in view of the use to be made of the Morrison data in Table 2, a few examples should be noted. Bear and Wallace (4) made analyses of second-cutting alfalfa-hay samples from 11 states. In terms of percentages of calcium plus magnesium, the range was from 1.44 to 3.16, the mean of samples from California and Utah, both of which were presumably irrigated, was 2.07; the value from Morrison is 1.49. The maximum and minimum values for sodium in the Bear and Wallace data are 0.02 for California and 0.14 percent for Utah; the Morrison value used is 0.14. Chloride in the Bear and Wallace data ranged from 0.18 to 1.03 percent; California and Utah were, respectively, 1.03 and 0.50; the Morrison value is 0.34.

Table 2 shows that it makes a great difference whether only seed or fruit are removed from the land or entire plants. Ten of the 20 entries in Table 2 represent entire tops as harvested. The minor removal of calcium, with less than 0.01 percent of other elements, by cattle and sheep on pasture has a special bearing on the selection of a mean general value for use in the calcium-requirement formula.

In view of the importance of pasturage in irrigated areas and the extensive use of combines in grain harvest, it seems that a mean value of 0.30 or 0.35 meq/l is amply high for calcium and magnesium removals in crop rotations in the United States. Since the primary object of the formulas is to maintain not more than 70 percent sodium in the soil solution, rather than to supply calcium for plant nutrition, a correction is necessary for the small amount of sodium that also is removed from the land. This correction for 70 percent Na is taken care of for the purpose of a general value if the 0.30 meq/l value for the calcium addition per acre foot of water is used. To maintain 70 percent sodium in a solution, it is necessary to have 0.429 meq/l of Ca and Mg for each meq/l of sodium. Conversely, if 1 meq/l of Na is removed by a crop, 0.429 meq/l of Ca plus Mg also may be removed without changing the 70 percent sodium. Accordingly, Na x 0.429 is deducted from the Ca plus Mg removals to obtain the *net Ca* requirement for any particular crop, Table 2. In Eastern countries where the vegetative parts of plants are extensively moved into the villages for animals and much of the manure is used for fuel, use of the Ca value 0.50 is recommended. The 0.30 meq/l value for Ca plus Mg taken by plants requires a further adjustment.

With leaching, calcium and magnesium are withdrawn by plant roots, in effect, from a moving soil solution (recurring downward movement). If the rate of downward movement is slow, the amount of calcium taken by the plant from a unit of water passing its roots will be greater than if the movement is rapid; in other words, a time and opportunity consideration is involved. This time-opportunity relation should be inversely related to the percentage of leaching. For example, neglecting surface evaporation, if four units of irrigation water are added in one case and two units drained versus four units added and one drained, the water would have remained in the rootzone 50 percent longer in the second case than in the first. The leaching correction of the 0.30 meq/l of calcium required by plants, for 70 percent sodium, thus becomes:

$$\text{Ca } c\text{:} \frac{0.30 \times (100 - d\%)}{100} = \text{required Ca.}$$

If in the above, d% is 10 then 0.27 meq/l of Ca is required for plants. If the d% is 50 then only 0.15 meq/l is required.

Water requirement and mineral values used in Table 2 might suggest that water requirements at Akron, Colorado, would be lower than those in a location such as Riverside, and that Morrison's predominantly (probable) Midwestern mineral-composition values are lower than should be expected under irrigation. Applied to hay crops, however, there is a compensating factor in the data even though it would be difficult to estimate. When Briggs and Shantz cropped their water-requirement cans, the plants were cut off at the lids, i.e., more plant was taken than would be the case with a mower; also Briggs and Shantz included in the plant weight all leaves and parts that fell from the plants. If the total water transpired by the entire plants had been charged against only the parts that are ordinarily removed from the land under field conditions, higher water requirements would have resulted. Stubble and fallen leaves do not permanently remove minerals from the land. Whether these considerations compensate for the possibly higher water requirements and mineral compositions under somewhat more arid field-irrigation conditions is uncertain, and, in any event, the writer does not know how the adjustment could be made, if any is needed.

The calcium requirements shown for plants in Table 2 are based only on the acre-feet of irrigation water consumed by transpiration. Under conditions of supplemental irrigation, the portion of rainfall that is not lost by evaporation contributes to growth, which also takes calcium from the soil, and would therefore increase the sodium percentage of the soil solution. It accordingly would be appropriate to footnote the use of an additional 0.30 meq/l of calcium (70 pounds of gypsum) for each acre-foot of water used in transpiration that is derived from rain.

Summation of Calcium Requirements

The total calcium requirement is represented as the sum of *a* (sodium in water adjustment), *b* (the HCO_3 precipitation adjustment) and *c* (for plant use); *a* often is a minus value and if so should be deducted from the sum of *b* and *c*. Total required calcium times the factor 234 converts required calcium to pounds of gypsum per acre-foot of water.

FINAL CALCULATION OF LEACHING

The addition of calcium to a water in the form of gypsum adds an equal amount, meq/l, of sulfate. This added sulfate is as toxic as the sulfate added by the irrigation water. Knowing the total addition of calcium, the tentative drainage formula now can be recalculated for a final value; the half-value of "total Ca" is used to correspond with the half-value used for SO_4. This recalculation takes the following form:

Required drainage final—D%:

$$\frac{Sw + \frac{1}{2} \text{ total Ca}}{2 \times Mss - (Sw + \frac{1}{2} \text{ total Ca})} = D\%$$

No correction has been made by the leaching formula for chloride and sulfate removed from the land in harvested crops. The average value for Cl + SO_4 in all crops of Table 2 is 0.125 meq/l; corresponding to the adjustment made in net Ca plus Mg for the usual rotation, 0.07 meq/l would be a corresponding creditable value. But if all the analyses of Table 2 had been of crops grown on irrigated land, it is possible that a value as high as 0.20 meq/l might have resulted. If such a deduction is applied to an irrigation water with an Sw value 5.0, the required leaching becomes 6.4 percent, whereas without the correction the required leaching is 6.7 percent. Corrections no larger than indicated on the basis of these assumed values appear too small to justify the further complication of the formulas.

Account is not taken by the formulas of the effect of $CaSO_4$ precipitation on the sodium percentages of the soil solution. Computations show that this can be a factor with waters especially high in Ca and SO_4, but such waters usually do not give rise to high sodium percentages in effluents when leaching is high enough for reasonable yields. Although critical tables show the solubility of $CaSO_4$ to be around 30 meq/l, depending on the concentrations of other ions, it is common to find higher concentrations of $CaSO_4$ in soil solutions. The second-foot soil solution of the Holtville soil contained 37.4 meq/l of Ca and 75.7 meq/l of SO_4.

Gypsiferous soils occasionally are found in arid regions. Until this gypsum has been dissolved and leached from the upper root zone, it is obvious that additional calcium is unnecessary.

Soil Sampling to Determine Existing Leaching Rates

As mentioned in the introduction, the formulas, in themselves, provide no information on the amount of water that will be passed through the rootzone with different rates of water application. Knowledge of the existing leaching percentages can be obtained only by sampling the soil. Measurements of the discharge volume from tile drains provide some insight but this volume, or the salinity of the discharge, does not differentiate between canal seepage and actual rootzone leaching. Measurements of the salinity of the saturation-percentage extracts of soil samples collected at various depths and different locations within fields become useful in this connection; but to reflect the concentration of the soil solution at field capacity, it is necessary to double the values obtained from such extracts. Comparisons of the chloride concentrations in the initial waters and in the extracts, after they are doubled, provides the most direct information on the rate of leaching that has existed. Electrical conductance measurements of extracts also can be doubled and used similarly. But in comparing conductivity values of the soil solution with the conductivity of the water supply, the latter value must be adjusted downward to omit the portion of the conductance of the water which results from the bicarbonate ion. Each meq/l of HCO_3 in a water contributes about 0.1 millimhos ($ECx10^3$) or 100 micromhos ($ECx10^6$) to the electrical conductivity of a water.

EXAMPLE WATERS

Seven water analyses from various sources and varied characteristics are reported in Table 3 together with the drainage and gypsum requirements for reasonable (Mss 40) and good yields (Mss 20). The computations (only those for Mss 40 are given) no doubt look rather tedious; but this is not actually the case. After setting up the table headings, only an hour with a calculator was required to compute the leaching and gypsum values for reasonable yields of the seven waters. This is no longer than the chemist ordinarily would take to convert his analytical data to meq/l and only a fraction of the time spent on the analyses themselves, not to mention the cost of collecting and shipping the samples.

The correlation between the required leaching and the electrical conductances of the seven waters is not very good; bicarbonate ion contributes too heavily to the conductances of waters of relatively low salinity for this to be the case. Furthermore, there is little proportionality between the sodium percentages of the waters and the required calcium (gypsum).

The drainage requirements for good yields tend to be about double or more those for reasonable yields. The gypsum requirements for good yields are only slightly lower than those for

Table 3. Comparisons of the leaching and gypsum requirements for reasonable and good yields of seven irrigation waters with examples of the computations for reasonable yields[1]

	Analyses								Required for:			
									Reasonable yields[3]		Good yields[4]	
Water[2]	EC × 10^6	Na %	Ca	Mg	Na	HCO_3	SO_4	Cl	Leaching	Gypsum	Leaching	Gypsum
1	171	59	0.49	0.29	1.11	1.55	0.09	0.25	1.4	360	2.3	276
2	420	31	2.35	.75	1.39	2.94	.98	.56	1.8	161	3.5	150
3	789	96	.24	.02	7.28	2.39	2.48	2.47	9.1	1392	19.8	1357
4	800	42	2.96	1.67	3.35	3.05	4.56	.76	4.0	5	8.2	excess
5	985	37	4.17	2.26	3.81	2.76	5.51	2.11	6.5	excess	13.9	excess
6	1120	51	4.14	1.49	5.77	3.58	4.97	3.02	10.4	72	22.5	excess
7	3700	62	7.63	6.78	23.02	1.70	12.44	23.33	58.6	excess	100+	—

Computations for reasonable yields[5]

						Ca required for:							
	$Cl+\frac{1}{2}SO_4$ (1)	80— $Cl+\frac{1}{2}SO_4$ (2)	Tent. d% (3)	100 —d% (4)	Na × 0.429 (5)	a (%Na) (6)	b (HCO_3) (7)	c (plants) (8)	Total a+b+c (9)	Gyp-sum (10)	$Cl+\frac{1}{2}SO_4$ $+\frac{1}{2}Ca$ (11)	80 — col. 11 (12)	final D% (13)
1	0.30	79.70	0.38	99.4	.48	—0.30	1.54	0.30	1.54	360	1.07	78.93	1.4
2	1.05	78.95	1.32	98.7	.59	—2.51	2.90	.30	.69	161	1.40	78.60	1.8
3	3.71	76.29	4.86	95.1	3.12	3.39	2.27	.29	5.95	1392	6.69	73.31	9.1
4	3.04	76.96	3.95	96.1	1.43	—3.20	2.93	.29	.02	5	3.05	76.95	4.0
5	4.87	75.13	6.48	93.5	1.63	—4.80	2.58	.28	—1.94	excess	4.87	75.13	6.5
6	7.36	72.64	10.13	89.9	2.45	—3.18	3.22	.27	.31	72	7.51	72.41	10.4
7	29.55	50.45	58.57	41.4	9.85	—4.56	.70	.12	—3.74	excess	29.55	50.45	58.6

[1] Water analyses in meq/l, leaching in percent of applied irrigation water and gypsum in pounds per acre-foot of water.

[2] Water sources: 1, well at Livingston, California (U. S. Sal. Lab. No. 6160); 2, Chapman lysimeter water; 3, well, Bakersfield, California (U. S. Sal. Lab. No. 18071) 4, Platte R., at Grand Island, Nebraska (U. S. Sal. Lab. No. 21,605); 5, Colorado R. wt. mean year ending Sept. 30, 1950 (U.S.G.S.); 6, Rio Grande, El Paso, (U. S. Sal. Lab. No. 18544); 7, Pecos R., Comstock, Texas, May, 1946.

[3] Drainage and gypsum for reasonable yields based on Mss of 40.

[4] Drainage and gypsum for good yields based on Mss of 20.

[5] Explanations of computations by column numbers:

(3) Col. 1 divided by col. 2 × 100.
(6) Ca to adjust percent Na; col. 5 less (Ca+Mg).
(7) Ca to offset HCO_3 prec.; HCO_3 × col. 4 ÷ 100.
(8) Ca for plants; 0.30 × col. 4 ÷ 100.
(9) Sum of cols. 6, 7, and 8.
(10) Gypsum required; col. 9 × 234.
(11) New value for $Cl+\frac{1}{2}SO_4$ to include half of the SO_4 (half of "total Ca") added as gypsum, i.e., col. 1 plus ½ of col. 9.
(13) Col. 11 divided by col. 12 × 100.

reasonable yields. The salinity of water number 7 would permit *reasonable* yields but is too great for *good* yields, i.e., the concentration of Cl plus $\frac{1}{2}SO_4$ in the water, 29.55 meq/l, is greater than the Mss 20 permissible for good yields. This result corresponds with crop experience with waters of similar analyses in the Pecos area.

Water number 2 has been used for 15 years on the Chapman lysimeters (11) at Riverside, California. As used without calcium nitrate fertilizer and with Sudangrass removed from the lysimeters, the average pH of the upper 3 feet of soil rose from an initial value of 6.74 to 8.56. With 100 pounds N as calcium nitrate (1.84 meq/l of Ca added per acre-foot of water) the pH was 8.24, and with 200 pounds N (3.70 meq/l Ca added per acre-foot) the pH was 7.96. The additions of Ca in terms of the irrigation water, as represented within the parentheses, were computed from the average amounts of irrigation water added to lysimeters without winter cover crops. On the basis of relations developed by Fireman and Wadleigh (23), the above pH of 8.56 probably would correspond to an exchange-sodium-percentage above 15 percent.

A good many irrigation waters that have caused highly-alkaline soil conditions when used sparingly can be used more abundantly with good drainage to correct the adverse soil reactions which were produced under sparing use. A more abundant use of water reduces the extent of calcium carbonate precipitation and also the amount of calcium taken by plants per unit of water. Some waters with initially low sodium percentages can be passed through the rootzone rapidly enough, particularly if HCO_3 is also low, that 70 percent sodium in the drainage effluent would never be exceeded. More abundant use also maintains lower concentrations of sulfate and chloride in the soil solution. The foregoing points can be tested for advantages in terms of soil solution concentrations and calcium requirements for any water by substituting higher leaching percentages in the formulas than those derived for good or reasonable yields. With such trial computations, it becomes possible to evaluate water costs, calcium costs, yield expectations, drainage costs, nitrate losses, and the like, in terms of the most economical net results.

Calculations by the formulas of the calcium requirements of a series of waters, in addition to those of Table 3, indicated a surprisingly high proportion which would benefit from calcium additions. This result raises two questions: do the formulas overestimate calcium needs, or are crops under irrigation commonly being supplied with too little calcium for the best growth of many plants?

In the Midwest and East, additions of a ton or more of ground limestone or marl commonly are made to non-calcareous soils per year. The commonly accepted viewpoint is that these additions serve the twofold purpose of correcting acidity and of supplying calcium for plant growth. A 1,500-pound addition of calcium carbonate dissolved in 2 acre-feet of water would increase the concentration of calcium by 5.5 meq/l. In rain-supplied lands, the calcium and magnesium lost by leaching and plant uptake are replaced by hydrogen ion with a consequent increase in acidity. Under irrigation, calcium uptake by plants and calcium carbonate precipitation increase the alkalinity of the soil solution; in this situation, sodium ion, rather than hydrogen ion, is involved. If the concentration of soluble calcium in the soil is low, the sodium of the irrigation water tends to replace exchange calcium; also, since plants do not take up bicarbonate ion and take little sodium, these ions may accumulate with the consequent development of sodium carbonate concentrations and pH values in the black-alkali range. The data of Arnon and Johnson (1) shifted the emphasis from H and OH ion relations to nutritional relations over a rather broad pH range.

It seems surprising that so many irrigation waters should show an evident need for more calcium than is being supplied by these waters. Field trials should be conducted to validate the conclusion that soluble calcium may be deficient in many irrigated soils where it is not now suspected. In the meantime, indications are that calcium deficiencies in irrigated soils may be more common than heretofore believed. On such a basis, calcium deficiencies as well as salinity become important characteristics of irrigated soils. Also, the 0.30 meq/l of calcium allowed for plant use appears as a minor addition relative to the amounts being added to Eastern soils.

REFERENCES

1. Arnon, D. I. and Johnson, C. M. Influence of hydrogen ion concentration on the growth of higher plants under controlled conditions. Plant Physiol. 17: 525-539. 1942.

2. Arnon, D. I. and Meagher, W. R. Factors influencing availability of plant nutrients from synthetic ion-exchange material. Soil Sci. 64: 213-221. 1947.

3. Ahi, S. M. and Powers, W. L. Salt tolerance of plants at various temperatures. Plant Physiol. 13: 767-789. 1938.

4. Bear, F. E. and Wallace, A. Alfalfa, its mineral requirements and chemical composition. New Jersey Agr. Exp. Station Bul. 748, 35 pp. 1950.

5. Berg, C. v.d. The influence of salt in the soil on the yield of agricultural crops. Trans. Fourth Inter. Cong. Soil Sci. 1: 411-413. 1950.

6. Berg, C.v.d. The influence of absorbed salts on growth and yield of agricultural crops on salt land. (Dutch with English summary) Versl. Landbouwk. Onderz. No. 58.5—'S-Gravenhage. 1952.

7. Bower, C. A. and Turk, L. M. Calcium and magnesium deficiencies in alkali soils. Jour. Amer. Soc. Agron. 38: 723-727. 1946.

8. Bower, C. A. and Wadleigh, C. H. Growth and cationic accumulation by four species of plants as influenced by various levels of exchange sodium. Soil Sci. Soc. of Amer. 13: 218-223. 1948.

9. Briggs, L. J. and Shantz, H. L. The wilting coefficient for different plants and its indirect determination. Bur. Plant Ind. Bul. 230. 1912.

10. Broadbent, F. E. and Chapman, H. D. A lysimeter investigation of gains, losses, and balance of salts and plant nutrients in an irrigated soil. Proc. Soil Sci. Soc. of Amer. 14: 261-269. 1950.

11. Burd, J. S. and Martin, J. C. Water displacement of soils and the soil solution. Jour. Agri. Sci. 13: 265-295. 1923.

12. Burgess, P. S. Alkali soil studies and methods of reclamation. Ariz. Agr. Exp. Sta. Bul. 123. 1928.

13. Christensen, P. D. and Lyerly, P. J. Water quality as it influences irrigation practices and crop production—El Paso and Pecos Areas. Tex. Agr. Exp. Sta. Circ. 132. 1952.

14. Clarke, F. W. The data of geochemistry. U. S. Geol. Survey, Bul. 770. 1924.

15. Cooper, W. C. Salt tolerance of avocados on various rootstalks. Texas Avocado Society Yearbook. pp. 24-28. 1951.

16. Cooper, W. C., Gorton, B. S., Olson, E. O. Ionic accumulations in citrus as influenced by rootstock and scion and concentration of salts and boron in the substrate. Plant Physiol. 27: 191-203. 1951.

17. Cooper, W. C. and Gorton, B. S. Toxicity and accumulation of chloride salts in citrus on various rootstalks. Amer. Soc. Hort. Sci. 59: 143-146. 1952.

18. Eaton, F. M. Boron in soils and irrigation waters and its effect on plants with particular reference to the San Joaquin Valley of California. U. S. Dep. Agi. Tech. Bul. 448, 1935.

19. Eaton, F. M. Water uptake and root growth as influenced by inequalities in the concentration of the substrate. Plant Physiol. 16: 545-564. 1941.

20. Eaton, F. M. Toxicity and accumulation of chloride and sulfate salts in plants. Jour. Agri. Res. 64: 357-402. 1942.

21. Eaton, F. M. Significance of carbonates in irrigation waters. Soil Sci. 69: 123-133. 1950.

22. Firemen, M., Mogen, C. A., Baker, G. O. Characteristics of saline and alkali soils in the Emmett Valley Area, Idaho. Agr. Res. Bul. 17, pp. 35, 1950.

23. Fireman, M. and Wadleigh, C. H. A statistical study of the relation between pH and the exchangeable-sodium-percentage of western soils. Soil Sci. 71: 273-285. 1951.

24. Gauch, G. H. and Wadleigh, C. H. Effect of high concentrations of sodium, calcium, chloride and sulfate on ionic absorption by bean plants. Soil Sci. 59: 139-153. 1945.

25. Gauch, H. G. and Wadleigh, C. H. Salt tolerance and chemical composition of Rhodes and Dallis grasses grown in sand culture. Bot. Gaz. 112: 259-271. 1951.

26. Gill, W. R. and Sherman, G. D. Properties of the gray hydromorphic soils of the Hawaiian Islands. Pacific Sci. 4: 137-144. 1952.

27. Hayward, H. E., Long, E. M., and Uhvits, R. Effect of chloride and sulfate salts on the growth and development of the Elberta Peach on Shalil and Lovell rootstocks. U. S. Dept. Agri. Tech. Bull. 922. 1946.

28. Hayward, H. E. and Spurr, W. B. The entry of water into corn roots—effect of osmotic concentration of the substrate. Bot. Gaz. 105: 152-164. 1943.

29. Hayward, H. E. and Spurr, W. B. Effects of isosmotic concentrations of inorganic and organic substrates on entry of water into corn roots. Bot. Gaz. 106: 131-139. 1944.

30. Hayward, H. E. and Wadleigh, C. W. Plant growth on saline and alkali soils. Advances in Agronomy 1: 1-38. 1949.

31. Kearney, T. H. The wilting coefficient of plants on alkali soils. Bur. Plant Ind. Circ. 109: 17-25. 1913.

32. Kelley, W. P., Laurence, B. M. and Chapman, H. D. Soil salinity in relation to irrigation. Hilgardia 18: 635-665. 1949.

33. Klintworth, H. The use of brak water for irrigation. Farming in South Africa 27: 45-51. 1952.

34. Long, E. M. Effect of salt additions to the substrate on the intake of water and nutrient by roots of approach grafted plants. Amer. Jour. Bot. 30: 594-601. 1943.

35. McGeorge, W. T. Some aspects of citrus tree decline as revealed by soil and plant studies. Ariz. Agr. Exp. Sta. Tech. Bul. 60. 1936.

36. McGeorge, W. T. Studies on plant food availability in alkaline-calcareous soils: seedling texts and soil analysis. Ariz. Agr. Exp. Sta. Bul. 94. 1942.

37. Magistad, O. C., Ayers, A. D., Wadleigh, C. H., and Gauch, H. G. The effect of salt concentration, the kind of salt, and climate on plant growth in sand cultures. Plant Physiol. 18: 151-166. 1943.

38. Martin, J. P., Harding, R. B., and Murphy, W. S. Effects of various soil exchangeable cation ratios on growth and chemical composition of citrus plants. Soil Sci. 76:285-295. 1953.

39. Morrison, F. B. Feeds and Feeding. Twenty-first Edition. Morrison Publ. Co. 1948.

40. Overstreet, R., Broyer, T. C., Isaacs, T. L. and Delwiche, C. C. Additional studies regarding cation absorption mechanisms of plants in soil. Amer. Jour. Bot. 29: 227-231. 1942.

41. Reeve, R. C., Allison, L. E., Peterson, D. F. Reclamation of saline-alkali soils by leaching. Utah Agr. Exp. Sta. Bul. 335, 52 pp. 1948.

42. Reitemeier, R. F. and Wilcox, L. V. A. A critique of estimating soil solution concentration from the electrical conductivity of saturated soils. Soil Sci. 61: 281-293. 1946.

43. Richards, L. A. Chemical and physical characteristics of saline and alkali soils of Western United States. Trans. Intern. Cong. Soil Sci., Amsterdam, 1: 378-383. 1950.

44. Shantz, H. L. and Piemeisel, L. N. The water requirement of plants at Akron, Colo. Jour. Agr. Res. 34: 1093-1190. 1927.

45. Scofield, C. S. Salt balance in irrigated areas. Jour. Agr. Res. 61: 17-39. 1940.

46. Thomas, E. E. Reclamation of white-alkali soils in the Imperial Valley. Calif. Agr. Exp. Sta. Bul. 601. 1936.

47. Thorne, D. W. Growth and nutrition of tomato plants as influenced by exchangeable sodium, calcium and potassium. Soil Sci. Soc. Amer. Proc. 9: 185-189. 1945.

48. Thorne, J. P., and Thorne, D. W. Irrigation waters of Utah, their quality and use. Utah Agr. Exp. Bul. 346: 1-64. 1951.

49. United States National Resources Committee. 1938. Regional Planning: Part VI. The Rio Grande joint investigation in the Upper Rio Grande Basin in Colorado, New Mexico, and Texas. 1936-1937. 566 pp. Washington.

50. United States Salinity Laboratory Staff. 1953. Diagnosis and improvement of saline and alkali soils. U. S. Dept. Agr. Handb. 60. 1953.

51. Wadleigh, C. H. and Ayers, A. D. Growth and biological composition of bean plants as conditioned by soil moisture tension and salt concentration. Plant Physiol. 20: 106-132. 1945.

52. Wadleigh, C. H. and Brown, J. W. The chemical status of bean plants afflicted with bicarbonate induced chlorosis. Bot. Gaz. 113: 373-392. 1952.

53. Wadleigh, C. H., Gauch, H. G., and Strong, D. G. Root penetration and moisture extraction in saline soil by crop plants. Soil Science 63: 341-349. 1947.

54. Wadleigh, C. H. and Gauch, H. G. Rate of leaf elongation as affected by the intensity of the total soil moisture stress. Plant Physiol. 23: 485-495. 1948.

55. Wilcox, L. V. The quality of water for irrigation use. U. S. Dept. Agri. Tech. Bul. 962. 1948.