IRRIGATION AND DRAINAGE PAPER **29**

water quality for agriculture

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS ROME

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by

R. S. AYERS
FAO Consultant
Soil and Water Specialist
University of California
Davis, California, U.S.A.

D. W. WESTCOT
Water Quality Specialist
Land and Water Development Division
FAO, Rome

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This edition is published in the hope of attracting expert comment. Although initially and somewhat ambitiously intended to cover all possible conditions, it was realized during its preparation that many interactions existed which could not be separated or covered in a short space. Comments and suggestions for improvement of the publication's practical application to the field would be welcomed and will be incorporated in a revised and possibly more complete edition.

Please forward comments and suggestions to:

Chief
Water Resources, Development and Management Service
Land and Water Development Division
Food and Agriculture Organization of the U.N.
00100 Rome, Italy

PREFACE

In many parts of the world the number of good quality supplies available for development is diminishing. Many of those presently available for development provide low quality water and in many cases use is being made of supplies once considered marginal or unfit for use. The pressing need for increased agricultural production is also having an impact on the better quality waters resulting in quality degradation as they move downstream. However, the important point is that these waters, although degraded, are still usable. Both the benefits from proper use and the problems of misuse are found at the field level. Therefore, adequate evaluation of the water is essential as well as knowledge of the methods to obtain maximum crop production.

This paper has been prepared to enable the user to obtain maximum crop production from the water supply available. The objectives are:

1. To present practical GUIDELINES that will allow the man-in-the-field to evaluate the quality of a given water supply for agricultural use.

2. To present enough discussion of the potential soil and cropping problems that the effect of the water supply is understood.

3. To present management alternatives that can be expected to improve production of adapted crops with the water supply available.

The GUIDELINES presented are based upon a long line of preceding guidelines developed and used in California agriculture by the University of California Extension Service, Experiment Station and teaching staff. The format of a recent set of guidelines (1974) prepared by the University of California Committee of Consultants has been followed and much of the basic data from these 1974 U.C. guidelines has been included.

The authors would like to express their grateful appreciation to Dr. J.D. Rhoades (USDA Salinity Laboratory), Dr. R. Branson (University of California) and Drs. Massoud and Kadry, Messrs. Dieleman and Doorenbos (Land and Water Development Division, FAO) as well as others for their most helpful suggestions and draft review.

It has been recognized that there is a need to promote effective use of irrigation water and this paper attempts to take solution and prevention of water quality problems down to the farmer's field level. The ultimate goal is that of maximum food production from the available supply of water.

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SYMBOLS AND ABBREVIATIONS

EC	=	electrical conductivity in mmhos/cm, unless otherwise specified

mhos/cm	=	1 000 mmhos/cm
mmhos/cm	=	1 000 μmhos/cm
sieman/metre (S/m)	=	10 mmhos/cm
mS/cm	=	mmhos/cm
μS/cm	=	μmhos/cm

ECe	=	electrical conductivity of saturation paste
ECsw	=	electrical conductivity of soil water
ECw	=	electrical conductivity of irrigation water
ECdw	=	electrical conductivity of drainage water
TDS	=	total dissolved solids
mg/l	=	milligrams of solute per litre of solution
ppm	=	parts per million. mg/l $\cong$ ppm
meq/l	=	milliequivalents per litre
pH	=	log hydrogen ion concentration
pHc	=	a theoretical, calculated pH of the irrigation water in contact with lime and in equilibrium with soil CO_2
m	=	metre (cm = centimetre, mm = millimetres, μ = micrometre)
m3	=	cubic metres (cc = cubic centimetres)
SAR	=	sodium adsorption ratio
adj SAR	=	adjusted sodium adsorption ratio
ESP	=	exchangeable sodium percentage
RSC	=	residual sodium carbonate
OP	=	osmotic potential (bars)
LR	=	leaching requirement
LF	=	leaching fraction
ET	=	evapotranspiration
RH	=	relative humidity
Ddw	=	depth of drainage water
Dw	=	depth of irrigation water
eq.wt.	=	equivalent weight
t/ha	=	tons per hectare

CONVERSION FORMULAE

meq/l	$\cong$	10	x	EC	in millimhos/cm
OP	=	-0.36	x	EC	in millimhos/cm
mg/l	$\cong$	640	x	EC	in millimhos/cm
mg/l	=	eq.wt.	x	meq/l	

SUMMARY

A field guide is presented for evaluating the suitability of waters for irrigation and obtaining maximum use from the available water supply. GUIDELINE values are suggested which relate to the general irrigation problems of salinity, permeability and specific ion toxicity. Discussions and examples are given along with possible management alternatives to deal with these problems.

Salinity is discussed from the standpoint of a reduction in soil water availability to the crop. New findings on the plant's response to salinity within its root zone have been incorporated into the GUIDELINES to improve the predictive capability. Updated crop tolerance values have recently become available and have been expanded to include crop tolerance to salinity of various irrigation waters. A method is also presented for calculating the minimum leaching requirement for the various crops and water qualities. Values calculated by this procedure represent potential water savings over presently used values.

Soil permeability problems are associated with low salinity water or a high sodium water. An improved method is presented to predict the potential of a reduction in the rate of water penetration into and through the soil. The effects of excessive sodium, of high bicarbonate or carbonate, and of total salt load of the water are taken into consideration. The method used is a modification of the sodium adsorption ratio (SAR) concept.

Specific ion toxicity is related to the effects of boron, sodium and chloride on sensitive crops. Other minor problems are discussed such as bicarbonate deposits from overhead sprinkling and production problems from high nutrient water. Tables showing recommended maximum concentrations of trace elements for irrigation waters and for toxic substances in drinking water for livestock are also presented.

This paper is intended to provide guidance in on-farm water management problems so that an understanding of these constraints can assist in developing the criteria for irrigation project preliminary planning, operation of an irrigation project or perhaps in the improvement of existing irrigation schemes. The GUIDELINES presented are based on experience in areas other than a given project area, therefore caution and a critical attitude should be taken when applying these to local conditions. The guides indicate the potential of a water for irrigation but the true suitability of a given water depends on the management capability of the water user and on the specific conditions of use. The guides should be useful in placing the water quality effects in perspective with the other factors affecting crop production with the ultimate goal of obtaining maximum production per unit of available water supply.

PART I WATER QUALITY EVALUATION

1. INTRODUCTION

In determining water availability for irrigation, information is required on both the quantity and quality; however, the quality need has often been neglected. Quality should infer how well a water supply fulfills the needs of the intended user and must be evaluated on the basis of its suitability for the intended use.

If two different water supplies are available, one will usually produce better results or cause fewer problems than the other and is therefore considered more acceptable or of better quality. In the case of drinking water, people have always expressed a preference for one water supply over another. The better tasting one becomes the preferred water supply. This is a personal preference, but taste is a simple evaluation based on the relative acceptability for the intended use.

Specific uses will have different quality needs. For example, most river waters are of good quality for irrigation but may be unacceptable for municipal use without treatment. After chlorination, low salinity water is of excellent quality for municipal use but may be too corrosive for industrial use without further treatment. Such a low salinity water may also cause soil permeability problems in irrigated agriculture.

Experience in use will give rise to "degrees" of acceptability which allow an assessment of the suitability of various waters for a particular use. With sufficient reported experience, this knowledge can be organized into guidelines.

This procedure has been the basis for the many guidelines for irrigation water quality that have been proposed and used over the last forty years to evaluate the soil and cropping problems associated with certain constituents in the irrigation water. One set of guidelines has built upon the previous set and each new set has improved our predictive capability. A good review and evaluation of the types of guidelines previously used to evaluate water quality for agriculture is given in the FAO/Unesco International Sourcebook on Irrigation, Drainage and Salinity (1973).

2. EFFECT ON AGRICULTURE

Water used for irrigation always contains measurable quantities of dissolved substances which as a general collective term are called salts. These include relatively small but important amounts of dissolved solids originating from dissolution or weathering of the rocks and soil and dissolving of lime, gypsum and other salt sources as water passes over or percolates through them.

The suitability of a water for irrigation will be determined by the amount and kind of salts present. With poor water quality, various soil and cropping problems can be expected to develop. Special management practices may then be required to maintain full crop productivity. With good quality water there should be very infrequent or no problems affecting productivity.

The problems that result from using a poor quality water will vary both as to kind and degree but the most common ones are:

- Salinity: A salinity problem related to water quality occurs if the total quantity of salts in the irrigation water is high enough that salts accumulate in the crop root zone to the extent that yields are affected. If excessive quantities of soluble salts accumulate in the root zone, the crop has extra difficulty in extracting enough water from the salty soil solution. This reduced water uptake by the plant can result in slow or reduced growth and may also be shown by symptoms similar in appearance to those of drought such as early wilting. Some plants exhibit a bluish-green colour and heavier deposits of wax on the leaves. These effects of salinity may vary with the growth stage and in some cases may go entirely unnoticed due to a uniform reduction in yield or growth across an entire field. This mechanism of water uptake has been studied extensively and it now appears the plant takes most of its water from and responds more critically to salinity in the upper part of the root zone than to the salinity level in its lower depths when using normal irrigation practices (Bernstein and Francois, 1973). Thus, managing this critical upper root zone may be as important as providing adequate leaching to prevent salt accumulation in the total root zone.

- Permeability: A permeability problem related to water quality occurs when the rate of water infiltration into and through the soil is reduced by the effect of specific salts or lack of salts in the water to such an extent that the crop is not adequately supplied with water and yield is reduced. The poor soil permeability makes it more difficult to supply the crop with water and may greatly add to cropping difficulties through crusting of seed beds, waterlogging of surface soil and accompanying disease, salinity, weed, oxygen and nutritional problems. It is evaluated firstly, from total salts in the water since low salt water can result in poor soil permeability due to the tremendous capacity of pure water to dissolve and remove calcium and other solubles in the soil and, secondly, from a comparison of the relative content of sodium to calcium and magnesium in the water. Furthermore, carbonates and bicarbonates can also affect soil permeability and must be evaluated. The adverse influence of sodium on soil permeability has been recognized for many years. But in many cases the evaluation of the sodium influence alone has proven to be in error basically because the interaction of three factors determines a water's long term influence on soil permeability. These factors are 1) sodium content relative to calcium and magnesium; 2) bicarbonate and carbonate content, and 3) the total salt concentration of the water. A simultaneous analysis of these has been applied to soils before but only recently has been applied to estimating the permeability hazard of irrigation waters to soils (Rhoades 1972).

- Toxicity: A toxicity problem occurs when certain constituents in the water are taken up by the crop and accumulate in amounts that result in a reduced yield. This is usually related to one or more specific ions in the water namely boron, chloride and sodium.
- Miscellaneous: Various other problems related to irrigation water quality occur with sufficient frequency that they should be specifically noted. These include excessive vegetative growth, lodging and delayed crop maturity resulting from excessive nitrogen in the water supply, white deposits on fruit or leaves due to sprinkler irrigation with high bicarbonate water and suspected abnormalities indicated by an unusual pH of the water.

Water quality and drainage problems are very often interrelated and adequate control of a potentially damaging water table is recognized as an essential requirement to successful long term irrigated agriculture. Salts will accumulate in the upper portions of a water table and if water tables are as close as two metres from the soil surface they can become an important contributing source of additional salts in the crop root zone. When uncontrolled water tables exist within the two metre depth, salinity problems have occurred, even where irrigation water quality is good. With high water tables of poor quality, salts can be expected to accumulate rapidly in the crop root zone whereas with good quality groundwater they will still accumulate but at a much slower rate.

3. APPROACH TO EVALUATING QUALITY

Irrigation water quality refers to its suitability for use. A good quality water has the potential to allow maximum yield under good soil and water management practices. However, with poor quality water, soil and cropping problems can be expected to develop which will reduce yields unless special management practices are adopted to maintain or restore maximum production capability under the given set of conditions.

The suitability of a water, from a quality standpoint, is determined by its potential to cause problems and is related to the special management practices needed or the yield reduction caused. Solution in most cases is at the farm level, meaning the evaluation must be done in terms of the specific use and potential hazard to crop production under the existing management capability and farm situation.

In this paper, this type of problem solution approach has been taken. It evaluates the most common problems encountered and the steps necessary to maintain an acceptable level of agricultural production with the available water supply. Water quality problems though often complex, generally occur in the four general categories previously discussed: salinity, permeability, toxicity, and miscellaneous. Each may affect the crop singly or in a combination of two or more. Such a combination may be more difficult to solve and may affect crop production more severely than a single problem acting by itself.

If the problems do occur in combination, the solution is more easily evaluated and understood if considered on a one-problem-at-a-time basis. Therefore the GUIDELINES and discussion which follow will consider each problem and its solution separately. By this procedure, a number of factors can be evaluated for each of the problem areas, such as:

- the level of salts in the water that can be expected to cause a certain type of problem;
- the mechanism of soil-water-plant interactions that cause the loss in production;
- the severity of the problem that can be expected following long term use of the water;
- the management alternatives that are available to prevent, correct or delay the onset of the problem.

4. WATER QUALITY EVALUATION

The initial step in determining the suitability of a water supply for irrigation use is to compare the water's quality against reported experiences. This evaluation can be made on a problem-by-problem basis if certain broad assumptions are made about the average conditions of use. In this section, the GUIDELINES for such a preliminary comparative evaluation of the potential of a water are presented. However, it is not enough to point out the limitations of a water supply without also pointing out methods to overcome or live with these limitations. In subsequent sections, the management alternatives available to adjust to or correct the potential problem are discussed.

4.1 GUIDELINES for Interpretation of Water Quality for Irrigation

GUIDELINES to evaluate water quality for irrigation using the problem approach are given in Table 1. They are limited to the various aspects of irrigation water quality that are normally encountered and which materially affect crop production. Emphasis is on the long term dominating influence of the water's quality on the soil-water-plant system as it affects crop production and soil and water management. The four most common problem areas are considered.

These GUIDELINES are practical and usable in general irrigated agriculture for evaluation of the more common constituents in surface waters, underground waters, drainage waters and sewage effluents. They are not intended however to evaluate the more unusual or special constituents sometimes found in waste waters such as pesticides and trace metals. Values for trace metal concentrations in irrigation waters, however, are given in another section (section 10.1) along with salinity and trace element limitations for animal drinking water (section 10.2).

The GUIDELINES of Table 1 are based on certain assumptions which are given in the pages immediately following the table. These should be clearly understood.

To use the GUIDELINES, certain laboratory determinations and calculations are needed. The laboratory determinations needed along with a description of the symbols used in the GUIDELINES are given in Table 2. The adjusted sodium adsorption ratio (adj. SAR) should also be calculated from the laboratory determinations. The calculation procedure is given in Table 3.

Analytical procedures for the laboratory determinations are discussed in USDA Handbook 60 (1954), FAO Soils Bulletin 10 (Dewis and Freitas, 1970), and Standard Methods of the American Water Works Association (1971). These or other recognized procedures for analysis should be followed. It is also very important to obtain representative samples to ensure the usability of the determinations made. Precautions to be taken for sampling are briefly discussed in Appendix A.

4.2 Use of the GUIDELINES

In the preceding general discussion and GUIDELINES of Table 1, the basic information needed for a field evaluation of the suitability of a water for irrigation has been presented. This should allow a determination that water "A" having constituents "X, Y and Z" in concentrations shown by laboratory analysis does or does not have a potential to limit crop production. Where limitations are indicated, the water may still be usable providing certain management steps are taken to alleviate the problem. These various solutions are discussed in the subsequent sections and several examples are given in order to illustrate better how the GUIDELINES can be used.

The GUIDELINES of Table 1 are a management tool and, as with all laboratory methods and interpretative tools in agriculture, they are developed to help the trained field man or scientist to better understand, characterize, interpret and hopefully improve the soil or plant response under a given set of conditions. Therefore, the user must constantly guard against drawing unwarranted conclusions based strictly on laboratory results alone. Laboratory data must be adequately related to field conditions or confirmed and tested by field trials or experience. If used in this spirit and remembering the basic assumptions, the GUIDELINES should be a useful tool for the preliminary evaluation of the suitability of a water supply for irrigation.

TABLE 1 - GUIDELINES FOR INTERPRETATION OF WATER QUALITY FOR IRRIGATION

IRRIGATION PROBLEM	DEGREE OF PROBLEM: No Problem	Increasing Problem	Severe Problem
SALINITY (affects crop water availability)			
ECw (mmhos/cm)	< 0.75	0.75-3.0	>3.0
PERMEABILITY (affects infiltration rate into soil)			
ECw (mmhos/cm)	> 0.5	0.5-0.2	< 0.2
adj. SAR 1/ 2/			
Montmorillonite (2:1 crystal lattice)	< 6	6-9 3/	> 9
Illite-Vermiculite (2:1 crystal lattice)	< 8	8-16 3/	> 16
Kaolinite-sesquioxides (1:1 crystal lattice)	< 16	16-24 3/	> 24
SPECIFIC ION TOXICITY (affects sensitive crops)			
Sodium 4/ 5/ (adj. SAR)	< 3	3-9	> 9
Chloride 4/ 5/ (meq/l)	< 4	4-10	> 10
Boron (mg/l)	< 0.75	0.75-2.0	> 2.0
MISCELLANEOUS EFFECTS (affects susceptible crops)			
NO_3-N (or) NH_4-N (mg/l)	< 5	5-30	> 30
HCO_3 (meq/l) [overhead sprinkling]	<1.5	1.5-8.5	>8.5
pH	[Normal Range 6.5 - 8.4]		

1/ adj. SAR means adjusted Sodium Adsorption Ratio and can be calculated using the procedure given in Table 3.

2/ Values presented are for the dominant type of clay mineral in the soil since structural stability varies between the various clay types (Rallings, 1966, and Rhoades, 1975). Problems are less likely to develop if water salinity is high; more likely to develop if water salinity is low.

3/ Use the lower range if ECw < .4 mmhos/cm;
Use the intermediate range if ECw = 0.4 - 1.6 mmhos/cm;
Use upper limit if ECw > 1.6 mmhos/cm

4/ Most tree crops and woody ornamentals are sensitive to sodium and chloride (use values shown). Most annual crops are not sensitive (use the salinity tolerance tables [Table 5]).

5/ With sprinkler irrigation on sensitive crops, sodium or chloride in excess of 3 meq/l under certain conditions has resulted in excessive leaf absorption and crop damage.

< means less than

> means more than

4.3 Assumptions in the GUIDELINES

The water quality GUIDELINES presented in Table 1 are intended to cover a wide range of conditions in irrigated agriculture and incorporate the newer concepts in soil-water-plant relationships as recently developed. However, several basic assumptions must be made to better define the range of usability of these GUIDELINES. They may need adjustment or a new set prepared if the water is used under conditions which are greatly different from these stated conditions or assumptions. If the assumptions are understood, the GUIDELINES of Table 1 should be useful as a practical guide to evaluate the suitability of a water for irrigation. The basic assumptions in these GUIDELINES are:

- Use of Water : The soil texture is sandy loam to clay loam, with good internal drainage. The climate is semi-arid to arid where effective annual rainfall is low [1/]. These guides therefore may need adjustment for a monsoon climate or for areas where high precipitation occurs part of the year. Drainage is assumed to be good and no uncontrolled shallow water table is present. Full production capability of all crops is assumed when the GUIDELINES indicate water quality is not a problem. The existence of a potential problem indicates the use of certain tolerant crops may be necessary to maintain full production capability and does not indicate the water is unsuitable for use on any crop.
- Methods and Timing of Irrigations : Surface and sprinkler methods of irrigation are assumed, including flood, basin, strip-check, furrow, corrugations and sprinklers, or any other which applies water on an "as needed" basis. This assumes that the crop utilizes a considerable portion of the stored soil water before the next irrigation. With these irrigation methods about 15% of the applied water is assumed to percolate below the rooting depth. The GUIDELINES are believed to be too restrictive for drip (trickle) irrigation and high frequency (near daily) sprinkler irrigation. They may need to be modified for subsurface irrigation.
- Uptake of Water by Crops : Uptake of water by the crop takes place from wherever water is most readily available in the rooting depth. This is normally about 40% from the upper one-quarter of the root zone, 30% from the second quarter, 20% from the third quarter, and 10% from the lowest quarter. Each irrigation will leach the upper soil area and maintain it at a relatively low salinity. Salinity will usually increase with depth and be greatest at the lower part of the rooting area. The average salt

1/ Effective rainfall is the amount of precipitation that is useful in meeting the crop water demand or the leaching requirement.

concentration of the soil solution of the rooting depth is assumed to be three times the concentration of the salts in the applied water and is believed to be representative of the salinity to which the crop responds. This corresponds to a leaching fraction of 16% on the basis of the 40-30-20-10% uptake of water by the crop and average root zone salinity.

The leached salts will be removed from the upper root zone and may accumulate to some extent in the lower root zone. Thus the salinity of the lower root zone is considered to be of less importance as long as the crop is relatively well supplied with moisture in the upper, "more active", root zone. The leaching requirement will control salts in this lower root zone.

- Degree of Problem : The division of Table 1 into "No Problem", "Increasing Problem" and "Severe Problem" is somewhat arbitrary since changes occur gradually and there is no clear-cut breaking point. Changes of 10 to 20% above or below the GUIDELINE values may have little significance if considered in proper perspective with other factors affecting yield. Many field studies and observations, as well as carefully controlled research experiments were used as a basis for this division. The divisions have proven to be practical under production agriculture conditions.

  Ordinarily no soil or cropping problem due to water quality would be experienced or recognized when using water containing less than the values shown for "No Problem" in Table 1. On the other hand, if water is used which equals or exceeds the values shown for the "Severe Problem", the water user would commonly experience soil or cropping problems associated with using this poor quality water. With water quality values between these guides, a gradually "Increasing Problem" should be experienced as the water quality deteriorates.

Large deviations from these assumptions might make it unsafe to use water which would otherwise be considered safe, or conversely, make it safe to use water which, under the assumed conditions, would be considered hazardous or of doubtful quality. Where sufficient experience, field trials, research or observations are available, the GUIDELINES can be modified to fit more closely to local conditions. Specific conditions that may modify these values include the leaching fraction, the conditions of drainage, method of irrigation, the climate and rainfall, physical soil conditions, tolerance to salinity of crops grown, and the chemical properties of the soil.

TABLE 2 - LABORATORY DETERMINATIONS NEEDED TO EVALUATE WATER QUALITY

Laboratory Determination	Reporting Symbol	Reporting Units 1/	Equivalent Weight
Electrical conductivity	ECw	mmhos/cm	-
Calcium	Ca	meq/l	20
Magnesium	Mg	meq/l	12.2
Sodium	Na	meq/l	23
Carbonate	CO_3	meq/l	30
Bicarbonate	HCO_3	meq/l	61
Chloride	Cl	meq/l	35.4
Sulphate	SO_4	meq/l	48
Boron	B	mg/l	-
Nitrate-Nitrogen 2/	NO_3-N	mg/l	14
Acidity-Alkalinity	pH	pH 3/	-
Adjusted Sodium Adsorption Ratio	adj. SAR 4/	-	-
Potassium 5/	K	meq/l	39.1
Lithium 5/	Li	mg/l	7
Iron 5/	Fe	mg/l	-
Ammonium-Nitrogen 2/ 5/	NH_4-N	mg/l	14
Phosphate Phosphorous 5/	PO_4-P	mg/l	31

1/ mmhos/cm = millimhos/cm at 25°C; (mmhos/cm x 640 ≅ mg/l)
meq/l = milliequivalents per litre;
mg/l = milligrams per litre

2/ NO_3-N means nitrogen in the form of NO_3 while NH_4-N means nitrogen in the form NH_4 reported as N in mg/l.

3/ Acidity (pH 1-7)
Alkalinity (pH 7-14)
Neutral (pH 7.0)

4/ Calculation procedures given in Table 3.

5/ Special situations only.

TABLE 3 - CALCULATION OF adj.SAR

The adjusted Sodium Adsorption Ratio (adj. SAR) is calculated from the following equation 1/ 2/ :

$$\text{adj.SAR} = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \left[1 + (8.4 - pHc) \right]$$

where Na, Ca and Mg are in meq/l from the water analysis and pHc is calculated using the tables given below which relate to the concentration values from the water analysis. The table values are then substituted in the pHc equation:

$$pHc = (pK'_2 - pK'c) + p(Ca+Mg) + p(Alk)$$

------Tables for calculating pHc --

$(pK'_2 - pK'c)$ is obtained from using the sum of Ca + Mg + Na in meq/l
p(Ca+Mg) is obtained from using the sum of Ca + Mg in meq/l
p(Alk) is obtained from using the sum of $CO_3 + HCO_3$ in meq/l
} Obtained from water analysis

Sum of Concentration (meq/l)	$pK'_2 - pK'c$	p(Ca+Mg)	p(Alk)
.05	2.0	4.6	4.3
.10	2.0	4.3	4.0
.15	2.0	4.1	3.8
.20	2.0	4.0	3.7
.25	2.0	3.9	3.6
.30	2.0	3.8	3.5
.40	2.0	3.7	3.4
.50	2.1	3.6	3.3
.75	2.1	3.4	3.1
1.00	2.1	3.3	3.0
1.25	2.1	3.2	2.9
1.5	2.1	3.1	2.8
2.0	2.2	3.0	2.7
2.5	2.2	2.9	2.6
3.0	2.2	2.8	2.5
4.0	2.2	2.7	2.4
5.0	2.2	2.6	2.3
6.0	2.2	2.5	2.2
8.0	2.3	2.4	2.1
10.0	2.3	2.3	2.0
12.5	2.3	2.2	1.9
15.0	2.3	2.1	1.8
20.0	2.4	2.0	1.7
30.0	2.4	1.8	1.5
50.0	2.5	1.6	1.3
80.0	2.5	1.4	1.1

1/ A nomogram for determining $Na/\sqrt{\frac{Ca + Mg}{2}}$ is presented in Appendix B.

2/ pHc is a theoretical, calculated pH of the irrigation water in contact with lime and in equilibrium with soil CO_2.

TABLE 3 - continued

Example pHc calculation:

Given:

Ca = 2.32 meq/l
Mg = 1.44 "
Na = 7.73 "

Sum = 11.49 meq/l

CO_3 = 0.42 meq/l
HCO_3 = 3.66 meq/l

Sum = 4.08 meq/l

From Tables and using the equation for pHc:

$pK'_2 - pK'c = 2.3$
p (Ca+Mg) = 2.7
p(Alk) = 2.4

pHc = 7.4

Substituting

$$\text{adj. SAR} = \frac{7.73}{\sqrt{\frac{3.76}{2}}} \left[1 + (8.4 - 7.4)\right]$$

$$\text{adj. SAR} = 5.64\,(2.0) = 11.3$$

NOTE: Values of pHc above 8.4 indicate a tendency to dissolve lime from the soil through which the water moves; values below 8.4 indicate a tendency to precipitate lime from the water applied.

(Ref. L.V. Wilcox, U.S. Salinity Laboratory, Mimeo Dec. 30, 1966 and Rhoades, 1972).

PART II PROBLEM SOLUTION

5. PROBLEM CONSIDERATION

The preceding brief discussion and Tables 1 - 3 have presented the basic tools for evaluating the suitability of a water for irrigation. If a potential problem is predicted practices may need to be adopted that will delay, correct or prevent its occurrence. Evaluating the management alternatives available to control the potential problem is therefore the second step in gaining maximum utilization of a given water supply. In the following sections each of the four problem areas shown in Table 1 will be reviewed, first as to its general cause, second, as to how the GUIDELINES are used to predict a potential problem (with examples) and, third, as to what management alternatives are available to help correct or prevent the occurrence.

Throughout these sections examples will be given to illustrate better how the GUIDELINES can be used. Three water analyses will be used to illustrate the individual steps necessary to complete an evaluation. The examples include water from the Tigris River at Baghdad, Iraq, (Hanna, 1970), from Tubewell 116 at Mona project, Pakistan (WAPDA, 1974) and from the Pecos River at Carlsbad, New Mexico, USA, (USDA, 1954). The water analyses are given in Table 4 with footnotes describing the conditions of use. Although these three water analyses are not complete they are probably adequate if it is known that the water concentrations of boron and nitrate or ammonium-nitrogen are not sufficiently high to be a problem to irrigated agriculture.

TABLE 4 - WATER ANALYSES OF THREE TYPICAL IRRIGATION SUPPLIES

Irrigation Water	Location	Date Sampled	ECw mmhos/cm	Milliequivalents per litre									Milligrams per litre			pH	adj. SAR
				Na	Ca	Mg	Sum Cations	Cl	SO_4	CO_3	HCO_3	Sum Anions	B	NO_3-N	NH_4-N		
Tigris 1/ River	Baghdad Iraq	1966-1969 (Ave)	0.51	1.4	2.6	2.2	6.2	1.5	1.6	0.3	2.6	6.0	*	1.8	*	7.8	2.5
Tubewell 116 2/	Mona Project Pakistan	7.12.1968	3.60	32.0	2.5	4.0	38.5	25.0	8.9	0	4.5	38.4	*	*	*	7.7	38
Pecos 3/ River	Carlsbad New Mexico USA	1946	3.21	11.5	17.3	9.2	38.0	12.0	23.1	0	3.2	38.3	*	*	*	*	8.6

* Not determined.

1/ Planned use of the Tigris River water is for basin irrigation of tomatoes and cotton on a loam soil under low rainfall (< 100 mm) and high evaporative conditions. Soil internal drainage is good, water table is deeper than 2 metres and adequate water is available for leaching. The soils are nonsaline-nonalkali. The dominant clay mineral is montmorillonite.

2/ Planned use of Tubewell 116 water is for basin irrigation of cotton and wheat on a loam soil under low rainfall and high evaporative conditions throughout most of the crop growing season although monsoon type rains may occur during summer. Soil internal drainage is good, water table is controlled below 2 metres and adequate water is available for leaching. These soils are nonsaline-nonalkali with illite clay dominating.

3/ Planned use of the Pecos River water is for furrow irrigation of cotton and basin irrigation of alfalfa on a loam to clay loam soil under low rainfall (< 100 mm) and high evaporative conditions. The growing season is about 170 days and infrequent but heavy thunderstorms may occur during the summer. Soil internal drainage is adequate but in some locations is slow, water table is deeper than 2 metres and adequate water is available for leaching. The soils are nonsaline with montmorillonite clay dominating.

6. SALINITY PROBLEM DISCUSSION

6.1 The Salinity Problem

A salinity problem due to water quality occurs if salts from the applied irrigation water accumulate in the crop root zone and yields are affected. The potential salinity problem caused by these salts in the irrigation water is evaluated by the GUIDELINES of Table 1.

With shallow water tables, a salinity problem may also exist due to upward movement of water and salts from the ground water as the water evaporates from the soil or is used by the crop. Such a salinity problem is related to high water tables and the lack of drainage; it is only indirectly related to salts in the irrigation water. Such a salinity problem is not included within the evaluation of the GUIDELINES. However, once the drainage problem is solved and the shallow water table stabilized, the GUIDELINES will apply.

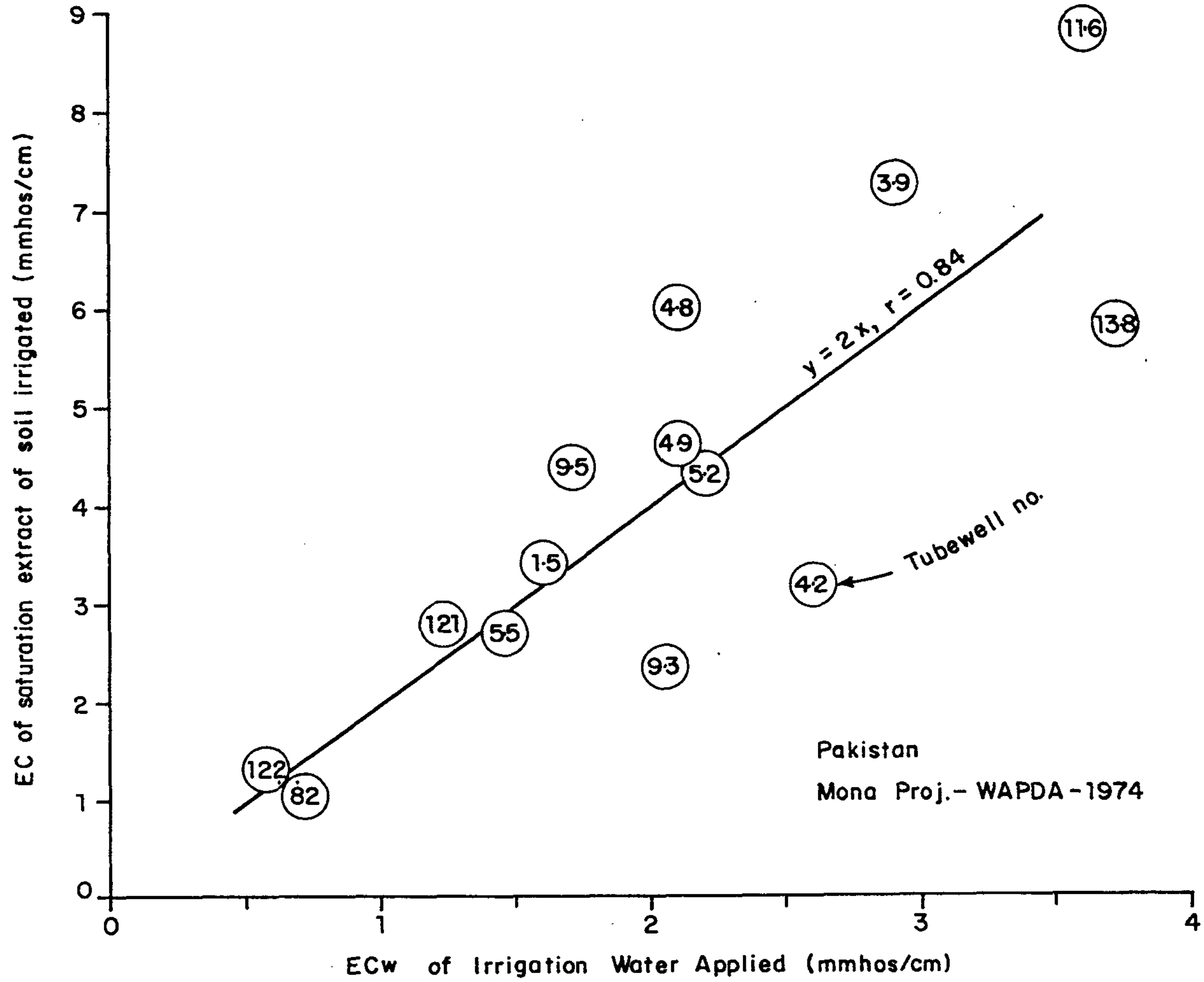
Most of the salts added with the irrigation water are left behind in the soil as water is removed by the crop. These may accumulate and reduce the availability of soil water to the crop. To avoid salt accumulation to an excess level, they must be removed in amounts about equal to the salts applied (salt balance concept). To dissolve and remove the salts adequate water must be applied to allow percolation through the entire root zone (leaching). This can be done at each irrigation but needs to be done only after the salts have accumulated to near damaging concentrations. Winter rainfall or inefficiencies of irrigation may accomplish this in some cases. The amount of leaching is referred to as the leaching fraction (LF) and is defined as the fraction of the water entering the soil that passes beyond the root zone.

If by leaching a long term salt balance is achieved, the average soil salinity of the root zone will be closely associated with the quality of the irrigation water applied as well as with the fraction of water moving through the root zone. The crop primarily responds to this average salinity and any increase in water salinity will result in an increase in average soil salinity as shown in Fig. 1. Such an increase may have little practical significance, unless the salt content rises sufficiently to affect the crop yield.

The GUIDELINES of Table 1 assume the average salinity of the soil water is about three times the salinity of the irrigation water and a LF of at least 15% is accomplished. This salinity, however, will vary with depth. The upper root zone will contain less salinity than the lower parts since more water percolates through the upper root zone than the lower. Salts will normally be leached out of this upper root zone but accumulate to higher concentrations in the lower rooting zone. The extent of this accumulation will depend upon the leaching that takes place.

If the water management, as locally applied, accomplishes more leaching than the GUIDELINES have assumed, salts will not accumulate to as great an extent, and slightly higher salinity in the irrigation water could be tolerated. If leaching is less, salts will

Fig. 1. INFLUENCE OF ECw OF IRRIGATION WATER UPON SOIL SATURATION EXTRACT (ECe) -3 YEARS CROPPING



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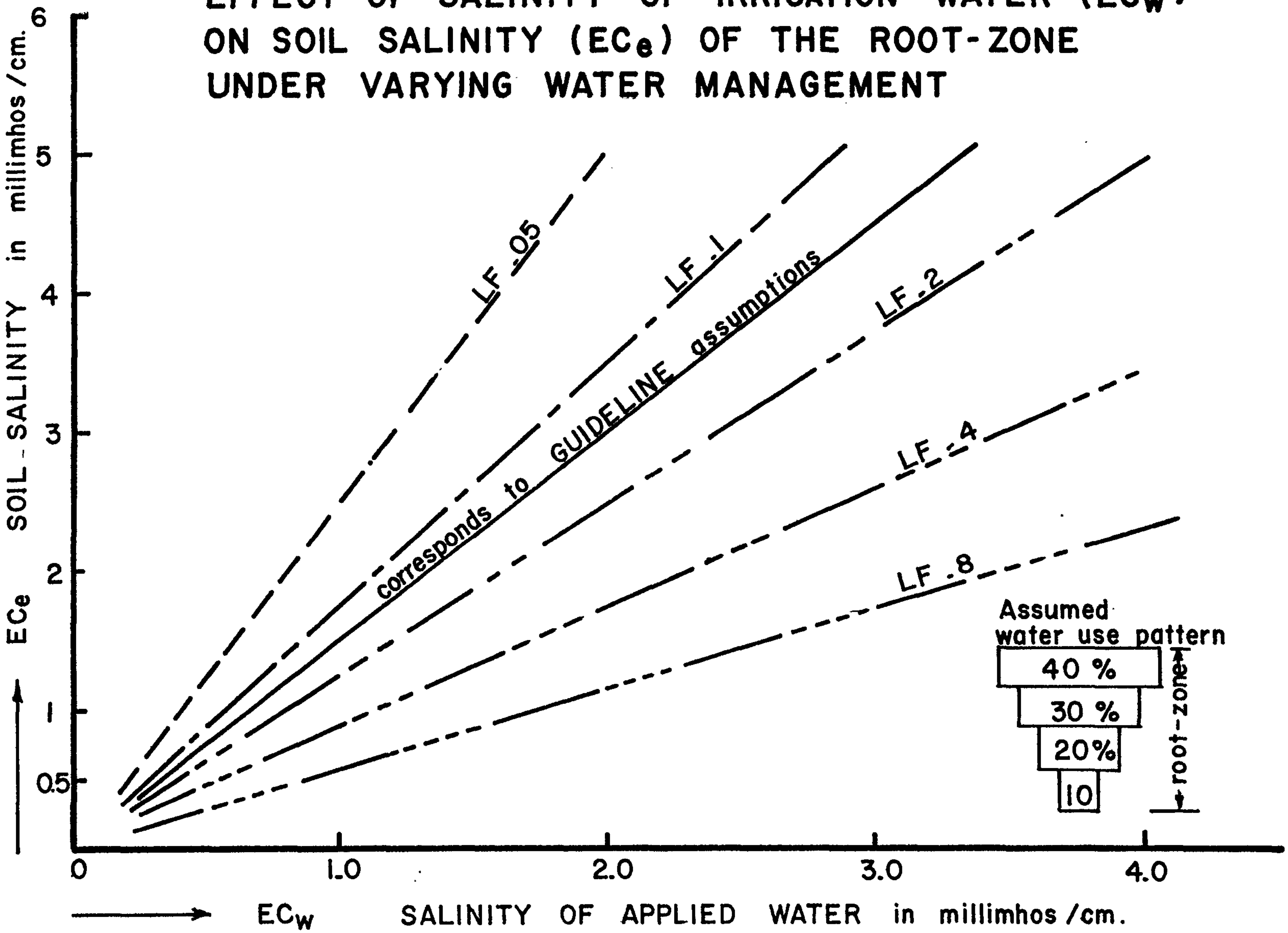
accumulate to a greater extent and salinity problems and yield reductions may be experienced at lower water salinity (ECw) than the GUIDELINES of Table 1 indicate. These comparisons are illustrated in Fig. 2 which shows the mean soil salinity (ECe) that is expected to develop due to salinity of the irrigation water (ECw) with various leaching fractions. The GUIDELINES of Table 1 assume 3ECw = ECsw, 1.5 ECw = ECe and 2 ECe = ECsw where ECw, ECe, ECsw are the electrical conductivity of the water, saturation extract of the soil, and soil water, respectively in mmhos/cm.

Fig. 2

EFFECT OF SALINITY OF IRRIGATION WATER (EC_w) ON SOIL SALINITY (EC_e) OF THE ROOT-ZONE UNDER VARYING WATER MANAGEMENT



If the leaching fraction or normal salt accumulation for the quality of water applied is known, a changed or new set of GUIDELINES could be prepared that would more closely fit local conditions of management and expected yield responses. This will be discussed further under management alternatives (Section 6.4). A few general soil-plant-water relationships are discussed in the following section to better understand water use by the crop and how this relates to the importance of salt control in irrigation agriculture.[1/]

6.2 Effects of Soil Salinity on Crop Yields.

A growing crop has a basic demand for water to produce the maximum yield. This is called evapotranspiration (ET) and includes water evaporating from the soil (evaporation) and water used by the crop (transpiration). ET for different crops and growth stages is primarily related to climate (day length, temperature, humidity, wind and radiation) but can be modified by salinity and the amount of soil water available.

Available soil water can be expressed in terms of soil water potential which is a measure of the force with which the water is held by the soil and the force the plant must overcome to obtain the water. Salinity also has an effect on soil water availability, decreasing its availability to the crop in proportion to its salinity. This is called the osmotic effect and can be measured as a force the plant must overcome (osmotic potential) [2/].

1/ A complete discussion on soil water storage and availability is given in Doneen 1971. Procedures to determine crop water requirements under varying conditions are covered in Doorenbos and Pruitt, 1975.

2/ The concept of osmotic potential due to salinity is the usual explanation for the decrease in the water availability to the crop from a salty soil solution. Several references have been written on the physiology of plant growth on salt affected soils and can be consulted for more detail on the subject (Bernstein and Hayward, 1958), (Hayward and Bernstein, 1958), (Poljakoff-Mayber and Gale, Editors, 1975). It is generally recommended (USDA, 1954) that osmotic potential be measured by its relationship to the salinity of the solution by using:

$$OP \cong -0.36 \times EC$$

where:

OP = osmotic potential in bars

EC = electrical conductivity of the solution in mmhos/cm (whether ECe, ECsw or ECw)

-0.36 = conversion factor (the negative indicates that the force acts in the the direction of decreasing potential.)

If two identical soils are at the same degree of wetness (soil water potential), but one is salt free and the other is salty, the crop will be able to extract and use more water from the salt free soil than from the salty soil. The reasons for this are not easily explained but the effect can be illustrated by looking at the properties of a salty solution. Salts in general seem to have an affinity for water which can be shown by two properties of a salty solution: a higher boiling and lower freezing point than pure water. This shows that additional energy must be expended to make steam or ice from a salty solution. It seems reasonable then to expect that additional energy must be expended by the plant if relatively salt free water is to be taken from the salty solution.

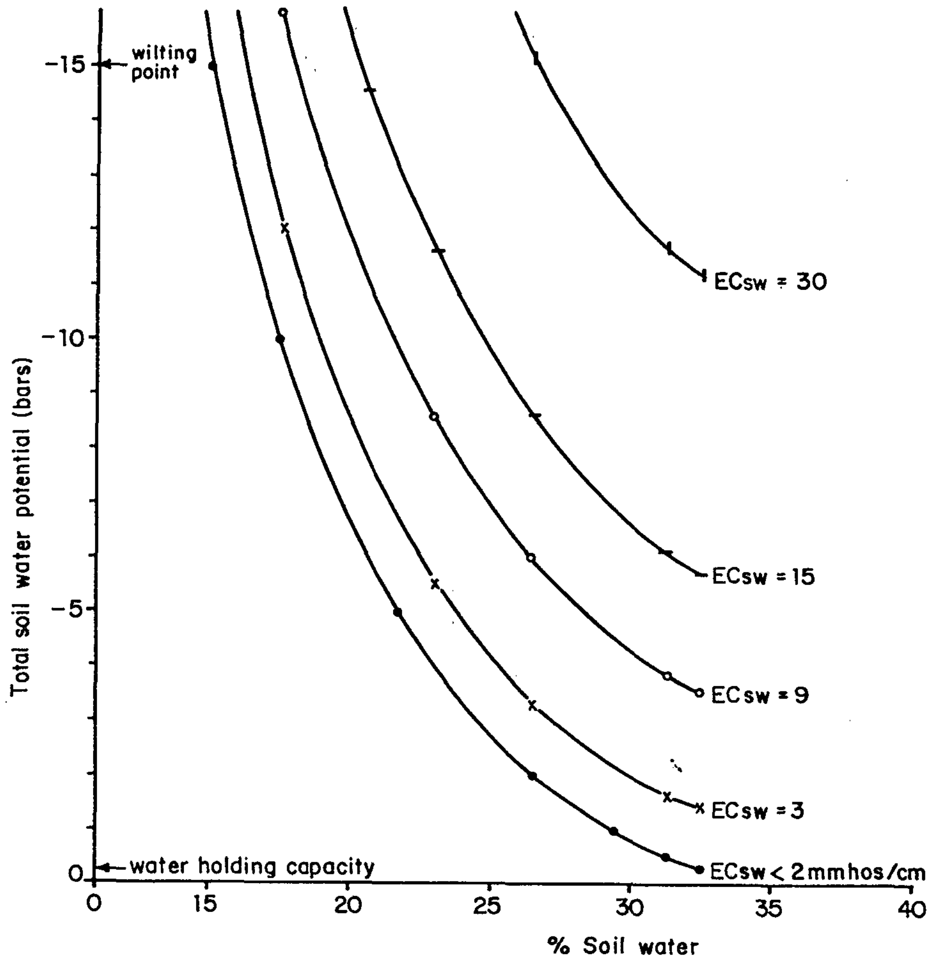
To withdraw water from a salty solution, the plant must not only overcome the soil water potential but also the osmotic potential due to the salts. For all practical purposes, the two potentials can be considered to be additive to determine the total potential against which the plant must work to draw water. This additive effect is illustrated schematically in Fig. 3 for the entire range of soil water availability[1/]. For example, using Fig. 3, a soil having an available water holding capacity of 16.5 cm of water per metre soil depth and an average soil salinity of EC_{sw}= 3 mmhos/cm, has the available soil water reduced to 12 cm when the average soil salinity is increased to EC_{sw} = 15 mmhos/cm and reduced to 6 cm per metre of soil depth when EC_{sw} = 30 mmhos/cm. In this theoretical example, if the crop has a constant ET demand of 6 mm/day, there is a 27 1/2 days supply of soil water at EC_{sw} = 3 mmhos/cm, 20 days supply at EC_{sw} = 15 mmhos/cm and a 10 days supply at EC_{sw} = 30 mmhos/cm. This illustrates why the common practice of irrigating more often when using saline water is needed.

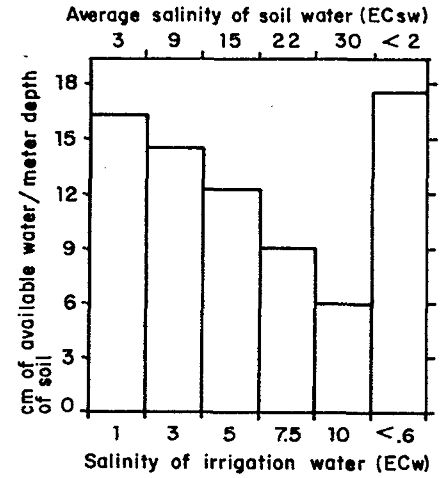
Since salinity (osmotic potential) and soil water (soil water potential) in the root zone are not uniform throughout, the plant roots are exposed to various levels of water availability due to differences in total potential. The plant will integrate the different total potentials throughout the root zone and obtain water from the zone where it is most readily available. This is generally the upper part of the root zone where the osmotic effects will be the least.

The soil salinity found in various parts of the root zone does not remain constant. Due to water use by the crop and evaporation from the soil surface, the salts are left behind in a shrinking volume of soil water.

1/ The values presented in Fig. 3 are theoretical as irrigations normally occur before the total available water is used. Although they may not be applied directly to field conditions, they do present the basic principles behind a reduction in soil water availability due to salinity and are in reasonably good agreement with field observations and experience.

Fig. 3. THEORETICAL AVAILABLE SOIL WATER AS INFLUENCED BY AVERAGE SOIL WATER SALINITY (ECsw) FOR A CLAY LOAM SOIL.



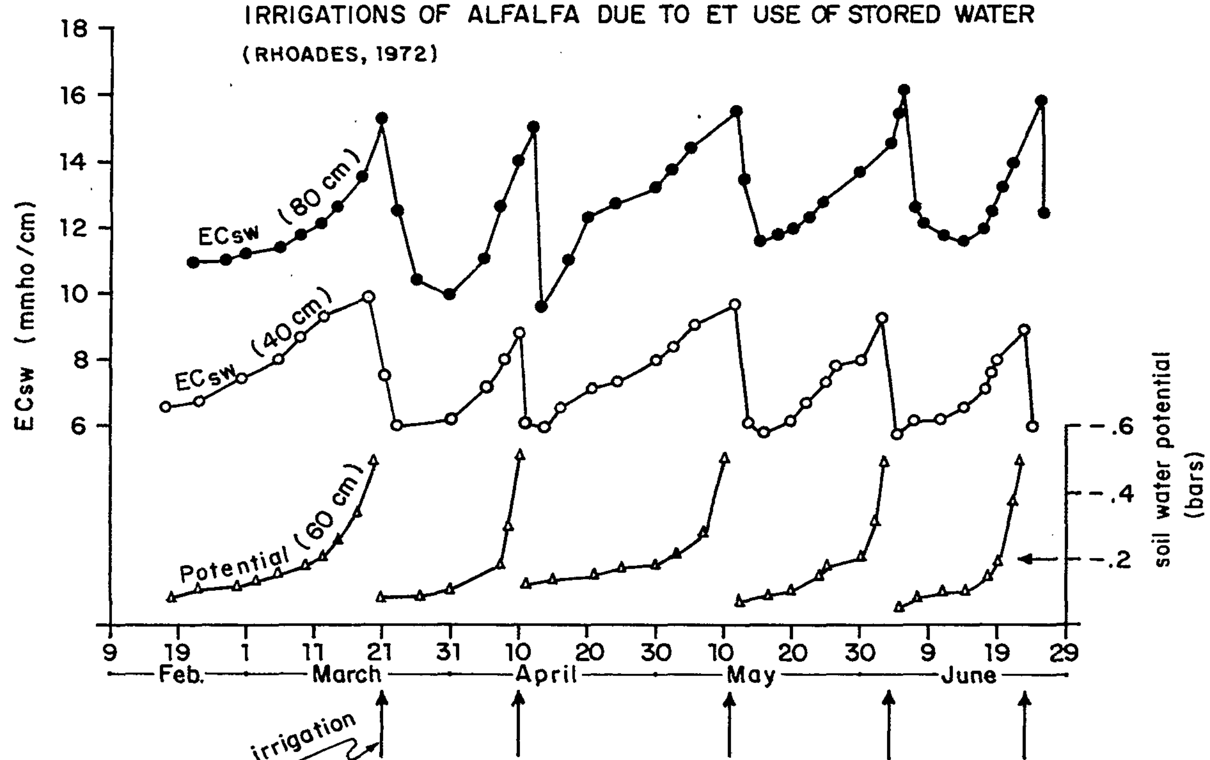


Assumptions:

1. Salinity in irrigation water x 3 = salinity of soil water
2. No removals or additions of salts from the soil water
3. Soil water depletion effects and salinity effects on water availability are additive (EC x.36 = osmotic pressure)
4. Available soil water is difference between % soil water at water holding capacity and at wilting point
5. Evapotranspiration (ET) by the crop is removing water from the soil

Thus, as the available soil water decreases, the water deficit and osmotic effects become greater during this dry-down period. The resulting increase in salt concentration can add appreciably to the severity of the salinity problem. This is illustrated in Fig. 4. It is shown at the 40 and 80 cm depth that immediately following an irrigation, soil water content is at a maximum and the concentration of dissolved salts is at a minimum, but each changes as water is consumed by the crop. This may become very important during periods of high ET demand when water movement toward the roots is not fast enough to dilute the salt concentration around the root and also supply the crop with adequate water. Thus the plant roots, at high ET demand, may be exposed to a much higher salt concentration than shown in Fig. 4, as anticipated from an analysis of a bulk soil sample (Sinha and Singh, 1976). If the rising water deficit and increasing salt (osmotic effect) reduce water availability to the crop sufficiently to result in a shortage of water for significant periods of time, reduced yields may be expected. Therefore managing both water supply and salinity, whether alone or in combination, to give the highest soil water availability to the crop seems to be the only effective way to manage a root zone salinity problem. Various management steps can be used to do this and these will be discussed in the subsequent sections.

Fig. 4. CHANGE IN SALINITY OF SOIL WATER (ECsw) BETWEEN IRRIGATIONS OF ALFALFA DUE TO ET USE OF STORED WATER (RHOADES, 1972)



6.3 Salinity Problem Evaluation

The presence or absence of a potential salinity problem is evaluated from the electrical conductivity of the irrigation water (ECw) as reported in the water analysis. ECw is reported in millimhos per centimetre (mmhos/cm) and by itself is usually an adequate measure of the potential salinity problem.

There have been various attempts to improve the ECw evaluation since some waters are relatively high in their content of dissolved lime (calcium carbonate and bicarbonate) or of gypsum (calcium sulphate). These waters may not contribute as greatly to a soil salinity problem as would waters of equal salinity but low in dissolved lime or gypsum. This reduced salinity effect is usually explained as being due to the low solubility of lime and gypsum. If these types of salts start to accumulate in the soil, their solubilities are soon exceeded and they begin to precipitate. This removes them from the soil water and they are no longer part of the overall soil salinity.

Recent computer procedures for evaluating the relative salt effects of these "unusual waters" (high calcium, high sulphate, high bicarbonate) indicate that the potential salinity problem may be discounted by 10 - 30% at leaching fractions in the efficient range of irrigation practice (10 - 20% leaching) and much less under less efficient irrigation.

On this basis, there seems no great need to quantitatively discount the salinity effects due to high gypsum or bicarbonate waters, particularly in view of the probable zone in which the precipitation would take place - the lower root zone - where changes in salinity are less important to crop performance.

A modest discounting of the potential salinity effect by as much as 20% seems reasonable for waters which are high in calcium and magnesium (20 to 30 meq/l), and are also accompanied by high bicarbonate and sulphate.

The use of the GUIDELINES of Table 1 for a water salinity evaluation can be illustrated by the three examples of waters given in Table 4:

Tigris River at Baghdad, Iraq

The ECw = 0.51 mmhos/cm is less than the GUIDELINE value for "No Problem". No salinity problems are to be expected. This assumes the application of sufficient water to supply both the crop ET demand and the leaching requirement and the absence of an uncontrolled shallow water table. Other assumptions of the GUIDELINES also apply.

Tubewell 116, Mona Project, Pakistan and Pecos River at Carlsbad, New Mexico, U.S.A.

The ECw = 3.6 mmhos/cm and ECw = 3.21 mmhos/cm are in the "Severe Problem" range of the GUIDELINES. Production of many crops might be severely affected due to use of this water but satisfactory production of many tolerant crops might still be possible if certain corrective practices were adopted. The use of such water may be entirely feasible particularly on light (sandy) soils. Such waters may be considerably better than "no water" and under many conditions might be usable. These two waters are both now being used successfully to produce good yields of salt tolerant crops.

If a potential salinity problem is indicated by the GUIDELINES, the water user may find that he can adopt certain management procedures or practices that may help to prevent the problem, delay its on-set, or correct it after the problem develops. Several of the management alternatives are discussed in the next section.

6.4 Management Alternatives for Salinity Problems

The major objective in choosing a management procedure to overcome a salinity problem is to improve soil water availability to the crop. Some of the management practices include:

- irrigate more frequently to maintain a more adequate soil water supply to the crop;
- plant crops that are tolerant of an existing or potential salinity problem;

- routinely use extra water to satisfy the leaching requirement;
- change method of irrigation to one that will give better salt control;
- change cultural practices.

More drastic practices to improve or restore productivity of a salt-affected soil might include:

- leach as needed to reduce concentration of accumulated salts;
- improve the uniformity of slope or level of land to allow for more uniform water application;
- modify soil profile to improve downward water percolation;
- establish artificial drainage if water tables are a problem;
- change water supply.

6.4.1 Irrigate More Frequently

As shown in Fig. 4, soil water salinity continually changes following an irrigation. More frequent irrigations could maintain better water availability in the upper part of the root zone. With each irrigation, this upper area is more thoroughly leached than the lower root zone, thus reducing the osmotic effects. However, with more frequent irrigations the average soil wetness would also be increased.

If it is possible to take water "on demand" or as needed, the frequency of irrigation can be adjusted to meet seasonal crop demands. A good knowledge of the crop needs is necessary to determine proper irrigation frequency. Several aids are available to decide crop needs and include such methods as 1) crop appearance, 2) field soil water content as determined by "feel", appearance or weight, 3) soil water sensing instruments such as tensiometers or gypsum (Bouyoucos) blocks on nonsaline soils, or 4) use of daily evapotranspiration data calculated from weather data. These methods are explained in more detail elsewhere (Doneen 1971, Doorenbos and Pruitt 1975).

If water is taken or supplied on a "rotational basis" (fixed interval) increasing the frequency of irrigation may not be possible and other practices will need to be considered.

There are often other effects that accompany a change in irrigation practices. For example, a change to more frequent irrigations may result in an unacceptably high water use. With a very efficient method of irrigation, irrigating more frequently may not greatly increase water use. However, where the irrigation method is less efficient, and cannot easily be adjusted as to depth of water applied per irrigation, more frequent irrigations almost invariably result in appreciable increases in water use.

6.4.2 Crop Selection

There is an approximate 10-fold range in salt tolerance of agricultural crops. This wide choice of crops greatly expands the usable range of water salinity for irrigation and emphasizes the fact that quality is specific for the intended use. For example, a water of ECw = 2.0, unsuited to production of a salt sensitive crop, such as field beans, may be of acceptable quality for field corn, cotton, or sugar beets. Field beans could be grown, however, but yield may be reduced to about 50% of "normal". More tolerant crops may show no reduction in yield.

If a potential salinity problem is indicated by the GUIDELINES, suitable crops can often be selected that are tolerant to the expected salinity. Crop tolerance tables for representative field, forage, vegetable and tree crops are given in Table 5. These incorporate older data from the crop tolerance tables of the U.S. Salintiy Laboratory (USDA, 1954), data of Bernstein (1964), and from the University of California Committee of Consultants (1974) but have recently been updated based on data of Maas and Hoffman (in press).

The tables now include the expected yield reductions of 0, 10, 25 or 50% due to effects of either increasing soil salinity (ECe) or to comparable increases in irrigation water salinity (ECw). The conversion from the soil salinity (ECe) to comparable water salinity assumes that the salinity of the irrigation water will concentrate three times in becoming soil water (ECw x 3 = ECsw) and that the soil salinity (ECe) reported as a saturation extract is one-half the salinity of the soil water (ECsw x 0.5 = ECe).

The tables also include the suggested maximum ECe at which reduction in yield would be 100% (if the entire root zone were at this salinity, the crop could not extract water and growth would stop). The maximum ECe value is obtained by extrapolating the decrease from the 0-10-25-50% yield reduction values to 100% as shown in Fig. 5 (five representative crops).

Maas and Hoffman (in press) indicate that each increase in soil salinity (ECe) in excess of the concentrations that initially begin to affect yield will cause a proportionate decrease in yield as shown in Fig. 5. They have proposed the following equation to express this straight line effect:

$$Y = 100 - b\,(ECe - a)$$

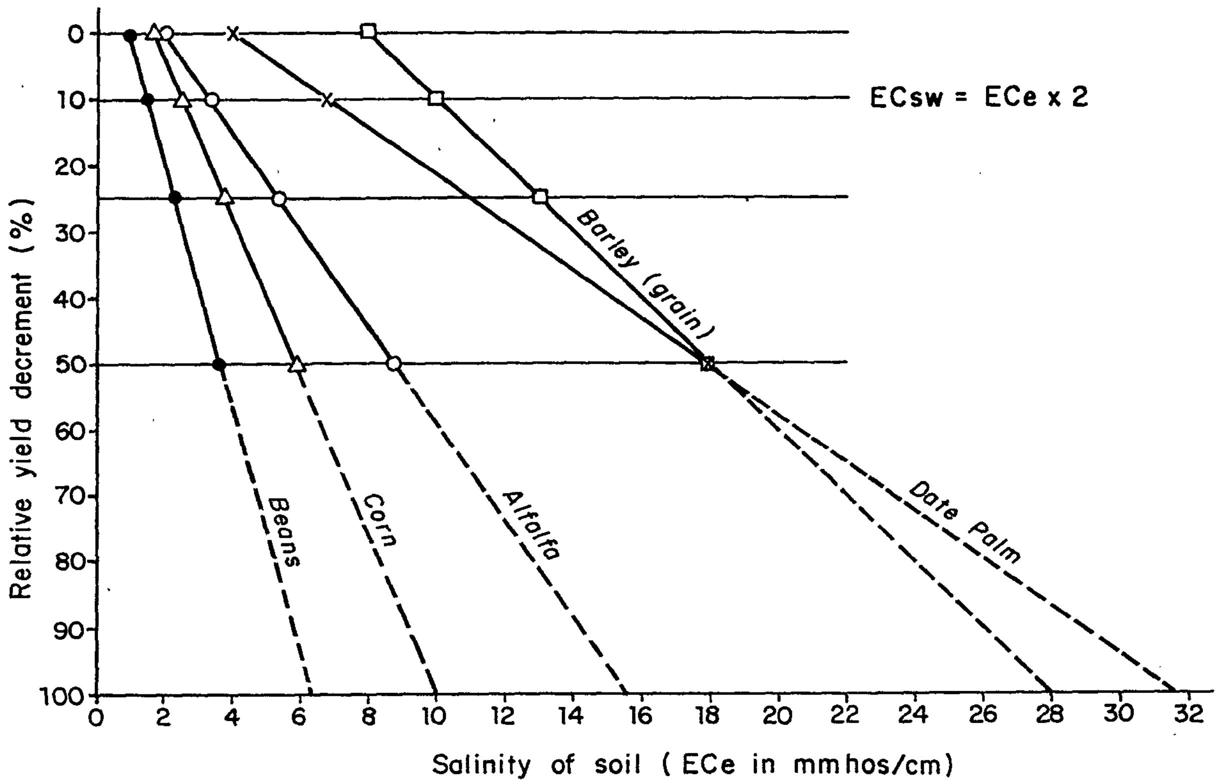
where Y = relative crop yield in %

ECe = salinity of the soil saturation extract (mmhos/cm)

a = salinity threshold value for the crop representing the maximum ECe at which a 100% yield can be obtained (mmhos/cm)

b = yield decrement per unit of salinity, or percent yield loss per unit of salinity (ECe) between the threshold value (a) and the ECe value representing the 100% yield decrement.

Fig. 5 METHOD OF DETERMINING MAXIMUM ECe



The crop tolerance tables (Table 5) were prepared using this formula when values were available. A few of the crops listed came from the other sources listed. The conversion from soil salinity (ECe) to comparable water salinity (ECw) assumes a leaching fraction in the range of 15-20%. Other important assumptions in the tolerance tables are that yields are closely related to the average salinity of the root zone and the water uptake is normally much higher from the upper root zone as assumed with the 40-30-20-10% relationship in the GUIDELINES.

These assumptions, which are illustrated in results from lysimeter trials, indicate that alfalfa, and presumably other crops, are more sensitive to relatively small quality changes (1 mmho/cm) in applied water and less sensitive to relatively large changes (10 to 20 mmhos/cm) in salinity of drainage water (Bernstein and Francois, 1973). The trials also indicate that increasing the leaching fraction to supply more leaching and drainage could readily compensate for and restore the yield losses due to excessive accumulation of salts in the lower root zone, but could not entirely correct the lowered productivity resulting from the poor quality of water applied.

Table 5

CROP TOLERANCE TABLE

Yield Decrement to be expected for Certain Crops due to Salinity of Irrigation Water when Common Surface Irrigation Methods are Used

Field Crops

CROP	0%		10%		25%		50%		MAXIMUM
	ECe[1/]	ECw[2/]	ECe	ECw	ECe	ECw	ECe	ECw	ECe[3/]
Barley [4/] (Hordeum vulgare)	8.0	5.3	10	6.7	13	8.7	18	12	28
Cotton (Gossypium hirsutum)	7.7	5.1	9.6	6.4	13	8.4	17	12	27
Sugarbeet[5/] (Beta vulgaris)	7.0	4.7	8.7	5.8	11	7.5	15	10	24
Wheat[4/ 6/] (Triticum aestivum)	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20
Safflower (Carthamus tinctorius)	5.3	3.5	6.2	4.1	7.6	5.0	9.9	6.6	14.5
Soybean (Glycine max)	5.0	3.3	5.5	3.7	6.2	4.2	7.5	5.0	10
Sorghum (Sorghum bicolor)	4.0	2.7	5.1	3.4	7.2	4.8	11	7.2	18
Groundnut (Arachis hypogaea)	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.5
Rice (paddy) (Ozyza sativa)	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11.5
Sesbania (Sesbania macrocarpa)	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	16.5
Corn (Zea mays)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Flax (Linum usitatissimum)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10

Table 5 continued

CROP	0% ECe	0% ECw	10% ECe	10% ECw	25% ECe	25% ECw	50% ECe	50% ECw	MAXIMUM ECe
Broadbean (Vicia faba)	1.6	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12
Cowpea (Vigna sinensis)	1.3	0.9	2.0	1.3	3.1	2.1	4.9	3.2	8.5
Beans (Phaseolus vulgaris)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5
Fruit Crops									
Date palm (Phoenix dactylifera)	4.0	2.7	6.8	4.5	10.9	7.3	17.9	12	32
Fig (Ficus carica) Olive (Olea europaea) Pomegranate (Puncia granatum)	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14
Grapefruit (Citrus paradisi)	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8
Orange (Citrus sinensis)	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8
Lemon (Citrus limonea)	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Apple (Pyrus malus) Pear (Pyrus communis)	1.7	1.0	2.3	1.6	3.3	2.2	4.8	3.2	8
Walnut (Juglans regia)	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Peach (Prunus persica)	1.7	1.1	2.2	1.4	2.9	1.9	4.1	2.7	6.5
Apricot (Pyrus armeniaca)	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	6
Grape (Vitis spp.)	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12

Table 5 continued

CROP	0% ECe	0% ECw	10% ECe	10% ECw	25% ECe	25% ECw	50% ECe	50% ECw	MAXIMUM ECe
Almond (Prunus amygdalus)	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.7	7
Plum (Prunus domestica)	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Blackberry (Rubus spp.)	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6
Boysenberry (Rubus spp.)	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6
Avocado (Persea americana)	1.3	0.9	1.8	1.2	2.5	1.7	3.7	2.4	6
Raspberry (Rubus idaeus)	1.0	0.7	1.4	1.0	2.1	1.4	3.2	2.1	5.5
Strawberry (Fragaria spp.)	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4
Vegetable Crops									
Beets 5/ (Beta vulgaris)	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15
Broccoli (Brassica italica)	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	13.5
Tomato (Lycopersicon esculentum)	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	12.5
Cucumber (Cucumis sativus)	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10
Cantaloupe (Cucumis melo)	2.2	1.5	3.6	2.4	5.7	3.8	9.1	6.1	16
Spinach (Spinacia oleracea)	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15
Cabbage (Brassica oleracea capitata)	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12

Table 5 continued

CROP	0% ECe	0% ECw	10% ECe	10% ECw	25% ECe	25% ECw	50% ECe	50% ECw	MAXIMUM ECe
Potato (Solanum tuberosum)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Sweet corn (Zea mays)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Sweet potato (Ipomea batatas)	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	10.5
Pepper (Capsicum frutescens)	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.5
Lettuce (Lactuca sativa)	1.3	0.9	2.1	1.4	3.2	2.1	5.2	3.4	9
Radish (Raphanus sativas)	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	9
Onion (Allium cepa)	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.5
Carrot (Daucus carota)	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.1	8
Beans (Phaseolus vulgaris)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5
Forage Crops									
Tall wheat grass (Agropyron elongatum)	7.5	5.0	9.9	6.6	13.3	9.0	19.4	13	31.5
Wheat grass (fairway) (Agropyron elongatum)	7.5	5.0	9.0	6.0	11	7.4	15	9.8	22
Bermuda grass [7] (Cynodon dactylon)	6.9	4.6	8.5	5.7	10.8	7.2	14.7	9.8	22.5
Barley (hay) [4] (Hordeum vulgare)	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20

Table 5 continued

CROP	0% ECe	0% ECw	10% ECe	10% ECw	25% ECe	25% ECw	50% ECe	50% ECw	MAXIMUM ECe
Perennial rye grass (Lolium perenne)	5.6	3.7	6.9	4.6	8.9	5.9	12.2	8.1	19
Trefoil, birdsfoot narrow leaf[9] (L. corniculatus tenuifolius)	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15
Harding grass (Phalaris tuberosa)	4.6	3.1	5.9	3.9	7.9	5.3	11.1	7.4	18
Tall fescue (Festuca elatior)	3.9	2.6	5.8	3.9	8.6	5.7	13.3	8.9	23
Crested Wheat grass (Agropyron desertorum)	3.5	2.3	6.0	4.0	9.8	6.5	16	11	28.5
Vetch (Vicia sativa)	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12
Sudan grass (Sorghum sudanense)	2.8	1.9	5.1	3.4	8.6	5.7	14.4	9.6	26
Wildrye, beardless (Elymus triticoides)	2.7	1.8	4.4	2.9	6.9	4.6	11.0	7.4	19.5
Trefoil, big (Lotus uliginosis)	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.5
Alfalfa (Medicago sativa)	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	15.5
Lovegrass[8] (Eragrostis spp.)	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14
Corn (forage) (Zea mays)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15.5
Clover, berseem (Trifolium alexandrinum)	1.5	1.0	3.2	2.1	5.9	3.9	10.3	6.8	19
Orchard grass (Dactylis glomerata)	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	17.5

Table 5 continued

CROP	0% ECe	0% ECw	10% ECe	10% ECw	25% ECe	25% ECw	50% ECe	50% ECw	MAXIMUM ECe
Meadow foxtail (Alopecurus pratensis)	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Clover, alsike, ladino, red, strawberry (Trifolium spp.)	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	10

FOOTNOTES

1/ ECe means electrical conductivity of the saturation extract of the soil reported in millimhos per centimetre at 25°C.

2/ ECw means electrical conductivity of the irrigation water in millimhos per centimetre at 25°C. This assumes about a 15-20% leaching fraction and an average salinity of soil water taken up by crop about three times that of the irrigation water applied (ECsw = 3 ECw) and about two times that of the soil saturation extract (ECsw =2ECe). From the above, ECe = 3/2 ECw. New crop tolerance tables for ECw can be prepared for conditions which differ greatly from those assumed in the GUIDELINES. The following are estimated relationships between ECe and ECw for various leaching fractions: LF = 10% (ECe = 2 ECw), LF = 30% (ECe = 1.1 ECw), and LF = 40% (ECe = .9 ECw). [See figure 2 and Appendix C.]

3/ Maximum ECe means the maximum electrical conductivity of the soil saturation extract that can develop due to the listed crop withdrawing soil water to meet its evapotranspiration demand. At this salinity, crop growth ceases (100% yield decrement) due to the osmotic effect and reduction in crop water availability to zero (see Fig. 5).

4/ Barley and wheat are less tolerant during germination and seedling stage. ECe should not exceed 4 or 5 mmhos/cm

5/ Sensitive during germination. ECe should not exceed 3 mmhos/cm for garden beets and sugar beets.

6/ Tolerance data may not apply to new semi-dwarf varieties of wheat.

7/ An average for Bermuda grass varieties. Suwannee and Coastal are about 20% more tolerant; Common and Greenfield are about 20% less tolerant.

8/ Average for Boer, Wilman, Sand, and Weeping varieties. Lehman appears about 50% more tolerant.

9/ Brood-leaf birdsfoot trefoil appears to be less tolerant than narrow-leaf.

Source: Data as reported by Maas and Hoffman (in press); Bernstein (1964), and University of California Committee of Consultants (1974).

Use of tolerance data: It must be recognized that actual production with water of the quality indicated can range from the full 100% potential down to zero, depending upon any one of many factors other than water quality. The values given in Table 5 represent the maximum production potential for the quality of water under optimum conditions of use.

The values suggested as tolerance limits to salinity of applied water (ECw) may seem high at first glance. However, comparing these suggested values with field trials using relatively poor quality waters, as reported for instance from Tunisia (Unesco/UNDP, 1970), from Pakistan (WAPDA, 1974) and others, there appears to be reasonably good agreement on salinity tolerance of crops tested.

Crop tolerance is presented in the tables as if tolerance was a fixed value. This is not exactly true. Crop tolerance does change with water management practices as well as with stage of growth, with rootstocks, with varieties and with the climate. For many crops the germinating and early seedling stage is the most sensitive - sugar beets, rice, wheat, barley and several vegetables - and soil salinity (ECe) in excess of 4 mmhos/cm in the area of the germinating seed may delay or inhibit germination and early growth. The tolerance values as presented in Table 5 are based on the response from late seedling stage of growth to maturity.

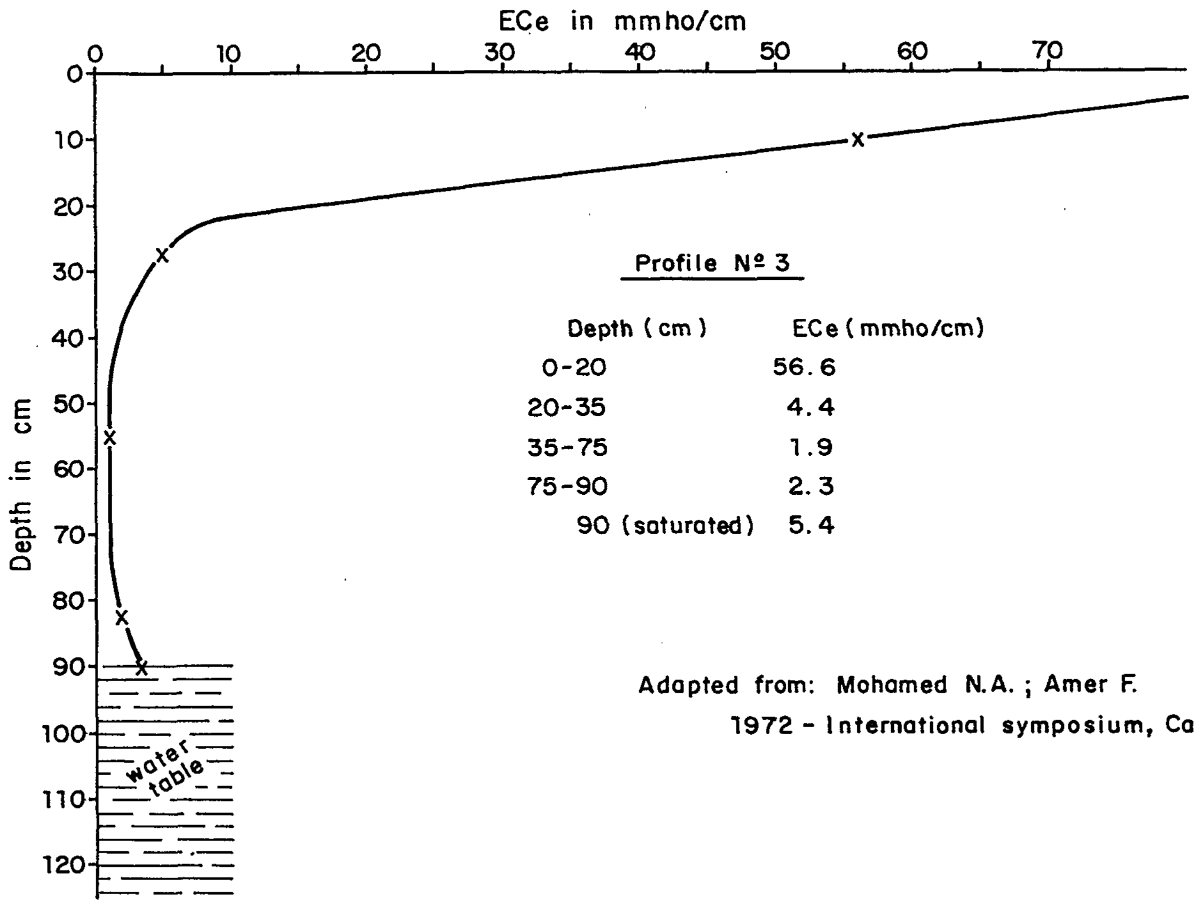
Rootstocks influence the salinity tolerance of certain tree crops such as citrus. Crop varieties, such as for grapes and almond, exhibit important differences in salt tolerance. The differences in salinity tolerance have been used in making both rootstock and variety selection for commercial plantings. Annual crops, too, show variation in response to salinity. Plant breeding and crop selection for salinity tolerance are just now being emphasized and results are stimulating new research for genetic salt tolerance among varieties.

Climate plays an important role in crop tolerance. In general, crops grown in cooler climates or during the cooler time of the year will be more tolerant to adverse salinity than during warmer periods and periods of low humidity or high evapotranspiration.

Fertilizers generally are not believed to increase salt tolerance of crops. However, they may increase yields if fertility is a limiting factor.

In some cases, experience may indicate that the tolerance limits are too high. The apparent discrepancy may be due to the presence of a high water table which acts as a primary source of added salinity. As stated before, in the presence of a high water table, salt distribution in the rooting zone will usually be different. Instead of salts increasing with depth, salts will often be highest near the surface, decreasing with depth as shown in Fig. 6. Under such conditions, surface salinity may be excessive and the full crop production potential for the quality of water as indicated in the tolerance table may not be possible until adequate drainage and water table control is accomplished by artificial drainage (open or covered drains or drainage wells) or by significant changes in water management. It is again emphasized that the tolerance tables and the GUIDELINES assume good drainage.

Fig. 6 Salinity Profile with High Water Table



Profile Nº 3

Depth (cm)	ECe (mmho/cm)
0-20	56.6
20-35	4.4
35-75	1.9
75-90	2.3
90 (saturated)	5.4

Adapted from: Mohamed N.A. ; Amer F.
1972 - International symposium, Cairo. p. 346

If the conditions of use or local experience indicate a different relationship than the 1:1.5 concentration factor for water salinity to soil salinity (ECe = 1.5 ECw), the present values for tolerance to salinity can be changed and new tables prepared. However, this should only be undertaken if well documented local experiences show the existing tables to be inaccurate. Changes based on a limited number of field trials or observations could prove equally inaccurate. The soil salinity values (EC e) for crop tolerance are good values, supported by extensive research. The relationship of irrigation water salinity to soil salinity varies with management and local conditions of use.

By selecting crops and by using good management, a water user may obtain better yields with the water available or may find that water considered "unusable" under his prior concept of quality may really be "usable" under certain situations. Poor water is often better than no water, and, if a water is usable, agriculture may need to find a use for it rather than discharge it as "waste".

6.4.3 Using Extra Water for Leaching

Most of the salts from the irrigation water that are left behind in the soil after crop water use are soluble and must be leached out. These salts will move with the water but the question that arises is how much water should be applied for leaching these salts out.

The leaching requirement (LR) for various crops or for an allowable average soil salinity can be calculated. The simplest and most widely used method to calculate LR has been the USDA method (USDA, 1954):

$$\frac{Ddw}{Dw} = LR = \frac{ECw}{ECdw}$$

where Ddw and ECdw are depth and concentration of the drainage water and Dw and ECw are for the irrigation water. This equation is based on a steady state salt balance condition or in popular terminology "what goes in, must come out and nothing changes form in between". It is important to understand the meaning of the number calculated for the LR. It represents the minimum amount of water (in terms of a fraction of applied water) that must pass through the root zone to control salts. The actual LR, however, is that amount of leaching water necessary to control salts in the root zone and this can only be determined by monitoring salinity control which is then related to field water management.

Under some conditions, however, differences in soils, drainage, and water application methods make leaching less than 100% efficient. Cracks, rootholes, wormholes, and other large pores can transport water quickly through the root zone when these channels are in contact with the irrigation water at or near the surface (Dieleman, 1963). Differences in leaching efficiency are also found with tile and open drainage systems; a larger fraction of leaching water flows through the soil next to the drains as compared to the interdrain area. Inclusion of a leaching efficiency factor would be necessary under such conditions. Such a factor has been included in some areas but should be determined under field leaching conditions (Dieleman, 1963; Unesco, 1970).

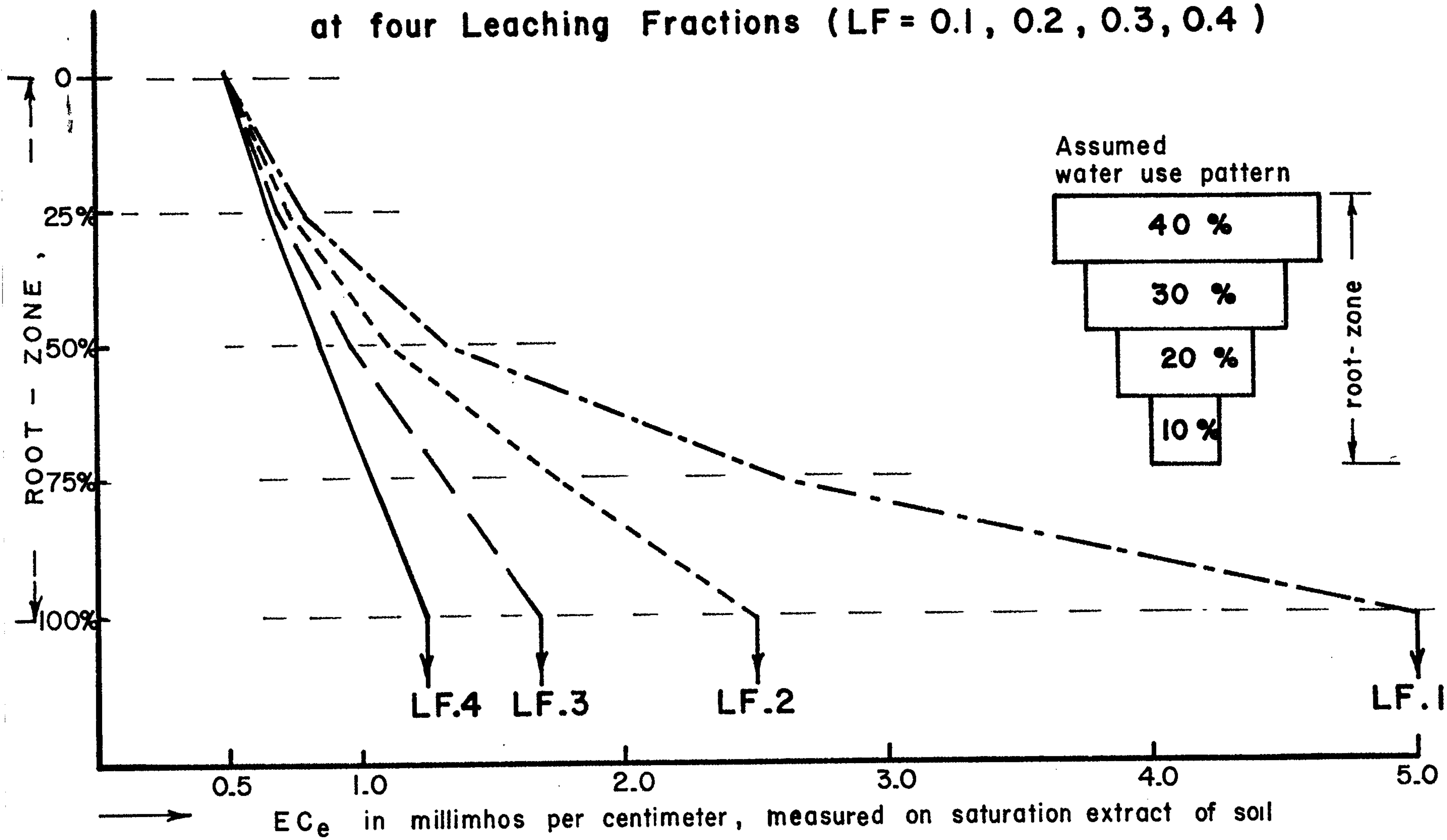
New research information shows that strict adherence to the assumption of steady state salt balance may not be necessary and salt accumulation can take place for short periods of time in the lower root zone. This can take place as long as salt balance is achieved over a long term period and the crop is adequately supplied with water in the upper root zone where the major water use occurs. Reducing the leaching fraction has been shown to have only a small effect on the salinity of this upper root zone since this area is adequately leached during each irrigation (Bernstein and Francois, 1973). However, the salinity of the lower root zone becomes greater, thus changing the concentration of the drainage water (Fig. 7). As a result of these findings, it is now suggested that the leaching fraction can be reduced from the values found by the older USDA method and adequate crop yields can still be maintained (Bernstein and Francois, 1973; Rhoades et al, 1973; Rhoades, 1974). The University of California Committee of Consultants (1974) also recommends a reduction from the older USDA method.

The reduced leaching concept should apply well under high frequency sprinkler or drip irrigation, as well as most conventional surface irrigation methods, provided that the interval between irrigations is not too great. The irrigation interval becomes a most important factor since the crop must respond to the force with which water is held in the soil and also to the osmotic effects caused by salinity, both of which vary over time (Fig. 4). As the irrigation interval becomes greater, the osmotic effect will become more dominant, especially when major water use begins to occur in the lower root zone. This would become even more critical when using poor quality water. More information is needed on crop response to water stress over time and beyond which critical values yields will be affected. This information is not yet available.

Calculation of the Leaching Requirement: The studies on reducing the leaching fraction show that an improvement in managing salts can be made, even under water-short conditions. Using the developed concepts, the minimum amount of leaching water needed to control salts can be calculated. Again, the LR value calculated is a theoretical amount of leaching water needed to control salts in the root zone based on field and laboratory experience. Actual field management and monitoring will determine whether this is adequate under the project conditions. The procedure used is based on Rhoades (1974) as presented at the Expert Consultation on the Prognosis of Salinity and Alkalinity (1975). The following steps are required:

Fig. 7

SALINITY PROFILE expected to develop after long term use of water of EC_w = 1.0 mmhos/cm. at four Leaching Fractions (LF = 0.1, 0.2, 0.3, 0.4)



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1. For surface irrigation (including sprinkler)

Step (1a)

Obtain the electrical conductivity (ECw) from the water analysis.

Step (1b)

Obtain the ECe value from Table 5 for a given crop appropriate to the tolerable degree of yield reduction (usually 10% or less). It is recommended that the ECe value for a 10% yield reduction be used for field application since factors other than salinity are limiting yields greater than this in most instances. Values for yield reduction less than 10% can be used if experience shows that near optimum yields can be obtained under the existing management conditions.

Step (1c)

Calculate the leaching requirement by:

$$LR = \frac{ECw}{5ECe - ECw}$$

where LR is the minimum leaching requirement needed to control salts with ordinary surface irrigation methods.

ECw is obtained from step 1a

ECe is obtained from step 1b.

2. For high frequency sprinkler or drip irrigation (near daily)

Step (2a)

Obtain the electrical conductivity (ECw) from the water analysis.

Step (2b)

Obtain the maximum ECe value from Table 5 for a given crop (100% yield loss)

Step (2c)

Calculate the leaching requirement by:

$$LR = \frac{ECw}{2\ (\max ECe)}$$

where LR is the minimum amount of leaching needed to control salts with high frequency irrigation.

ECw is obtained from step 2a

Max ECe is obtained from step 2b

The factor 2 is obtained from (ECsw = 2ECe).

Once the crop evapotranspiration demand (ET) and the desired leaching requirement are known, the net water requirement can be found using:

$$\text{net water requirement} = \frac{ET}{1-LR}$$

where LR is expressed as a fraction.

Rainfall may provide a portion of the crop ET demand or it may accomplish part or all of the needed leaching. This will be dependent upon soil conditions and rainfall patterns. This will need to be taken into consideration in determining net water requirements.

Under many irrigation practices, the inefficiencies in water application may apply sufficient extra water to accomplish the necessary leaching. This will be especially true where low leaching requirements are needed such as with good quality water.

The LR calculated above should be adequate to control salts unless already present in excess of the crop's tolerance, in which case, an initial heavy leaching may be needed to remove the accumulated salts. After this initial leaching, full potential production may again be restored.

Example:

Sorghum is being irrigated by basins on a uniform loam soil using Pecos River Water (Table 4). ECw = 3.2 mmhos/cm. With an ET demand of 5 mm/day and irrigated every 20 days, 100 mm of water would be used. If the application efficiency is 0.65, 100/.65 = 155 mm of water must be applied with each irrigation to meet crop ET demand. How much additional water should be applied for leaching?

Step 1

Given:

ECw = 3.2 mmhos/cm
ECe = 5.1 mmhos/cm (Table 5 for sorghum at 10% yield loss)

$$LR = \frac{3.2}{5(5.1) - 3.2} = .14$$

Step 2

Determine the amount of water to be applied for crop ET and long term salt control (can be calculated on an irrigation, monthly or seasonal basis)

Given:

ET = 100 mm/irrigation
LR = .14 (from Step 1)

$$\text{Net Water Requirement} = \frac{100}{1-.14} \cong 116 \text{ mm/irrigation}$$

The deep percolation losses (55 mm) are larger than the leaching requirement. If the deep percolation losses are assumed to be uniform and no runoff occurs, there is no need to add the leaching requirement to the unavoidable deep percolation losses. Uniform application of this water along with increasing efficiency of application should be encouraged.

Timing of Leaching Irrigations. The timing of leachings does not appear to be critical provided crop tolerances are not exceeded for extended or critical periods of time. The leaching can be done at each irrigation, each few irrigations, once each year, or after long intervals. Regardless of the method used, adequate soil and crop monitoring should be used. Soil and plant tissue analysis can be used as an aid to determine the need and timing of leachings.

In most cases, an annual leaching during non-crop or dormant periods, as during the winter season, is preferred. Rainfall in some cases may be adequate to accomplish all the needed leaching.

Maximizing the efficiency of leaching or reducing the LR may reduce water needs. In most instances flexibility in the management choice may be limited but several management steps suggested here may possibly apply to the particular irrigation situation:

a) plant crops during the cool season instead of the warm season since LR is related to the ET demand;

b) plant more salt tolerant crops, thus reducing the water needed for leaching;

c) apply soil management practices that limit flow into and through large pores, such as tillage to reduce the number of surface cracks;

d) use irrigation methods such as sprinklers which apply water below the infiltration rate of the soil thus reducing water movement through large pores. This will require more irrigation time but uses less water than continuous ponding (Oster et al., 1972);

e) use alternate ponding and draining instead of continuous ponding (Oster et al., 1972);

f) wet the soil prior to the start of the winter rains where rainfall is insufficient to do a complete leaching. Even a little rainfall on a wet soil is efficient in leaching since the rain moves deeper into the soil, as well as providing high quality water to the upper root zone;

g) where drains exist, leach in stages: first leach the area in the centre between drains followed by leaching closer to the drains (Yaron, et al., 1973).

Soil conditions may prevent flexibility in how the leaching requirements are applied. If soil infiltration rates are low, leaching may need to be postponed until after cropping. The effects of fallow periods on soil salinization will need to be considered. Water availability may also prevent flexibility thus allowing only after harvest or pre-sowing leachings or scheduling of leachings outside periods of peak water requirements. Leaching outside peak water use periods will also reduce the design capacity of the distribution system and may influence drainage design factors as well.

6.4.4 Change Method of Irrigation

It may be easier to control salinity under sprinkler and drip irrigation than under surface irrigation. However, sprinkler and drip irrigation are not adapted to all qualities of water and all conditions of soil, climate or crop. Several important factors should be considered before attempting to improve salinity control by changing the method of irrigation.

a) Surface irrigation

Flood, basin, furrow and border methods apply water at intervals to allow the crop to utilize as much as 50% or more of the available water in the root zone before the next irrigation. As water is used by the crop during each interval between irrigations the soils become drier and the soil water becomes saltier and therefore even less water is available to the crop (Fig. 4).

The benefits of more frequent irrigation and routine leaching have been discussed. Surface irrigation methods are often not sufficiently flexible to allow adjustments in timing and depth of water. For example, it may not be possible to reduce the depth of water applied below 80 to 100 mm per irrigation. As a result, irrigating more frequently may reduce salinity but may also waste water, cause waterlogging and result in reduced yield.

In such cases, to achieve appreciable improved water and salinity management, a change in method of irrigation to sprinklers or drip may be needed. Such a change is costly and will need to be justified in terms of improved yield, improved crop adaptability, or other benefits that can realistically be expected.

b) Sprinkler irrigation

A good sprinkler system design must meet the requirements of the crop for water (ET), of the soil as to rate of application and water storage capacity, and of the water and crop as to leaching requirement (LR). Special on-site conditions and peculiarities of crops, soil, water supply or climate must also be considered (Pillsbury, 1968).

With adequate system design and management, movable and solid set sprinklers can apply water with good uniformity and with rates of application low enough to prevent run-off. This results in an excellent overall water supply to the crop and adequate and uniform leaching. Depth of water applied can also be controlled by adjustments in the duration of application.

Sprinklers are sometimes used to aid germination and early seedling growth at which time the crop may be particularly sensitive to salinity, high temperatures and soil crusting. With solid set systems used for crop germination, irrigations are applied once or more each day for several days and for relatively short periods of 1 to 3 hours duration. After 10 to 14 days the sprinklers are removed to another field and the process is repeated. In this way a sprinkler system can be used for germinating several different fields in a season. With portable or wheel-roll systems, irrigations are frequent enough to maintain low salinity and reduce soil problems such as crusting. Solid set sprinkler systems have been used quite extensively for lettuce.

Sprinklers often allow much more efficient use of water and a reduction in deep percolation losses. If water application is in close agreement with crop needs (evapotranspiration and leaching), drainage and high water table problems can be greatly reduced which should improve salinity control.

Sprinklers do offer a hazard to sensitive crops when using poor quality water. Crops such as grapes, citrus and most tree crops are sensitive to relatively low concentrations of sodium and chloride and under low humidity conditions may absorb excessive and toxic amounts from the sprinkler applied water which wets the leaves. Salt concentrates on the leaves as water evaporates between rotations of the sprinkler. These salts are then absorbed and may cause damage. This sometimes occurs with rotating sprinkler heads and low rates of application when either sodium or chloride in the water exceeds about 3 meq/l. The toxicity shows as a leaf burn (necrosis) on the outer leaf-edge and can be confirmed by leaf analysis. Irrigating during periods of higher humidity, as at night, has often greatly reduced or eliminated the problem. Annual crops, for the most part, are not sensitive to low levels of sodium and chloride. Recent research indicates, however, that they may be more sensitive to salts taken up through the leaf during sprinkling than to similar water salinities applied by surface or drip methods (Bernstein and Francois, 1975). These problems are discussed more thoroughly under toxicity problems (section 8.3.7

Where water salinity is in the range of "Severe Problem" several trials should be made to test the suitability of sprinkling under local conditions of use. This may even be needed for crops not presently considered to be sensitive to specific ion toxicities.

c) Drip (trickle) irrigation

Drip irrigation is a method which supplies the quantity of water needed on almost a daily basis. Water is applied from each of many small emitters at a low rate. The timing and duration of each irrigation can often be regulated by time clocks (or hand valves) with adjustments in water applied being made through the duration of irrigation, by changing the number of emitters, or both (FAO, 1973).

With good quality water yields with drip irrigation should be equal to, or slightly better, than other methods under comparable conditions. With poor quality water yields may be better with drip due to the continuous high moisture content and daily replenishment of water lost by evapotranspiration. Frequent sprinkler irrigation might give similar results but the leaf burn and defoliation of sensitive species would not be expected with drip irrigation. If poor quality water is used and crop tolerances are exceeded by the usual methods of irrigation, a better yield may be possible with drip, although yields may not be as high as those found using good quality water. However, even with no expected yield benefit, other benefits such as possible savings in water, fertilizer or labour may be great enough in special cases to justify the added investment costs of the drip system.

With the drip method salts do accumulate both at the soil surface and within the soil at the outside edges of the area wetted by the emitters (Fig. 8). Salts may also accumulate below the emitters but the daily irrigations, if properly applied, should maintain a slight but nearly continuous downward movement of moisture to keep these salts under control. With time the salt accumulation at soil surfaces and in wetted fringe areas between emitters can become appreciable. Such accumulation is a hazard if moved by rain into the root zone of the crop or, in the case of annual crops, if a new planting is made in these salty areas without prior leaching. If rainfall is sufficient each season to leach the accumulating salts, no problems should be anticipated. However, if rainfall is insufficient or infrequent, problems may result. Leaching by sprinklers or surface flooding prior to planting has been effective in removing accumulated salts. This will require a second irrigation system and use of additional water but may allow continued production utilizing poor quality water.

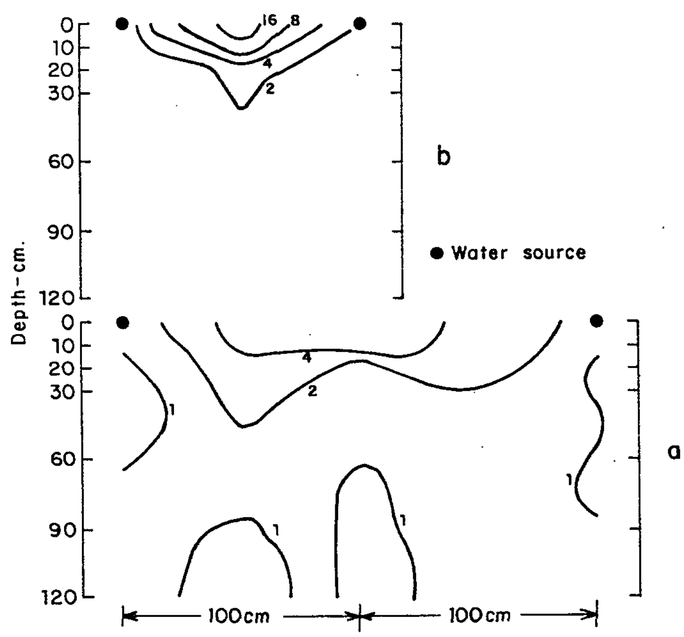


Fig. 8 SALT DISTRIBUTION PATTERN (ECe) AFTER TRICKLE IRRIGATION: a NO OVERLAP BETWEEN WETTING FRONTS; b WITH OVERLAP. (From YARON et al., 1973)

6.4.5 Changes in Cultural Practices for Salinity Control

a) Pre-plant irrigation

Salts often accumulate in the top few centimetres of the soil during non-crop periods. Where high water tables complicate salinity control, fallow and idle lands may rapidly accumulate surface salts particularly in hot arid climates. Under such conditions, both crop germination and yield can be seriously reduced.

A heavy pre-plant irrigation to leach these surface salts will improve germination and early growth and is sometimes an essential practice. It is made far enough in advance of the desired planting date to allow for cultivation to remove weeds and preparation of a seedbed.

In a furrow irrigated field extra cautions on salt accumulation in the ridges must be considered. The practice of knocking off the top of the ridge before planting can be used. Care must be taken, however, on seed placement. Methods to prevent salt accumulation in the ridges will be discussed in the next section.

It may be possible to apply an irrigation prior to the onset of limited winter rains. The soil profile is then filled with water and the winter rains provide excess water for leaching. This technique is particularly beneficial because it provides high quality water for leaching (rainfall) and moves salts out of the seeding area; thus germination problems are not experienced.

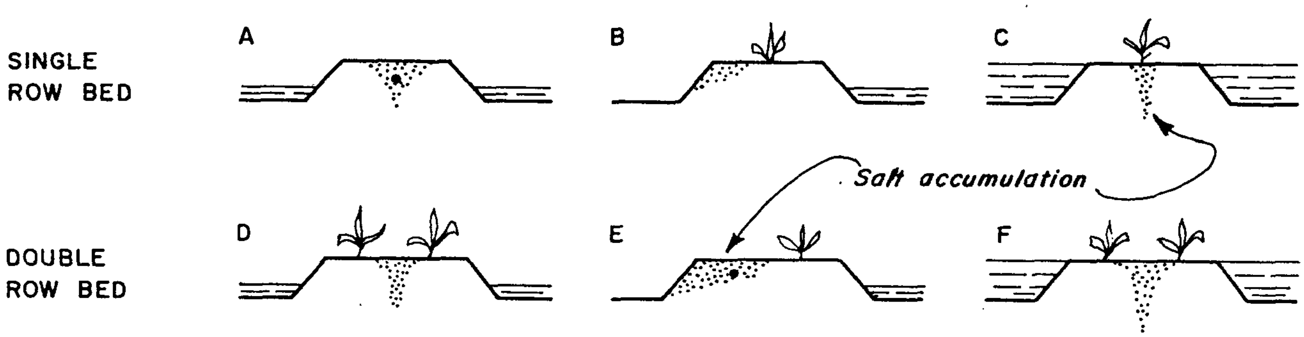
b) Placement of seed

Obtaining a satisfactory stand of furrow irrigated crops on saline soils or when using poorer quality water is a particularly serious problem. Growers sometimes compensate by planting two or three times as much seed as normal. In other cases, appropriate adjustments in planting procedures are made to ensure that the soil area around the germinating seeds is low in salinity. This can be done by selecting suitable planting practices, bed shapes and irrigation management.

If salinity is a problem, planting seeds in the centre of a single-row raised bed will place the seed exactly in the area where salts are expected to concentrate (Fig. 9a). A double-row raised planting bed by comparison may offer an advantage (Fig. 9d). The two rows are placed so that each is near a shoulder of the raised bed, thus placing the seed away from the area of greatest salt accumulation. By this method higher soil and water salinities can be tolerated than with the single-row plantings because the water moves the salts through the seed area to the centre of the ridge.

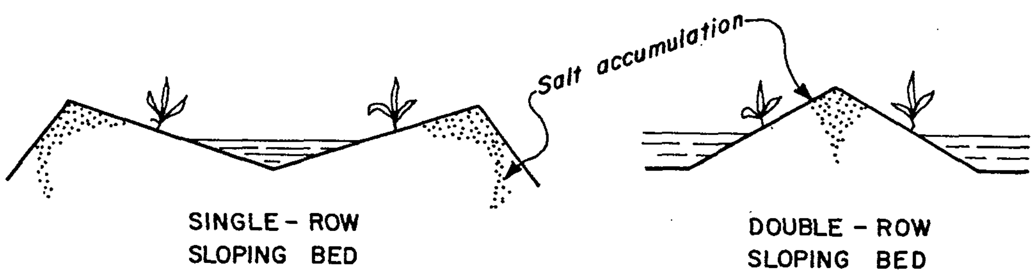
There are other alternatives. Alternate furrow irrigation may help. If the beds are wetted from both sides, the salts accumulate in the top and centre of the bed (Figs. 9a and 9d) but if alternate furrows are irrigated, the salt can be moved beyond the single seed row (Fig. 9b). The salts may still accumulate but the extent will be reduced. The longer the water is held in the wet furrow, the lower the salt accumulation. Off-centre, single-row planting on the shoulder of the bed closest to the watered furrow (Fig. 9e) has also been used and aids germination under salty soil conditions. Double-row planting under alternate row irrigation is not recommended.

Fig. 9 FLAT TOP BEDS AND IRRIGATION PRACTICE



(Bernstein, Fireman and Reeve - 1957)

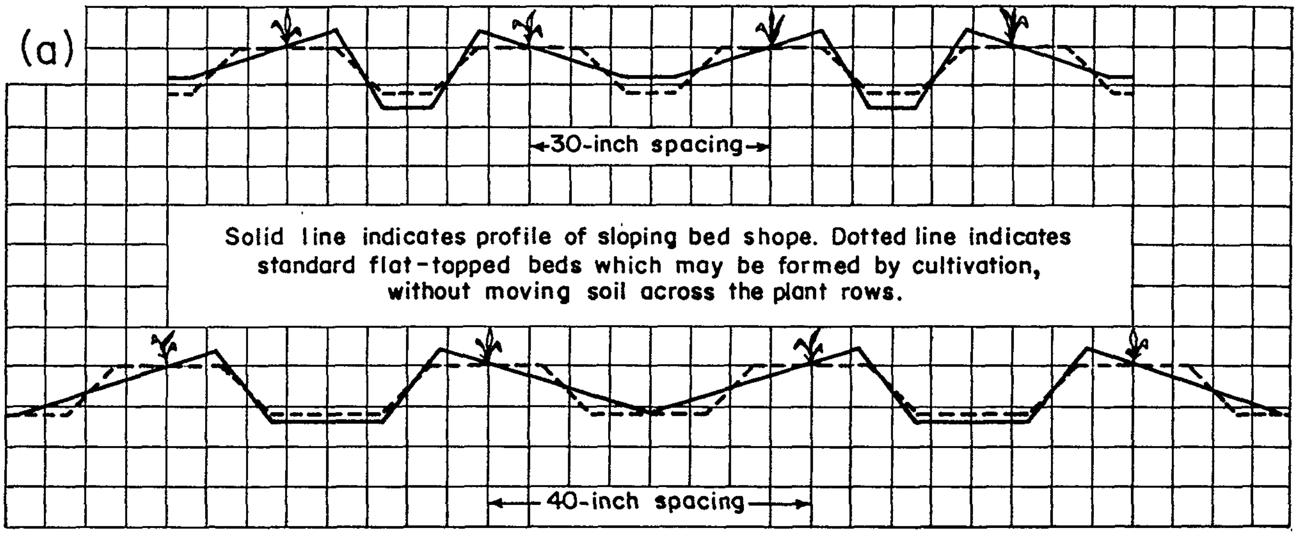
Fig. 10 SALINITY WITH SLOPING BEDS



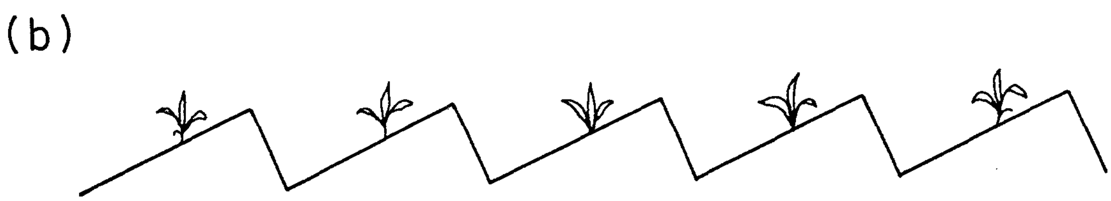
(Bernstein and Fireman.-1957)

With either single or double-row planting, if salts are expected to be a problem, increasing the depth of water in the furrow can also be an aid to improved germination (Figs. 9c and 9f). Still better salinity control can be achieved by using sloping beds with seeds planted on the sloping side and the seed row placed just above the water line (Fig. 10). Irrigation is continued until the wetting front has moved well past the seed row. A correct configuration of the single-row sloping bed for ease in cultivation to convert back to a conventional raised bed is shown in Fig. 11a (Bernstein and Ayers, 1955). This reshaping is usually done after germination or during the early growth period.

Fig. 11 SLOPING SEEDBEDS



Bernstein and Ayers - 1955

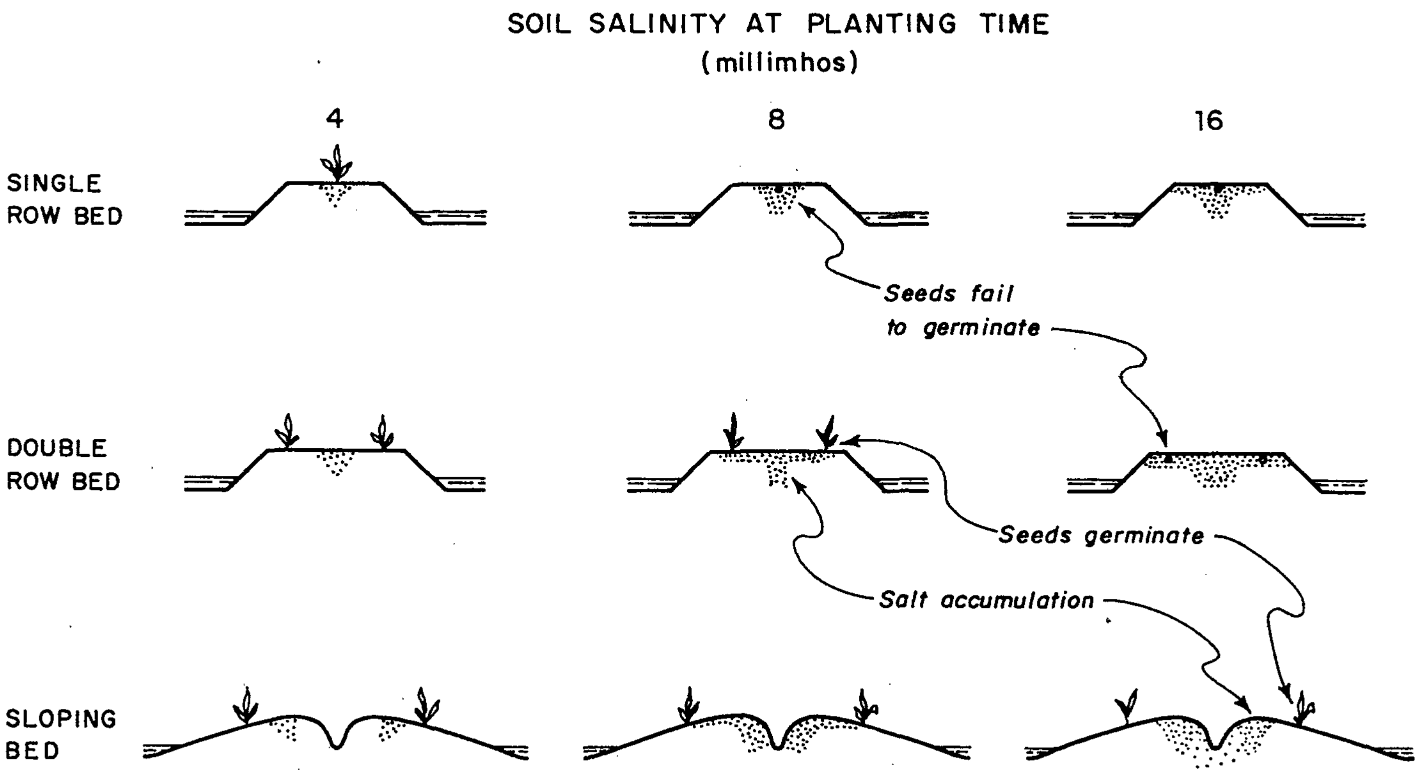


Another modification of the single-row sloping bed design is shown in Fig. 11b which has been used for both salinity and temperature control.

This is used for crops planted in winter or early spring where soil temperatures of a few degrees warmer are important. The sloping side is oriented toward the south in the northern hemisphere. Where cooler soil temperatures may be desired, reversing this slope (facing away from the sun) has been used successfully.

In the diagrams of Fig. 12 an approximation is given of the effectiveness of modifying the shape of the planting beds. Actual response will depend on the initial soil salinity, the irrigation method, the water quality and the crop tolerance during germination.

Fig. 12 BED SHAPES AND SALINITY EFFECTS



The pattern of salt build-up depends on bed-shape and irrigation method. Seeds sprout only when they are placed so as to avoid excessive salt build-up around them.

(Bernstein, Fireman and Reeve - 1955)

The larger seeded crops, such as corn (maize), have been planted in the water furrow as an aid to salt control during germination. Grapes, too, have sometimes been grown with problem waters by placing the vine row at the bottom of the wide flat furrows or at the bottom of wide, gently sloping V-shaped furrows.

Salinity problems have been aggravated when permanent crops such as tree crops and citrus are planted on raised beds and surface irrigated with poor quality water. Salts gradually accumulate in the raised beds to the extent that in a few years crop tolerance is exceeded.

c) Fertilization

Chemical fertilizers, manures, sludges and soil amendments contain salts and if placed too close to the germinating seedling or to the growing plant may cause salinity and toxicity problems. For example, an application of 50 kg per hectare of nitrogen in the form of ammonium sulphate would cause no salinity problem if spread uniformly over the one hectare area. However, if drilled with the seed at planting time, it would probably reduce germination or growth of seedlings and might result in crop failure.

If salinity is expected to be a problem, care should be taken in placement and timing of fertilization. Seedlings are sensitive to salts and, while small, require little fertilization. Where salts are a problem, lower than normal early fertilizer applications may be desirable and the main application made at a later date. Soil analysis for ECe, N, P and K prior to planting can be helpful in deciding on split fertilization practices.

Salt tolerance of a crop is little affected by increasing fertility. However, if both salinity and low fertility are limiting yields, correction of the most limiting factor should give a yield increase. If, however, the fertility is adequate and salinity is limiting yield, further increasing the fertility should not be expected to increase yield or improve the salt tolerance of the crop (Bernstein, Francois, Clark, 1974).

6.4.6 Major Changes Sometimes Required for Salinity Control

The foregoing management alternatives require relatively simple changes in soil, crop and water management. Other procedures are available, however, that involve major changes in operational procedures and may require special engineering and design considerations. These are often costly but may improve existing soil conditions and make efficient irrigation and crop management much easier.

a) Leach to remove salts

An initial major reclamation or leaching may be necessary before adequate crop yields are possible. However, salts may also accumulate from the irrigation water to excessive concentrations and an intensive or periodic leaching may be needed. As a rule of thumb, about a 30 cm depth of water leached through a 30 cm depth of soil should remove about 80% of the soluble salts (Fig. 13).

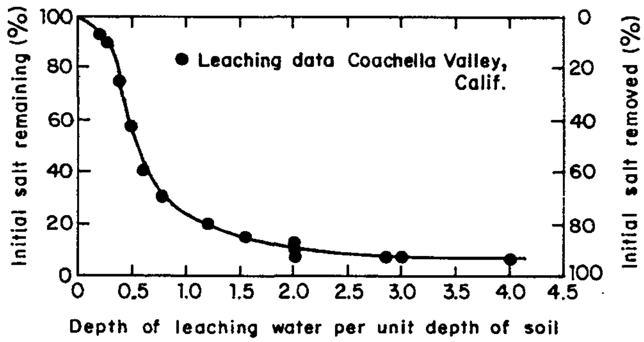


Fig. 13 DEPTH OF WATER PER UNIT DEPTH OF SOIL REQUIRED TO LEACH A HIGHLY SALINE SOIL (From REEVE et al., 1955)

The degree of salt removal during leaching can be markedly influenced by the method used. Traditionally, saline soils have been leached by continuous ponding for many days or weeks. It has been shown, however, that intermittent ponding or sprinkling uses less water and is as effective as continuous ponding (Oster et al, 1972).

Attempts to remove salts from the soil surface by surface runoff and overland flow are relatively ineffective. Surface flushing will remove a part of the salt s but quantities removed are usually inadequate to accomplish reclamation.

When reclaiming tile drained lands, it is often better to irrigate heavily with intervals of drying, as with intermittent flooding and sprinkling. This increases the number of times that salt is moved from between the tile lines by the water level dropping. It can also be accomplished without a major revision of the field layout and salt tolerant crops can be grown to keep the soil open thus speeding up the process (Dieleman, 1963).

b) Land grading

In many instances the lands are not sufficiently smooth to allow satisfactory water distribution and land grading is needed to improve surface drainage. Slight rises in portions of an irrigated field quickly result in salinity problems. Graded lands may also become uneven due to cultivation or other reasons and may need re-levelling or grading every few years as a continuing aid to salinity control and better water management.

Land can be graded to any one of several slopes but sprinklers or drip irrigation may not require that the land be graded. For sprinklers it may still be desirable to smooth to eliminate low areas where water may collect or particularly steep areas which may cause run-off.

By grading, high spots can be eliminated and required slopes can be provided that will allow for adjustments in rate of water application and more uniform infiltration into the soil. This land grading operation,however, often causes a certain amount of soil compaction and it is advisable to follow the land grading by subsoiling, chiselling, or ploughing to break up any compaction caused by the heavy land grading equipment. This follow-up sub-soiling should further improve uniformity of water penetration. Land planing by use of long wheel-base scrapers to smooth the land surface, although a good practice, is sometimes discussed as being "land grading" since some soil is moved from high spots to low. Land planing cannot be considered as equal to, nor as a suitable substitute for, needed land grading.

c) Profile modification

Soils sometimes have layers of clay, sand or hardpan which impede or inhibit root and water penetration. Water management and salinity control can be greatly simplified if these layers are broken up, destroyed, or at least rendered more permeable to roots and water. Subsoiling and chiselling may improve internal drainage of the profile but results are often short lived. Deep ploughing, however, should result in permanent improvement. Deep ploughing, or slip ploughing, is usually done after land grading and before leaching. This is a drastic and costly treatment and will probably necessitate growing an annual crop such as barley to be followed by a touch-up grading to re-establish proper grade.

d) Establish artificial drainage

In areas where salinity is a factor, both surface and subsurface drainage problems greatly complicate water management for salinity control.

Surface drainage problems are usually characterized by ponding and waterlogging due to slopes that are too flat or due to slow water penetration and uneven land. This results in additional problems of aeration, disease, weed control and nutrient supply. Surface drainage problems complicate control of salinity due to the variation in water penetration over the field. Land grading and proper design of surface drainage systems will be needed.

A subsurface drainage problem may occur due to the presence of a clay barrier, hardpan layer, bed rock or simply a subsoil textural change. Other reasons are rising ground water tables due to over irrigation, seepage of irrigation water, leakage from canals, or other changes in water management. They may rise to cause waterlogging of the root zone or even surface ponding may result. Some water tables, if of good quality, are sometimes useful as a source of water.

Temporary or permanent shallow water tables (1.5 to 2 metres or less) are all too frequently the cause of accumulating salts because first, controlling salinity is very difficult since leaching may be ineffective, and secondly, moisture rises through the soil by capillarity due to evaporation from the soil surface and crop use of water. This transports salts to the surface (Fig. 6). This has occurred in many irrigated areas even with very good quality water. The rate of accumulation, however, will depend up on the local drainage conditions and the dissolved salts in the irrigation water. This is illustrated in the following two examples:

i. The Tigris-Euphrates river plain in Iraq is one of the oldest known irrigated areas of the world. River water salinity for most of the irrigated area is excellent (ECw = 0.3 to 0.7 mmhos/cm). It may have taken as long as one or two thousand years of irrigation before salinity problems developed. Records indicate salinity problems were present in some areas by 2400 B.C. and farmers were turning from wheat to barley because it was a more salt tolerant crop. Other areas of the plain were apparently troubled by salinity problems in about 100 B.C. (Jacobsen and Adams, 1958).

   Most of the Tigris-Euphrates plain today is severely troubled with both salinity and high water table problems. Since the natural water quality of both the Tigris and the Euphrates is excellent, salinity should normally not be a problem. However, with inadequate drainage and the high water tables that developed, there was no way to control and permanently remove any significant portion of the salinity. The salts slowly accumulated from the applied irrigation water and productivity declined. Drainage and reclamation projects are now being implemented and the area will no doubt again become a very productive agricultural area.

ii. In the Imperial Valley of California, severe drainage and salinity problems developed in certain locations within 10 to 20 years of the start of irrigation with Colorado River water. The high water table and drainage problems were associated with leakage from distribution systems (canals) and over-irrigation of the sandier soils. A rapid build-up of salt occurred due to the salt content of the river water (ECw = 1.0 to 1.2 mmhos/cm) and the resultant accumulation of salt in the soil from high water tables and inadequate leaching. The problem has largely been solved by an extensive under drainage (tile) and collection system (open drains), and export of the drainage waters to a suitable salt sink for evaporation. With drainage restored, leaching again became effective. Imperial Valley is today an exceptionally productive agricultural area.

To reduce the surface salinity prior to planting, heavy pre-plant irrigations are used. Even though pre-plant irrigations may be successful, any salt reduction is often temporary. The salinity problem will build up during each season and may be expected to get progressively more severe.

A more effective approach to managing or correcting the salinity problem associated with high water tables is first to solve the drainage problem followed by solving the salinity problem in the usual manner - by intermittent leaching.

High water table problems are solved primarily by artificial drainage - by open or covered drains, or by drainage wells. Suitable means for collection, transport and disposal of unusable drainage waters must also be included. With good drainage established, both the water table problems (aeration, rooting depth, diseases, etc) and the salinity problems can be more easily managed and controlled.

e) Change or blending water supplies

A change of water supply is a simple but drastic solution to a high ECw problem. Frequently this may not be possible. Where different sources of water supply are available a blend may help reduce the hazard of one water. Any change in quality due to blending may be evaluated by use of the GUIDELINES of Table 1. An example is shown in Table 6. Dilution, of course, degrades the better water and improves the poorer water. Whether the result is acceptable may depend to a great extent upon the specific situation as to water availability, overall basin water management plans, long range salinity management and many other factors. Salinity of the resulting blend can be calculated from the following relationship:

$$\left[\text{ECw (mmhos/cm) x proportion of 1 used}\right] + \left[\text{ECw (mmhos/cm) x proportion of 2 used}\right] = \text{Resulting ECw of mix}$$

Example:

From Table 6, a blend of 75% canal water and 25% Tubewell 116 water is made. What is the resulting ECw ?

Canal water	0.23	x	0.75	=	0.17
Tubewell 116	3.60	x	0.25	=	0.90
Resulting ECw (mmhos/cm)				≅	1.07

Table 6 - COMPARISON OF ECw and adj.SAR FOR THREE DIFFERENT QUALITIES OF WELL WATER DILUTED WITH CANAL WATER [1/]

% Canal Water Used	Tubewell 116 [2/] ECw	Tubewell 116 [2/] adj.SAR	Well water X [2/] ECw	Well water X [2/] adj.SAR	Well water Y [2/] ECw	Well water Y [2/] adj.SAR
none	3.60	37.4	2.08	40.9	4.00	5.50
20% (4:1)	2.93	32.3	1.71	32.1	3.25	4.82
25% (3:1)	2.76	29.9	1.62	28.7	3.06	4.54
33 1/3% (2:1)	2.48	27.0	1.47	26.7	2.75	4.23
50% (1:1)	1.92	21.2	1.16	19.6	2.12	3.56
66 2/3% (1:2)	1.35	15.0	0.84	13.1	1.48	2.82
75% (1:3)	1.07	11.0	0.69	9.64	1.17	2.43
80% (1:4)	0.90	9.90	0.60	7.77	0.98	2.12
90% (1:9)	0.57	4.70	0.42	4.14	0.61	1.53
95% (1:19)	0.40	2.99	0.32	2.51	0.42	1.15

1/	ECw mmhos/cm	Ca meq/l	Mg meq/l	Na meq/l	HCO_3 meq/l	Cl meq/l	SO_4 meq/l	SAR	pHc	adj.SAR
Canal water	0.23	1.36	0.54	0.48	1.84	0.29	0.17	0.49	7.87	0.76
Tubewell 116	3.60	2.48	4.04	32.0	4.46	25.09	8.90	17.72	7.29	37.4
X well water	2.08	0.99	1.20	20.46	10.66	6.03	6.01	19.55	7.31	40.9
Y well water	4.00	16.5	15.8	8.60	2.40	35.7	2.60	2.14	6.83	5.5

2/ Discussed under blending for permeability problem control.

7. PERMEABILITY PROBLEM DISCUSSION

7.1 The Permeability Problem

A permeability problem occurs if the irrigation water does not enter the soil rapidly enough during an irrigation to replenish the soil with water needed by the crop before the next irrigation. The reduced permeability is generally a problem of the upper few centimetres of soil but occasionally may occur at deeper depths. This results in a decreased water supply to the crop just as a salinity problem does - but for a different reason. Permeability reduces the quantity of water placed into storage while salinity reduces the availability of the water in storage.

Permeability refers to the ease with which water enters and percolates down through the soil and is usually measured and reported as an infiltration rate. An infiltration rate of 2.5 mm/hour is considered low while 12 mm/hour is relatively high. This can be affected however by many factors other than water quality including physical characteristics, such as soil texture, layering or stratification, and compaction, and chemical characteristics such as type of clay minerals and exchangeable cations. The GUIDELINES of Table 1 refer to permeability problems as they relate directly to the unfavourable changes in soil chemistry caused by the quality of the irrigation water applied and are related to one of two causes - low salinity or high sodium in the irrigation water. They do not relate to problems of physical soil characteristics such as texture and compaction.

7.1.1 Low Salinity Waters

Low salinity waters are corrosive and tend to deplete surface soils of readily soluble minerals and salts. They have a strong tendency to dissolve rapidly all sources of calcium from the surface soil causing the finer soil particles to disperse, to fill pore spaces and to seal the soil surface. Very low salinity waters (ECw < 0.2 mmhos/cm) often result in soil permeability problems and the lower the ECw, the greater the potential of a permeability problem.

7.1.2 High Sodium Waters

High sodium in the irrigation water can cause a severe soil permeability problem. Meeting the crop water demand under these conditions may become extremely difficult. In addition, other problems such as crop germination, soil aeration, disease and weed control due to surface water ponding and stagnation may need special consideration.

The most commonly used method to evaluate the potential has been the Sodium Adsorption Ratio (SAR) according to the equation:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad \text{(USDA Handbook 60, 1954)}$$

where Na = Sodium in meq/l

Ca + Mg = Calcium plus magnesium in meq/l

For SAR values greater than 6 to 9, the irrigation water could be expected to cause a permeability problem on the shrinking-swelling types of soil.

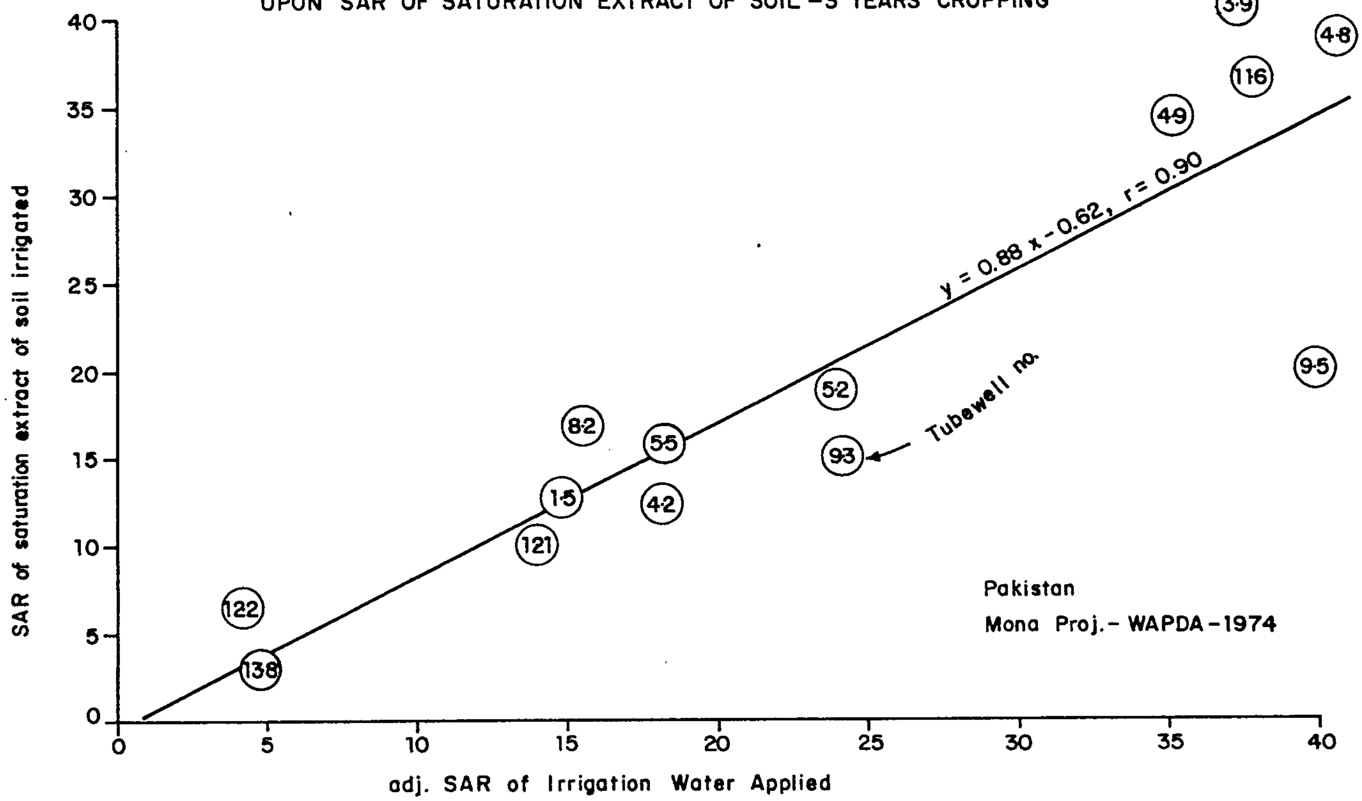
Permeability problems, however, are also related to the carbonate (CO_3) and bicarbonate (HCO_3) content in the irrigation water and this is not considered in the SAR procedure. When drying of the soil occurs between irrigations, a part of the CO_3 and HCO_3 precipitates as Ca-$MgCO_3$ thus removing Ca and Mg from the soil water and increasing the relative proportion of Na which would increase the sodium hazard. This effect on soil permeability has been evaluated separately by the Residual Sodium Carbonate (RSC) method (Eaton, 1950, USDA, 1954). Values of RSC have been suggested (Wilcox et al, 1953) on which a water's suitability could be judged. Each of these methods (SAR and RSC) have been used to evaluate the permeability hazard independently of each other although considerable interaction between the ions was known to occur. Each has been useful and has been used in many parts of the world with varying degrees of success.

Recent research however has added refinements to the previous concept of SAR and RSC, and a newer procedure is suggested. The GUIDELINES of Table 1 use this new procedure which employs a modification of the previous SAR and now called the adjusted Sodium Adsorption Ratio (adj. SAR) method. The older SAR procedure is modified to include changes in soil water composition that are expected to result due to certain combinations of water salts which will either dissolve lime from the soil, (adding calcium) or will result in deposition of lime from the soil water (reducing calcium). The adj. SAR is then related to predominant soil clay mineralogy as shown in Table 1. The adj. SAR is calculated using the semi-quantitative equation as given in Table 3:

$$\text{adj. SAR} = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \left[1 + (8.4 - pHc) \right]$$

This procedure will more correctly predict the potential for a soil permeability problem than do the older SAR and RSC procedures. Fig. 14 shows a good correlation between adj. SAR of irrigation water and SAR of saturation extracts of surface soils (0-15 cm) in Pakistan where tubewell waters are being used in field trials with "normal" on-farm surface irrigation (water table controlled by tubewells).

Fig. 14 INFLUENCE OF ADJ. SAR OF IRRIGATION WATER UPON SAR OF SATURATION EXTRACT OF SOIL -3 YEARS CROPPING



7.2 <u>Permeability Problem Evaluation</u>

To evaluate the potential for a permeability problem, a water analysis or series of analyses is needed that is representative of the conditions of use. Data used from the analysis include ECw, Na, Ca, Mg, CO_3 and HCO_3 as shown in Table 2. The interpretative values of the GUIDELINES in Table 1 are related to the dominant type of clay mineral. High adj. SAR is more damaging to shrinking-swelling type soils (montmorillonite) than to the non-swelling types (illite-vermiculite and kaolinite).

To illustrate the use of the GUIDELINES of Table 1, the three water analysis in Table 4 will be evaluated for their potential to cause a permeability problem due to low salinity effects (ECw) and sodium effects (adj. SAR).

<u>Tigris River at Baghdad, Iraq</u>

<u>Low salinity effects:</u> ECw = 0.51 mmhos/cm is greater than the GUIDELINE value (ECw = 0.5 mmhos/cm) for "No Problem". However, since the GUIDELINE values that separate the expected "degree of problem" are not fixed points, values 10 to 20 percent above or below a suggested value will need to be considered. Although permeability is not expected to be a problem, some consideration should be given to adopting practices to maintain or improve permeability.

Sodium effects: adj. SAR = 2.5 is well below the GUIDELINE value (adj. SAR < 6.0) for "No Problem". A permeability problem, therefore, is not expected since the sodium hazard from using Tigris River water is low.

Tubewell 116, Mona Project, Pakistan

Low salinity effects: ECw = 3.6 mmhos/cm is greatly in excess of the GUIDELINE value (ECw >0.5 mmhos/cm) for a potential permeability problem. No problem is expected to occur due to low salinity.

Sodium effects: An adj. SAR = 38 is greatly in excess of the GUIDELINE value for a severe permeability problem. If this water is used for irrigation, special cropping practices will probably be necessary for long term satisfactory production. The salinity, however, is high enough that it may partially off-set or reduce to some extent the expected problems due to high adj. SAR but a generally severe problem should be anticipated on all but very sandy soils. Special management may need to be adopted during the heavy monsoon rains. This sudden application of low salinity rain water to sodium soils caused by tubewell water may result in poor aeration, disease, and weed problems. This high adj. SAR may also cause a toxicity problem to certain crops (section 8). This water could be used successfully by blending with canal water or perhaps could be used on sandy or loamy sand soils.

Pecos River at Carlsbad, New Mexico, U.S.A.

Low salinity effects: ECw = 3.21 mmhos/cm is greatly in excess of the GUIDELINE value (ECw < 0.5 mmhos/cm) where permeability problems might be expected to occur.

Sodium effects: An adj. SAR = 8.6 is considered to be in the increasing problem range and special cropping practices may be necessary for long term production. The salinity and Ca-$MgSO_4$ of this water is high enough to off-set or reduce to some extent the problems expected due to adj. SAR. The high Ca-$MgSO_4$ will also provide an available source of calcium and problems may not develop. Caution must be used and this water should be field tested to determine if any cropping practices may be needed to maintain good permeability since many crops, including cotton, are sensitive to oxygen stress caused by standing water.

In the three examples just given, a range of expected permeability problems has been shown. In many instances, farmers are successfully using these or similar waters and have learned to live with or overcome their problems. If problems become severe enough to reduce appreciably crop yields corrective action may be needed. The type of corrective alternatives available are discussed in the next section.

7.3 Management Alternatives for Permeability Problems

Since the permeability problem only reduces the volume of water placed into storage for crop use, there seems little need to take corrective action until either the crop water demand or the leaching requirement can no longer be satisfied. Other problems caused by reduced permeability, however, may also force corrective action. Included are problems such as waterlogging, crusting or compaction, poor aeration and germination or excessive weed and disease. These may be just as important in reducing yields as is an actual water shortage to the crop due to poor soil permeability. Corrective practices available include both "chemical" and "physical" methods.

The suggested practices that maintain or bring about a beneficial change in the soil or water chemistry include:-

- using soil or water amendments (gypsum, sulphur, sulphuric acid, etc.)
- blending or changing the irrigation water supply.

The physical methods include cultural practices that manipulate the soil to increase infiltration or reduce the rate of water flow over the soil and allow more "opportunity time" for infiltration:

- irrigating more frequently
- cultivating and deep tillage
- increasing the time allotted (duration) for an irrigation
- changing direction of irrigation to reduce grade (slope) of the land
- collecting and re-circulating runoff water
- with sprinklers, matching rate of water application to soil infiltration rate
- using organic residues.

To illustrate better why such practices are expected to be helpful each will be discussed from a general standpoint. This will help in selecting one of these or similar local practices that are applicable.

7.3.1 Using Soil or Water Amendments

Improved permeability should result if either the sodium in the irrigation water is reduced or the calcium and magnesium are increased. At present there is no process available for removing salts such as sodium from irrigation water which is low enough in cost for use in general agriculture. Chemicals, however, can be added to the soil or water to increase the calcium and improve the sodium to calcium ratio. Under favourable conditions this may improve water penetration into and through the soil. The chemicals used either supply calcium directly (as from gypsum) or supply an acid or acid forming substance (sulphuric acid or sulphur) which dissolves calcium from lime ($CaCO_3$) in the soil or reduces the bicarbonates in the water. Trials should always be conducted to determine if results are sufficiently beneficial to justify the use.

Gypsum, sulphur or sulphuric acid are the most commonly used soil amendments while gypsum, sulphuric acid and sulphur dioxide are used as water amendments. Granular gypsum has been applied broadcast to soils at rates of 2 to 20 t/ha. For land reclamation where sodium problems are extreme, rates as high as 40 t/ha have been used. Where the permeability problem is primarily in the soil surface, granular gypsum may be more effective if left on the soil surface or mixed with soil to a shallow depth, rather than worked deeper into the soil. It is estimated that no more than about 700 kg of gypsum per 1 000 m^3 of water can be dissolved from soil applied gypsum in any one year. Even so, soon after a gypsum application the surface soils may be rapidly leached and again exhibit the characteristic surface permeability problem while gypsum is still present a few centimetres below the surface.

Water applications usually require considerably less gypsum per hectare than soil applications. Water applications are particularly effective with low salinity water (EC_w < 0.5 mmhos/cm). They are less effective, however, with higher salinity water because of the low solubility of gypsum (about 0.25%) which allows too little calcium to dissolve to effectively balance the high sodium. For water applications, finely ground gypsum (0.25 mm, or finer - not granular or rock) is added more or less continuously and at a constant rate during the entire irrigation period. Gypsum applied in the water will usually supply no more than 1 to 4 meq/l of calcium to the irrigation water. Improvements in rate of water penetration will vary but increases of 30% to 400% can be expected where gypsum is effective. Improvement will depend on the soil situation as well as the water's calcium and salinity content.

<u>NOTE</u>:	1 meq/l of calcium from 100% gypsum is 86 kg gypsum per 1 000 m^3 of water.

Sulphur is effective for soil application to correct a sodium problem if lime ($CaCO_3$) is present in the soil. It furnishes calcium indirectly; by first oxidizing to an acid which in turn reacts with lime to furnish calcium. The oxidation process (by soil bacteria) is rather slow and requires a warm, well aerated moist soil. Since sulphur is applied to the soil and is not water soluble, it is effective for improving sodium problems below the soil surface but is not expected to improve surface permeability problems because the gypsum formed will be readily leached to lower depths. Sulphur has been used successfully for reclamation of calcareous soils in conjunction with good quality irrigation water.

Sulphuric acid is also used and can be applied directly to the soil or in the irrigation water. It reacts rapidly with soil lime since it does not have to go through the oxidation process. In some cases this gives a more rapid improvement to a permeability problem than does gypsum. However, the ultimate effect is about the same as that of an equivalent amount of gypsum. Sulphuric acid is highly corrosive and dangerous to handle It may damage concrete pipes, steel culverts, checkgates, and aluminium pipe (ONLY EXPERIENCED OPERATORS SHOULD USE).

Amendments other than gypsum, sulphuric acid and sulphur can be used. The benefits of any amendment should be tested in field trials as to cost, safety in use and effectiveness. Other amendments, however, will not be discussed but Table 7 gives comparative data of several common materials.

Table 7 - WATER AND SOIL AMENDMENTS AND THEIR RELATIVE EFFECTIVENESS IN SUPPLYING CALCIUM

Amendment	Tons equivalent to 1 ton of 100% gypsum 1/
Gypsum ($Ca\ SO_4 \cdot 2H_2O$)*	1.00
Sulphur (S)**	0.19
Sulphuric acid (H_2SO_4)*	0.61
Ferric Sulphate ($Fe_2(SO_4)_3 \cdot 9H_2O$)**	1.09
Lime Sulphur (9% Ca + 24% S)*	0.78
Calcium chloride ($CaCl_2 \cdot 2H_2O$)*	0.86
Calcium nitrate ($Ca(NO_3)_2 \cdot 2H_2O$)*	1.06

* Suitable for use as a water or soil amendment

** Suitable only for soil application

1/ The above are based on 100% pure materials. If not 100% make the following calculation to find tons (X) equivalent to 100% material

$$X = \frac{100 \times \text{tons}}{\%\ \text{purity}}$$

Example: If gypsum is 80% purity, $X = \frac{100 \times 1.00}{80} = 1.25$ tons
This says 1.25 tons of 80% gypsum is equivalent to 1 ton of 100% gypsum. (Fireman and Branson, 1965)

Amendments should only be used when they are needed and the demonstrated results justify their use and not just in the hope they may do some good. Chemical amendments cost money. They may be useful where soil permeability is low due to low salinity, excess sodium or carbonate/bicarbonate in the water. They will not be useful, however, if poor permeability is due to problems of soil texture, soil compaction, restrictive layers (hardpans, claypans) or high water tables. If the crop is receiving adequate water for near maximum yields, amendments will not increase yield but may make water management a little easier though at an additional cost for amendments, handling and application.

Example:

A low salinity water (ECw = 0.15 mmhos/cm) is being used for irrigation of citrus. Permeability problems have been experienced in the past causing oxygen stress (water ponding at the surface). Since fruit set was taking place, it was decided to add gypsum to the water to increase percolation and prevent waterlogging and oxygen stress at this critical time. On this 5 ha plot the needed irrigation was 100 mm. The gyp sum available was 70% pure and an increase of 2 meq/l of Ca was needed in the water. How much gypsum should have been purchased?

Given:

Total water requirement = 5 000 m^3

86 kg of 100% pure gypsum / 1 000 m^3 = 1 meq/l Ca

Calculation:

86 x 5 x 2 = 860 kg of 100% pure gypsum needed for 2 meq/l

$\frac{860 \times 100}{70} \cong$ 1 230 kg of 70% pure gypsum needed.

7.3.2 Blending or Changing Water Supplies

In some cases, problems are most easily solved by abandoning the problem water supply and substituting a better quality one. In many cases an alternative source of good quality may not be available. An alternate source of water, however, may be available which can be blended. The quality of such a mixture can be evaluated if a detailed water analysis of each source is available. The resulting concentrations can then be evaluated by means of the GUIDELINES of Table 1.

The effect of blending on the adj. SAR is shown in Table 6 while an example calculation is given here:

Example:

A canal supply is available to blend with Tubewell 116 (Table 4) water to the extent of 75% canal water and 25% Tubewell 116 water. What is the adj. SAR of the blended water supply?

Given	Ca + Mg meq/l	Na meq/l	HCO_3 meq/l	adj. SAR	ECw mmhos/cm
Tubewell 116	6.5	32.0	4.5	38.0	3.6
Canal water	1.9	0.5	1.8	0.76	0.23

(meq/l of (a) x proportion of (a) used) + (meq/l (b) x proportion of (b) used)
= resulting blend meq/l

Calculation:

Ca + Mg = (6.5 x 0.25) + (1.9 x 0.75) = 3.1 meq/l (blend)
Na = (32.0 x 0.25) + (0.5 x 0.75) = 8.4 meq/l (blend)
HCO_3 = (4.5 x 0.25) + (1.8 x 0.75) = 2.5 meq/l (blend)

From Table 3,

$$\text{adj. SAR} = \frac{8.4}{\sqrt{\frac{3.1}{2}}} \left[1 + (8.4 - (2.3 + 2.8 + 2.6))\right]$$

Blended water, adj. SAR = 10.9 ≅ 11
Blended water, ECw ≅ 1.07 mmhos/cm

7.3.3 Irrigating More Frequently

If the crops deplete the soil water and suffer water stress between irrigations, one obvious solution is to irrigate more often. This is a simple and effective solution particularly for shallow rooted crops or on soils whose initial infiltration rate is high but drops rather quickly.

The benefits of irrigating more frequently (an increased degree of wetness) were discussed for a salinity problem since the maintenance of a higher average soil water content reduced the average salt concentration to which the crop was exposed. From the soil permeability standpoint, this will also maintain a lower soil sodium adsorption ratio since dilution favours the adsorption of calcium and magnesium over sodium and losses of calcium due to precipitation will be kept to a minimum. This should be particularly applicable to high bicarbonate and high adj. SAR waters where severe drying between irrigations is believed to remove appreciable quantities of calcium by precipitation. The salinity problem evaluation (section 6.4.1) should be referred to for more discussion.

7.3.4 Cultivation and Deep Tillage

Cultivation or deep tillage is another effective but temporary solution to a permeability problem. Cultivation roughens the surface soil but is usually done for reasons other than to improve water penetration. However, where penetration problems are severe, cultivation or tillage may be particularly helpful. A rough, cloddy furrow or field as compared to a smooth one will improve penetration for the first irrigation or two. A normal cultivation procedure can sometimes be modified to leave a rougher surface.

Deep tillage (chiselling, subsoiling) can be expected to improve penetration for only one or two irrigations since most permeability problems occur at or near the soil surface, and the surface will soon revert to the original condition. Even though this does not result in permanent improvement it may improve the situation enough to make an appreciable difference in the crop yield. Deep tillage physically tears, shatters and rips the soil at deeper depths and is done prior to planting or during periods of dormancy when root pruning or root disturbances of permanent crops is less disruptive. Deep tillage should only be done when soils are dry enough to shatter and crack. If done wet, increased compaction, aeration and permeability problems can be expected.

With low salinity waters (ECw $<$ 0.5 mmhos/cm) the permeability problem usually occurs in the upper few centimetres of soil. A surface crust or nearly impermeable surface soil is a typical characteristic. Cultivation can break this surface crust, roughen the soil and open cracks and air spaces that will slow the flow of water and greatly increase the surface area exposed for infiltration.

In contrast, the permeability problem due to high sodium waters (high adj. SAR) may occur initially near the surface but progressively extend to deeper depths as the season advances or from year to year. Cultivation and deep tillage may permit increased quantities of water to enter the soil but usually only for a relatively short period of time.

7.3.5 Increasing Duration of Irrigation Application

Extending the duration of irrigation long enough to get the desired penetration has limitations since aeration, waterlogging, excessive runoff and surface drainage problems can result. However, by reducing the volume of flow and slowing the rate of advance of water over the field, the irrigation may be extended sufficiently to allow enough water to enter the soil. A pre-plant irrigation can safely be extended to the time necessary to fill completely the entire rooting depth to its field water holding capacity without damaging the crop. A pre-plant irrigation is sometimes the only opportunity to wet the deeper part of the crop root zone.

7.3.6 Changing Direction of Irrigation to One of Less Slope

This is particularly adapted to irrigation with furrows and strip-checks where the irrigation direction can be changed to one with less slope. This increases the duration of irrigation or opportunity time for infiltration to take place. Contour irrigation can also be used on uneven or warped surfaces. Existing distribution systems may complicate or negate such a change. The furrow patterns are often complicated on uneven terrain but can be arranged by preparing a topographic base map. (Methods for laying out a system are described by Brown (1963) and Kohler (1953).) In some cases, such a topographic base map can help to decide whether additional land levelling is needed to aid in more uniform water distribution and management.

7.3.7 Collecting and Recirculating Runoff Water

There may be no possible way to increase the quantity of water entering the soil except by running the water for a longer period. In which case, much of the water would simply run off the field. The additional runoff and wastage may cause other problems. Runoff can be controlled by collecting it in a sump at the low side of the irrigated field, and pumping it back up-slope through a pipeline to be recirculated into the irrigation stream. This surface runoff picks up very little salt and is only slightly degraded after passing through the field. By collecting and recirculating it, water is conserved, the crop is supplied with more water, and quantity of water and depth of penetration may be more easily regulated.

7.3.8 Matching Water Application Rate to Soil Infiltration Rate (Sprinklers)

Permeability problems with sprinkler irrigation are usually a design problem and evidenced by runoff or ponding in the field. If runoff occurs, a major adjustment in application rate is difficult since sprinklers are usually designed to apply water at a given rate when operated at a certain pressure. Changing pressure to apply less water may distort the areal uniformity of application and cause both excesses and deficiencies of water in the area being wetted. Some adjustment is possible, however, by changing to a smaller orifice at each sprinkler head and compensating for any increased pressure by using more sprinklers per set to irrigate a larger area. In some cases, a complete redesign of the system may be necessary. Another alternative is stopping the irrigation at the time runoff begins, and re-irrigating at a later time to supply adequate water to the crop.

7.3.9 Using Organic Residues

Crop residues left on the soil or worked into a rough cloddy soil surface will often improve water penetration. The more fibrous crop residues such as from cereal and sudan grass, which do not decompose and break down as rapidly, have improved penetration, whereas crop residues from the legumes generally have not. Presumably, the cereal and sudan straw physically keep the soil porous by maintaining channels and voids which improve water penetration. To be very effective, however, relatively large quantities of crop or other organic residues are usually needed; as with manure where from 40 to 400 metric tons per hectare have been used to improve water penetration. Rice hulls, sawdust, shredded bark and many other waste products in large volumes (10 to 20 percent by volume in the upper 15 cm depth) have been used with varying degrees of success. Nutritional upsets, salinity effects with manure, nitrogen shortages developing from use of sawdust, and chloride or potassium toxicities or upsets with rice hulls have been noted. From a long term standpoint, however, the return of organic residues to the soil is considered to be beneficial in that this helps to maintain soil structure as well as returning needed nutrients to the soil.

8. TOXICITY PROBLEM DISCUSSION

8.1 The Toxicity Problem

A toxicity problem is different from the salinity and the permeability problems, in that a toxicity occurs within the crop itself as a result of the uptake and accumulation of certain constituents from the irrigation water and may occur even though salinity is low. The toxic constituents of concern are sodium, chloride or boron. They can reduce yields and cause crop failure. Not all crops are equally sensitive but most tree crops and other woody perennial-type plants are. Toxicity problems of sodium and chloride, however, can occur with almost any crop if concentrations are high enough. Toxicity problems often accompany and are a complicating part of a salinity or permeability problem. Sprinkler irrigation may cause special toxicity problems due to sodium and chloride being absorbed through the leaves. Other trace elements which may cause toxicities are discussed in section 10.1.

8.1.1 Sodium

Most tree crops and other woody-type perennial plants are particularly sensitive to low concentrations of sodium. Most annual crops are not so sensitive, but may be affected by higher concentrations.

Use of an irrigation water high in sodium will usually result in a soil high in sodium but it may take several irrigations to cause the change. The crop takes up sodium with the water and it is concentrated in the leaves as water is lost by transpiration. Damage (toxicity) can result if sodium accumulates to concentrations that exceed the tolerance of the crop. Leaf burn, scorch and dead tissue along the outside edges of leaves are typical symptoms.

Sodium toxicity is often modified and reduced if calcium is also present. Moderate amounts of calcium may reduce sodium damage and higher amounts may even prevent it. Since the effect of sodium is dependent on both the sodium and calcium, a reasonable evaluation of the potential toxicity is possible using the sodium adsorption ratio (SAR) for the soil water or from the adjusted sodium adsorption ratio (adj. SAR) of the irrigation water.

The symptoms of sodium toxicity occur first on the oldest leaves since a period of time (days or weeks) is normally required before accumulation reaches toxic concentrations. Symptoms usually appear as a burn or drying of tissue at the outer edges of the leaf and as severity increases, progressing inward between the veins towards the leaf centre. Sodium toxicity can be confirmed by chemical analysis of the leaf tissue and by comparing sodium content of damaged leaf blades with that of normal leaf blades from undamaged areas nearby.

Sodium in leaf tissue in excess of 0.25 to 0.50 percent (dry weight basis) is typical of sodium toxicity for many tree crops. A combination of soil analysis, water analysis and plant tissue analysis will greatly improve the chances of a correct diagnosis of the problem.

Sodium sensitive crops include deciduous fruits, nuts, citrus, avocado and beans. The GUIDELINES of Table 1 use the adj. SAR to evaluate the sodium hazard of the irrigation water to these sensitive crops. If soil analyses are available showing the exchangeable sodium percentage (ESP), Table 8 can be used to give the relative tolerances of representative crops. An approximate soil ESP can be obtained using the nomogram in Appendix B. However, such estimates may be greatly in error if gypsum is present in the soil.

8.1.2 Chloride

Most tree crops and other woody perennial plants are sensitive to low concentrations of chloride while most annual crops are not. However, even the less sensitive crops may be affected at higher concentrations. Chloride is not adsorbed by soils but moves readily with the soil water. It is taken up by the roots and moved upward to accumulate in leaves similar to sodium. The toxicity symptom for chloride, however, is different: the leaf burn or drying of leaf tissues typically occurs first at the extreme leaf tip of older leaves rather than at the edges and progresses from the tip back along the edges as severity increases. Excessive leaf burn is often accompanied by abnormal early leaf drop and defoliation.

Chemical analysis of leaf blades can be used to confirm a probable chloride toxicity. Chloride content of leaves of sensitive crops in excess of 0.3 to 0.5 percent (dry weight basis) is often indicative of a toxicity. Petioles of some crops (grapes) are often used for analysis rather than leaves. Interpretative values will vary with crop and part of the plant used for analysis. For an evaluation of chloride in the irrigation water, use the GUIDELINES of Table 1. For chloride in the soil saturation extract, use the chloride tolerances of Table 9.

8.1.3 Boron

Boron is one of the essential elements for plant growth but is needed in relatively small amounts. If excessive, boron then becomes toxic. A boron toxicity problem is usually associated with boron in the irrigation water [1/], but may be caused by boron occurring naturally in the soil. The sensitivity to boron appears to affect a wide variety of crops while sodium and chloride toxicities were mostly centred on the tree crops and woody perennials.

1/ Few surface streams have boron problems. Boron is more prevalent in well waters and springs from geothermal areas or near earthquake faults.

Boron is taken up by the crop and is accumulated in the leaves and other parts of the plant. Toxicity symptoms typically show first on older leaf tips and edges as either a yellowing, spotting or drying of leaf tissues (or these in combination). The yellowing or spotting in some cases is followed by drying which progresses from near the tip along the leaf edges and toward the centre between the veins (interveinal). A gummosis or exudate on limbs or trunk is also sometimes very noticeable on seriously affected trees such as almonds.

Many sensitive crops show toxicity symptoms when boron concentrations in leaf blades exceed 250 to 300 ppm (dry weight). Some crops, however, are sensitive but do not accumulate boron in leaf blades. Stonefruits (peaches, plums, almonds, etc.), and pome fruits (pear, apple and others) even though being damaged by boron, may not accumulate boron in leaf tissue to the extent that leaf analysis is a reliable test. With these crops, the boron problem must be confirmed from the soil and water analysis, plant symptoms and growth characteristics.

A wide range of crops have been tested for boron tolerance by using sand culture methods. These crops have been grouped as to relative tolerance to boron in Table 10.

8.2 Toxicity Problem Evaluation

To evaluate the potential for a toxicity problem, a water analysis is needed that includes B, Na, Ca, Mg, Cl, CO_3 and HCO_3. The potential toxicity problem applies to irrigation of certain sensitive crops since these would be expected to do poorly if concentrations exceed the "severe problem" potential. Toxicities may occur independent of osmotic effects but in many instances will occur concurrently with either a salinity or permeability problem. The crop tolerance tables (Table 5) reflect a combination of both these (salinity-toxicity) since it would be difficult to separate them.

The three examples of Table 4 are evaluated in the following to illustrate the use of the GUIDELINES of Table 1 in evaluating a water's potential to cause a toxicity problem.

Tigris River at Baghdad, Iraq

The adj. SAR (2.5) and chloride (1.5 meq/l) are less than the GUIDELINE value for "No Problem". Toxicity, therefore, is not expected to be a problem. (Boron was not reported.)

Tubewell 116, Mona Project, Pakistan

The adj. SAR (38) and chloride (25.0 meq/l) are both in excess of GUIDELINE values for "Severe Problems". Satisfactory production of sensitive crops would be very difficult. Many other crops which are not so sensitive might be well adapted and these concentrations might not be sufficiently toxic to reduce yields greatly. Under extreme conditions of low humidity, sprinkler irrigation may cause leaf burn or defoliation on crops normally thought to be tolerant to sodium and chloride (boron information was not available).

Table 8 - TOLERANCE OF VARIOUS CROPS TO EXCHANGEABLE SODIUM (ESP) UNDER NON-SALINE CONDITIONS (Pearson 1960)

Tolerance to ESP and range at which affected	Crop	Growth response under field conditions
Extremely sensitive (ESP = 2-10)	Deciduous fruits Nuts Citrus (Citrus spp.) Avocado (Persea americana Mill.)	Sodium toxicity symptoms even at low ESP values
Sensitive (ESP = 10-20)	Beans (Phaseolus vulgaris L.)	Stunted growth at these ESP values even though the physical condition of the soil may be good
Moderately tolerant (ESP = 20-40)	Clover (Trifolium spp.) Oats (Avena sativa L.) Tall fescue (Festuca arundinacea Schreb.) Rice (Oryza sativa L.) Dallisgrass (Paspalum dilatum Poir.)	Stunted growth due to both nutritional factors and adverse soil conditions
Tolerant (ESP = 40-60)	Wheat (Triticum aestivum L.) Cotton (Gossypium birsutum L.) Alfalfa (Medicago sativa L.) Barley (Hordeum vulgare L.) Tomatoes (Lycopersicon esc.Mill.) Beets (Beta vulgaris L.)	Stunted growth usually due to adverse physical conditions of soil
Most tolerant (ESP = more than 60)	Crested and Fairway wheatgrass (Agropyron spp.) Tall wheatgrass (Agropyron elongatum (Host) Beau.) Rhodes grass (Chloris gayana Kunth)	Stunted growth usually due to adverse physical conditions of soil

NOTE: Estimates of the equilibrium ESP can be made from the irrigation water or more preferably from the SAR of the soil saturation extract using the nomogram in Appendix B. This estimation method is not applicable where soil gypsum is present. Effectiveness of any planned corrective action should be field tested before being applied on a large scale. Soils at ESP = 20-40 and above will usually have too poor physical structure for good crop production. The research results given above were obtained with soils whose structure was stabilized with Krilium.

Table 9 - CHLORIDE TOLERANCES IN THE SATURATION EXTRACT OF SOIL FOR FRUIT CROP ROOTSTOCKS AND VARIETIES IF LEAF INJURY IS TO BE AVOIDED (Bernstein, 1965)

Crop	Rootstock or variety	Maximum permissible Cl in saturation extract meq/l
	Rootstocks	
Citrus (Citrus spp.)	Rangpur lime, Cleopatra mandarin	25
	Rough lemon, tangelo, sour orange	15
	Sweet orange, citrange	10
Stone fruit (Prunus spp.)	Marianna	25
	Lovell, Shalil	10
	Yunnan	7
Avocado (Persea americana Mill.)	West Indian	8
	Mexican	
Grape (Vitis spp.)	Salt Creek,1613-3	40
	Dog Ridge	30
	Varieties	
Grape (Vitis spp.)	Thompson Seedless, Perlette	25
	Cardinal, Black rose	10
Berries* (Rubus spp.)	Boysenberry	10
	Olallie blackberry	10
	Indian Summer raspberry	5
Strawberry (Fragaria spp.)	Lassen	8
	Shasta	5

* Data available for single variety of each crop only.

Table 10 - RELATIVE TOLERANCE OF CROPS AND ORNAMENTALS TO BORON 1/:

Tolerance Decreases in Descending Order in each Column
(Wilcox, 1960)

Tolerant	Semitolerant	Sensitive
4.0 mg/l of boron	2.0 mg/l of boron	1.0 mg/l of boron
Athel (*Tamarix aphylla*)	Sunflower, native (*Helianthus annus* L.)	Pecan (*Carya illinoensis* (Wang.) K. Koch)
Asparagus (*Asparagus officinalis* L.)	Potato (*Solanum tuberosum* L.)	Walnut, black and Persian or English (*Juglans* spp.)
Palm (*Phoenix canariensis*)	Cotton, Acala and Pima (*Gossypium* sp.	Jerusalem artichoke (*Helianthus tuberosus* L.)
Date palm (*P. dactylifera* L.)	Tomato (*Lycopersicon esculentum* Mill.)	Navy bean (*Phaseolus vulgaris* L.)
Sugarbeet (*Beta vulgaris* L.)	Sweetpea (*Lathyrus odoratus* L.)	American elm (*Ulmus americana* L.)
Mangel (*Beta vulgaris* L.)	Radish (*Raphanus sativus* L.)	Plum (*Prunus domestica* L.)
Garden beet (*Beta vulgaris* L.)	Field pea (*Pisum sativum* L.)	Pear (*Pyrus communis* L.)
Alfalfa (*Medicago sativa* L.)	Ragged-robin rose (*Rosa* sp.)	Apple (*Malus sylvestris* Mill.)
Gladiolus (*Gladiolus* sp.)	Olive (*Olea europaea* L.)	Grape (Sultanina and Malaga) (*Vitis* sp.)
Broadbean (*Vicia faba* L.)	Barley (*Hordeum vulgare* L.)	Kadota fig (*Ficus carica* L.)
Onion (*Allium cepa* L.)	Wheat (*Triticum aestivum* L.)	Persimmon (*Diospyros virginiana* L.)
Turnip (*Brassica rapa* L.)	Corn (*Zea mays* L.)	Cherry (*Prunus* sp.)
Cabbage (*Brassica oleracea* var. *capitata* L.)	Milo (*Sorghum bicolor* (L.) Moench)	Peach (*Prunus persica* (L.) Batsch)
Lettuce (*Lactuca sativa* L.)	Oat (*Avena sativa* L.)	Apricot (*Prunus armeniaca* L.)
Carrot (*Daucus carota* L.)	Zinnia (*Zinnia elegans* Jacq.)	Thornless black berry (*Rubus* sp.)
	Pumpkin (*Cucurbita* spp.)	Orange (*Citrus sinensis* (L.) Osbeck)
	Bell pepper (*Capsicum annuum* L.)	Avocado (*Persea americana* Mill.)
	Sweetpotato (*Ipomoea batatas* (L.) Lam.)	Grapefruit (*Citrus paradisi* Macfad.)
	Lima bean (*Phaseolus lunatus* L.)	Lemon (*Citrus limon* (L.) Burm. f.)
2.0 mg/l of boron	1.0 mg/l of boron	0.3 mg/l of boron

1/ Relative tolerance is based on boron in irrigation water at which boron toxicity symptoms were observed when plants were grown in sand culture. Does not necessarily indicate a reduction in yield.

Pecos River at Carlsbad, New Mexico, U.S.A.

The adj.SAR (8.6) is just below and the chloride (12.0 meq/l) is above the GUIDELINE value for "Severe Problems". Satisfactory production of sensitive crops would be difficult especially if water is used sparingly (low leaching fraction). Many less sensitive crops, however, might be well adapted since the concentrations are not greatly in excess of the GUIDELINE values. Even some crops of medium sensitivity may be grown successfully if proper management techniques are used. Under extreme conditions of low humidity which are frequent in the area, sprinkler irrigation may cause leaf burn or defoliation of sensitive crops and perhaps on occasion of crops normally thought to be tolerant to sodium and chloride (boron information was not available).

If sensitive crops are to be grown there are management steps that can be taken to reduce the crop losses or restore the production capability. These will be briefly discussed in the next section.

8.3 Management Alternatives for Toxicity Problems

The toxicity problems occur at relatively low concentrations in the irrigation water. If sensitive crops are to be grown, certain management practices may be needed which either reduce the effective concentration of the toxic substances or make adjustments that improve production under existing concentrations.

Practices to reduce the effective concentration of toxic constituents include:

- irrigate more frequently;
- use additional water for leaching;
- in the case of sodium toxicity, use an amendment, such as gypsum or sulphuric acid;
- change or blend water supplies.

Practices to adjust to existing conditions include:

- plant crops less sensitive;
- use additional nitrogen to maximize fertility of the soil for growth of a crop such as citrus;
- improve water management where this is contributing to the toxicity problem by the inability to control and properly distribute water. This may include increased leaching fraction, periodic leaching, land grading, profile modification and artificial drainage as discussed under salinity problem control;
- special techniques to be used when irrigation is by sprinklers.

8.3.1 More Frequent Irrigations

As the crop uses water from the soil between irrigations, the salts are concentrated and may increase the severity of an existing toxicity problem. The concentrating effect and the benefits of increasing irrigation frequency have previously been discussed for both the salinity and permeability problem, and therefore they will not be repeated here. These sections should be referred to (sections 6.4.1 and 7.3.2).

8.3.2 Using Additional Water for Leaching

Additional leaching can be directed either towards prevention of a problem by using extra water so problems do not develop or towards correction after a problem becomes known.

If too little water is leached through the root zone an accumulation of toxic ions will occur. Therefore, if toxic concentrations are present, leaching will be needed to restore soil productivity.

For leaching of chloride, the same general discussion applies as was covered in the salinity section. The same "rule of thumb" would apply as for leaching of salts - a 30 cm depth of water leached through a 30 cm depth of soil should remove about 80% of the chloride.

The leaching of boron is much more difficult than of chloride. The "rule of thumb " here is that about three times as much leaching water is required to correct a boron problem as would be required to correct an equally severe salinity problem (Reeves et al., 1955).

For a sodium problem that is initially present prior to irrigation or that may have developed following irrigation, it may be necessary to add soil amendments (gypsum, sulphur, etc), to restore soil productivity. This was discussed in detail under the Permeability Problem section (section 7.3.1).

Once a toxic condition has been corrected, extra water for leaching may be helpful to reduce or prevent the development again. Even though these three toxicities (chloride, boron and sodium) are quite different, the concept of a leaching requirement to reduce the problem potential is still valid (Rhoades, 1968, 1974). This is discussed in the following few paragraphs.

For control of chloride, the leaching requirement as discussed for salinity should apply. However, if the chloride is more limiting than total salinity, the leaching requirement equation can be modified, thus the leaching requirement equation becomes (Rhoades, 1974):

$$LR_{Cl} = Clw/Cldw$$

where Clw represents the chloride in the irrigation water and Cldw represents the maximum permissible concentration of chloride in the drainage water. Limited information is available however on the maximum permissible values for Cldw and thus use of this equation must be accompanied by good judgement and an adequate margin of safety.

For sodium, the toxicity effect occurs at a lower adj. SAR value than for a permeability problem. Some research reports indicate high leaching fractions (LF) can be used to maintain a low soil SAR where a high adj. SAR is expected to cause a problem. A leaching fraction in excess of about 30 percent may be required (Bower et al, 1968 and Rhoades, 1974). The reduction of a sodium toxicity problem by deliberately adding these large quantities of water may cause aeration and drainage problems. Such an approach should be taken with caution and applied only after careful evaluation of other alternatives, their costs and effectiveness.

For boron, the concentrations in the irrigation water and soil water are closely related. In many field evaluations the soil saturation extract of the upper root zone usually approaches about the same concentration as the irrigation water applied. Where a potential boron problem is indicated, the boron crop tolerance table (Table 10) may be useful in selecting tolerant crops. There are limits to which boron can be reduced but it should be possible to reduce and maintain soil boron in the saturation extract at or a little less than the boron concentration in the water applied.

Plant symptoms along with soil, plant and water analyses are very useful in monitoring sodium, chloride and boron (and many other toxicity or nutritional problems) and aid in evaluating the adequacy or inadequacy of the soil, water or crop management practices. If no toxicity problem exists, or if present practices are sufficiently close to the suggested practice, benefits should not be expected from use of additional quantities of water.

8.3.3 Using an Amendment

An amendment such as gypsum added to soil may help correct a sodium toxicity problem. It should not be expected to be of appreciable benefit for chloride or boron except as the amendment might improve soil permeability and allow increased leaching to take place. Recent research at the U.S. Salinity Laboratory indicates that soil application of sulphuric acid may materially speed boron reclamation. This is presently under field test.

Gypsum is the most commonly used soil amendment for sodium toxicity problems. Sulphur and other acid forming materials do not directly supply calcium to the soil but the acids that are formed react with lime if present in the soil to release soluble calcium. In some cases, where bicarbonates are excessive, an acid material such as sulphuric acid added to the water can reduce their concentration. Amendments were discussed in more detail under the Permeability Problem discussion and this should be referred to (section 7.3.1)

The use of an amendment to correct or reduce a problem should be thoroughly tested in field trials in order to evaluate its effectiveness and determine benefits as related to costs. In general, where salinity is relatively low the beneficial response is much greater than where salinity is high since it is much easier to change the sodium-calcium ratio at relatively low salinity.

8.3.4 Changing or Blending of the Water Supply

If an alternative supply is available, but not adequate in quantity, a blend of waters may offer an overall improvement in quantity and quality and may reduce the problem potential. Blending is especially effective for a sodium toxicity problem since the proportions of monovalent and divalent cations absorbed on the soil are concentration dependent, with dilution favouring adsorption of cations of highest valence such as calcium and magnesium over sodium (Schofield, 1947). An example of the quality change resulting from blending along with more details of how to evaluate a blend are given under the Salinity and Permeability Problem discussion (sections 6.4.6 and 7.3.2).

8.3.5 Planting Crops Less Sensitive

Crop selection in many instances offers a very practical solution to a toxicity problem. There are degrees of sensitivity to boron, chloride and sodium just as there are degrees of sensitivity to salinity. Tables 8, 9 and 10 give the information now available on the tolerance of crops to sodium, chloride and boron respectively. The selection of more tolerant rootstocks offers another method of adapting the crop to the existing conditions. Certain rootstocks differ in their ability to exclude chloride as can be seen from Table 9.

8.3.6 Using Additional Nitrogen

If both salinity and low fertility are limiting yields, correction of either the salinity or fertility problem should result in a yield increase. This also should apply for toxicities. However, in the case of citrus, a boron toxicity seems to be reduced if nitrogen, as measured by leaf analysis, is maintained a little in excess of normal.

For example, the recommended leaf analysis for nitrogen in navel oranges is 2.2 to 2.4% N, but if boron is a problem, adding fertilizer nitrogen to raise leaf nitrogen to 2.6% is believed to be beneficial and to enable the citrus to better tolerate the boron and show less overall damage.

This additional nitrogen may increase vegetative growth of fruit crops, such as citrus. This maintains adequate leaf area for photosynthesis and growth. Whether this practice will be beneficial in other crops is not known at this time.

8.3.7 Improved Water Management

Includes practices to control better and distribute water on the field such as land grading, profile modification and artificial drainage. These have been discussed under Salinity Problem Control (see section 6.4.6).

8.3.8 Special Toxicity Effects Due to Sprinkler Irrigation

Overhead sprinkling of certain crops can cause special toxicity problems not encountered when irrigating by other surface methods. Excess quantities of sodium and chloride can be absorbed through leaves wet by the sprinkler and can cause leaf burn and, in some severe cases, defoliation. This occurs primarily during periods of high temperatures and low humidity and with rotating type of sprinkler heads. In between rotations of the sprinkler, water evaporates and salts are concentrated. The leaves absorb appreciably more salts during this alternate wetting and drying cycle than if sprayed continuously.

The leaf burn or crop damage seems to be primarily of specific toxicity due to uptake and accumulation of sodium or chloride. Toxicity occurs with sensitive crops at relatively low sodium or chloride concentrations. Toxicity has been reported to occur on citrus in several irrigated valleys of California, at concentrations as low as 3 meq/l of either sodium or chloride in the irrigation water. With furrow or flood irrigation these same concentrations cause no toxicity effects or leaf burn (Harding et al, 1958). Slight damage has been reported for more tolerant crops such as alfalfa under extremely high evaporative conditions at ECw = 1.3 mmhos/cm containing 6 meq/l sodium and 7 meq/l chloride. In contrast, little or no damage has occurred with waters as high as ECw = 4.0 mmhos/cm where sodium was 24 meq/l and chloride was 37 meq/l when evaporation conditions were low (Nielson, 1975). Several vegetable crops tested were fairly insensitive to foliar effect at very high concentrations in the semi-arid conditions of California (Ehlig and Bernstein, 1959).

Damage can occur from salt concentration accumulating on the external leaf surface due to salt spray. This may occur along the sea coast or downwind from sprinklers.

Relative crop tolerances to sodium and chloride in sprinkler applied irrigation water are not well established but, in general, crops sensitive to sodium or chloride are most sensitive to foliar absorption from sprinkler applied water. Most annual crops are not expected to be sensitive.

Where foliar absorption has been a problem, several practices are being followed which greatly reduce the problem.

Sprinkler irrigation at night: Night sprinkling has been surprisingly effective in reducing or eliminating the sodium and chloride toxicity due to foliar absorption. Humidity generally rises at night and winds may decrease.

Increase speed of rotation of sprinkler heads: Frequent or continuous wetting results in less absorption than intermittent wetting. Use of sprinkler heads that rotate at 1 revolution per minute or less are recommended. Changing the speed of rotation will probably involve a change of the sprinkler head.

Sprinkling during periods of low humidity and high evaporative demand: If weather patterns for an area are known or can be forecast, and soil conditions allow for storage of sufficient quantities of water for the crop to use between irrigations, then irrigations can be timed to avoid these critical periods as much as possible.

Crop selection for quality of water: If overhead sprinklers must be used, it may not be possible to grow certain sensitive crops such as beans or grapes. Local experience may have to be relied upon as guidelines to the crops more tolerant to local conditions.

Grow crops during the cooler time of year: Autumn - winter - spring are usually periods of lower temperature and higher humidity, and crops do not need to be irrigated as often. Crops adapted to the cooler season of the year can be harvested before the periods of extreme low humidity. In some cases late-spring, early-summer maturing crops may complete their growth cycle before the sodium or chloride can accumulate to concentrations that cause damage.

Change irrigation method: A change to another irrigation method such as furrow, flood or basin may be necessary. Under-tree sprinklers have been used in some cases but lower leaves, if wetted, may still show symptoms due to foliar absorption. Drip irrigation could also be used.

9. MISCELLANEOUS PROBLEM DISCUSSION

9.1 Miscellaneous Problems

From the standpoint of the GUIDELINES, there are just a few specific miscellaneous problems mentioned. These are concerned with nitrogen, bicarbonate and pH.

There are others which occur less frequently but will not be considered in detail here. Trace element toxicities, however, are discussed in the next section.

9.1.1 Nitrate and Ammonium Nitrogen

These two forms of nitrogen are nutrients which stimulate crop growth. If excessive quantities are present, production may be upset or maturity of the crop delayed. Concentrations occurring in water vary from zero to more than 100 milligrams per litre and in the GUIDELINES are reported as either nitrate-nitrogen (NO_3-N), or as ammonium-nitrogen (NH_4-N)[1/].

Nitrogen in the irrigation water acts the same as fertilizer nitrogen and excesses will cause problems just as fertilizer excesses cause problems. Production of nitrogen sensitive crops may be affected at nitrogen concentrations above 5 mg/1 (5 kg N per 1 000 m^3 of water) from either nitrate or ammonium. Sugar beets, for example, under excessive nitrogen fertilization grow to large size but with low purity and low sugar content and the amount of sugar produced per hectare may actually be reduced. Grapes, in some instances, grow too vigorously and yields are reduced, or grapes are late in maturing. Maturity of apricots, citrus and avocado may also be delayed and fruit may be poorer in quality. For many grasses and grain crops, lodging may appear due to excessive vegetative growth.

At more than 30 mg/l nitrogen (30 kg N per 1 000 m^3 of water), severe problems are expected with nitrogen sensitive crops. For crops not sensitive, more than 30 mg/l nitrogen may be adequate for high crop production and little or no fertilizer nitrogen may be needed. Less than 5 mg/l nitrogen has little effect even for the nitrogen sensitive crops. However, algae and aquatic plants in streams, lakes, ponds and canals are often stimulated and when temperature, sunlight and other nutrients are optimum, very rapid growth or algae blooms can occur. This excessive growth may result in plugged pipelines, sprinklers and valves to the point that either mechanical controls, such as with screens and filters, or chemical control such as with copper sulphate may be necessary.

1/ Many methods are used to report nitrogen since it is combined in many organic and inorganic complexes. Important, however, is the amount of nitrogen (N). Therefore, to allow comparisons, reporting should be in nitrogen regardless of its combination (i.e. 10 mg/l N is in 45 mg/l NO_3 or 13 mg/l NH_4 but both should be reported as 10 mg/l NO_3-N or 10 mg/l NH_4-N).

9.1.2 Bicarbonate

Bicarbonate, even at very low concentrations, has been a problem primarily when fruit crops or nursery crops are sprinkler irrigated during periods of very low humidity (RH < 30%) and high evaporation. Under these conditions, white deposits are formed on fruit or leaves which are not washed off by later irrigation. The deposit reduces the marketability of fruit and nursery plants.

A toxicity is not involved but as the water on the leaves partially or completely evaporates between rotations of the sprinkler, the salts are concentrated and CO_2 is lost to the atmosphere. If the concentration effect and CO_2 loss is great enough the less soluble constituents in the water, such as lime ($CaCO_3$), will precipitate and deposit on fruit and leaves.

9.1.3 pH

pH is a measure of the acidity or alkalinity of water. It is of interest as an indicator but is seldom of any real importance by itself. The main use of pH is a quick evaluation of the possibility that the water may be abnormal. If an abnormal value is found, this should be a warning and the water needs further evaluation and possible corrective measures taken. The pH scale ranges from 1 to 14, with pH = 1 to 7 being acid, 7 to 14 being alkaline, and pH = 7.0 being neutral. A change in pH, as from pH 7 to pH 8 represents a 10-fold decrease in acidity or a 10-fold increase in alkalinity. The normal range for irrigation water is from pH 6.5 to pH 8.4. Within this range crops have done well. Irrigation waters having pH outside this range may still be satisfactory but other problems of nutrition or toxicity become suspect.

9.2 Miscellaneous Problem Evaluation

To evaluate the potential for a miscellaneous type problem, a water analysis is needed that includes HCO_3, NO_3-N, NH_4-N and pH. The potential should be evaluated for the crops that are sensitive and a thorough analysis should be conducted if an abnormal pH is found. Nitrate-nitrogen should normally be included in all water analyses, while ammonium-nitrogen should be included where sewage effluent or waste waters containing fertilizer residues are suspected.

The three examples of Table 4 will be evaluated to illustrate how the GUIDELINES of Table 1 can be used to evaluate the potential for any one of the miscellaneous problems.

Tigris River at Baghdad, Iraq

The nitrate-nitrogen (1.8 meq/l) is considerably less than the GUIDELINE value for "No Problem". Ammonium-nitrogen cannot be evaluated. The bicarbonate (2.6 meq/l) is within the "Increasing Problem" range. If the crop is sprinkler irrigated during periods of very low humidity and high evaporation, a white deposit of lime may accumulate on the fruit or foliage of certain crops which might, without removal, reduce the market acceptability. pH (7.8) is in the normal range.

Tubewell 116, Mona Project, Pakistan

Bicarbonate (4.5 meq/l) falls within the "Increasing Problem" range. If sprinklers are used, the possible effect of a slight to moderate white deposit of lime on fruit or foliage needs to be considered. pH (7.7) is in the normal range. The nitrate-nitrogen should have been determined for this sample but was not.

Pecos River at Carlsbad, New Mexico, U.S.A.

Bicarbonate (3.2 meq/l) is in the "Increasing Problem" range. If sprinklers are used on market fruits or nursery plants a slight to moderate white deposit of lime on fruit or foliage may occur. pH and nitrate-nitrogen should have been determined for this analysis but were not.

9.3 Management Alternatives for the Miscellaneous Problems

The management alternatives that are effective for waters high in nitrogen are:

- plant crops that are not sensitive and which can effectively utilize the nitrogen from the irrigation water;
- where an alternative water source is available, blend or change water supplies to reduce nitrogen to more acceptable levels;
- use alternative water supplies or blend to acceptable concentrations during the critical growth stages of the crop. Crops are not sensitive to nitrogen at all stages of growth. Utilizing a high nitrogen content water as a fertilizer early in the season but blending or changing supplies during critical periods may be possible;
- t he nitrate and ammonium-nitrogen occurring in irrigation water is readily available to crops, therefore, fertilizer nitrogen rates supplied to crop should be reduced by an amount very nearly equal to that available from the water supply. Ammonium-nitrogen is seldom present at more than one mg/l unless ammonia fertilizer or sewage effluent is being added to the water;
- denitrification may be possible but is not often used.

Some of the management alternatives for correction of the white deposit due to bicarbonates would be the same as discussed under special toxicity effects due to sprinkler irrigation (section 8.3.7):

- irrigate at night during critical periods;
- if sprinklers rotate too slowly, increase the speed of rotation;
- do not sprinkle during periods of very low humidity;
- change irrigation method.

In addition to these, an acid amendment to the water can be used. This has been used for special crops (ornamentals). One worker recommends the addition of sulphuric acid to 90 percent of the HCO_3 equivalent (Rhoades, 1976).

For a pH problem, lime can be applied to correct low pH or soil acidity problems, and soil sulphur, gypsum or other acid material may be used to correct a high pH or extreme alkalinity problem. Correction of soil pH problems are of much greater importance than water pH problems. The soil is a good buffer, therefore an adverse water pH will normally be changed upon contact with the soil. The cause of the adverse water pH should be of more importance.

Many low salinity waters have a very low buffering capacity and a pH outside the normal range should not cause undue alarm. Again the source of the adverse pH should be sought out. The pH of a low salinity water will be immediately changed by the soil.

PART III OTHER CONSIDERATIONS

10. OTHER WATER QUALITY CONSIDERATIONS

10.1 Trace Element Toxicities

Trace elements will cause growth reductions due to toxicities although very little field experimentation has been done to determine water quality criteria for these. Suggested maximum concentrations of trace elements in irrigation waters are shown in Table 11 (National Academy of Sciences, 1972). These concentrations are based on the protection of soils for plant production under long continued use of the water. Criteria for short term use is also suggested for soils that have high capacities to inactivate these trace elements.

An indepth discussion of the suggested concentrations is presented in recent publications (National Academy of Sciences, 1972, and Pratt, 1972). The criteria presented should be adjusted when more reliable estimates become available.

10.2 Water Quality for Livestock

Excessive salinity in water can cause physiological upset or death of livestock. The effects of salinity are usually due to upsets in water balance rather than related to any specific ion. A guide for use of saline water for livestock and poultry is presented in Table 12 (National Academy of Sciences, 1972).

Some ions can cause specific problems. The National Academy of Sciences has proposed recommendations for levels of toxic substances (Table 13). Recommendations for safe concentration of these toxic substances are very much dependent upon the quantity of water an animal consumes each day and the weight of the animal. For any of the values presented in Tables 12 and 13, there are a number of variables such as these, but the values given represent an appropriate margin of safety. The original discussions presented in the National Academy of Sciences publication, and other sources of information, should be consulted prior to using a water of questionable quality.

Table 11 - RECOMMENDED MAXIMUM CONCENTRATIONS OF TRACE ELEMENTS IN IRRIGATION WATERS

Element (symbol)	For Waters Used Continuously on all soils mg/l	For Use up to 20 Years on Fine Textured Soils of pH 6.0 to 8.5 mg/l
Aluminum (Al)	5.0	20.0
Arsenic (As)	0.1	2.0
Beryllium (Be)	0.1	0.5
Boron (B)	1/	2.0
Cadmium (Cd)	0.01	0.05
Chromium (Cr)	0.1	1.0
Cobalt (Co)	0.05	5.0
Copper (Cu)	0.2	5.0
Fluoride (F)	1.0	15.0
Iron (Fe)	5.0	20.0
Lead (Pb)	5.0	10.0
Lithium (Li) 2/	2.5	2.5
Manganese (Mn)	0.2	10.0
Molybdenum (Mo)	0.01	0.05 3/
Nickel (Ni)	0.2	2.0
Selenium (Se)	0.02	0.02
Vanadium (V)	0.1	1.0
Zinc (Zn)	2.0	10.0

These levels will normally not adversely affect plants or soils. No data available for Mercury (Hg), Silver (Ag), Tin (Sn), Titanium (Ti), Tungsten (W).

1/ See Table 1.

2/ Recommended maximum concentration for irrigating citrus is 0.075 mg/l.

3/ For only acid fine textured soils or acid soils with relatively high iron oxide contents.

Source: Environmental Studies Board, Nat. Acad. of Sci., Nat. Acad. of Eng. Water Quality Criteria 1972.

Table 12 - GUIDE TO THE USE OF SALINE WATERS FOR LIVESTOCK AND POULTRY

Total Soluble Salts Content of Waters (mg/l)	
Less than 1 000 mg/l (EC < 1.5)	Relatively low level of salinity. Excellent for all classes of livestock and poultry.
1 000 - 3 000 mg/l (EC = 1.5 - 5)	Very satisfactory for all classes of livestock and poultry. May cause temporary and mild diarrhea in livestock not accustomed to them or watery droppings in poultry.
3 000 - 5 000 mg/l (EC = 5 - 8)	Satisfactory for livestock, but may cause temporary diarrhea or be refused at first by animals not accustomed to them. Poor waters for poultry, often causing water feces, increased mortality and decreased growth, especially in turkeys.
5 000 - 7 000 mg/l (EC = 8 - 11)	Can be used with reasonable safety for dairy and beef cattle, for sheep, swine and horses. Avoid use for pregnant or lactating animals. Not acceptable for poultry.
7 000 - 10 000 mg/l (EC = 11 - 16)	Unfit for poultry and probably for swine. Considerable risk in using for pregnant or lactating cows, horses, or sheep, or for the young of these species. In general, use should be avoided although older ruminants, horses, poultry, and swine may subsist on them under certain conditions.
Over 10 000 mg/l (EC > 16)	Risks with these highly saline waters are so great that they cannot be recommended for use under any condition.

Source: Environmental Studies Board, Nat. Acad. of Sci., Nat. Acad. of Eng. Water Quality Criteria 1972

Table 13 - RECOMMENDATIONS FOR LEVELS OF TOXIC SUBSTANCES IN DRINKING WATER FOR LIVESTOCK

Constituent	Upper Limit
Aluminum (Al)	5 mg/l
Arsenic (As)	0.2 mg/l
Beryllium (Be)	no data
Boron (B)	5.0 mg/l
Cadmium (Cd)	.05 mg/l
Chromium (Cr)	1.0 mg/l
Cobalt (Co)	1.0 mg/l
Copper (Cu)	0.5 mg/l
Fluoride (F)	2.0 mg/l
Iron (Fe)	no data
Lead (Pb)	0.1 mg/l 1/
Manganese (Mn)	no data
Mercury (Hg)	.01 mg/l
Molybdenum (Mo)	no data
Nitrate + Nitrite (NO_3-N+NO_2-N)	100 mg/l
Nitrite (NO_2-N)	10 mg/l
Selenium (Se)	0.05 mg/l
Vanadium (V)	0.10 mg/l
Zinc (Zn)	24 mg/l
Total Dissolved (TDS) Solids	10 000 mg/l 2/

1/ Lead is accumulative and problems may begin at threshold value = 0.05 mg/l.

2/ See Table 12.

Source: Environmental Studies Board. Nat. Acad. of Sci., Nat. Acad. of Eng. Water Quality Criteria 1972

10.3 Use of Sewage Effluent for Irrigation

Sewage effluent has been used for crop irrigation for many years and its use is increasing, particularly in water short areas. Effluent can be a usable water resource if suitable precautions are taken and due consideration is given to possible long term effects on the total water supply from increases in salts, nutrients and trace elements. If properly managed, the nutrients and trace elements in the sewage effluent can be an asset to agriculture. Use of effluent usually assumes at least primary treatment, (separation of solids from liquid) and usually secondary (separation, aeration and digestion, and discharge of clear stable liquid).

Decisions regarding the use of sewage effluent cannot be based on general statements. They must be based on water, soil and environmental considerations. Present knowledge is sufficient to allow irrigation of crops with sewage effluent where water quality fits within the GUIDELINES presented in Table 1. The other factors in the use of sewage effluent for irrigation involve management to avoid problems of disease, contamination, odours, trace element toxicities, along with aesthetic factors. These can be managed but the needed management must be evaluated on a case-by-case basis.

Sewage effluent can be a usable supplemental water supply and its use should be considered. A well managed irrigation system using a mix of irrigation water and sewage effluent can reduce the pollution potential as compared to disposal in rivers and other water bodies. The use of sewage effluent, however, requires a higher level of management than the use of usual water supplies primarily related to public health and public acceptance. There are certain health precautions required by local health officials but these normally are not sufficiently restrictive to prevent the irrigation of selected crops. The nutrients contained in this can also be of benefit if properly used.

The GUIDELINES of Table 1 can be used to assess the water quality related problems of salinity, permeability and toxicity but the miscellaneous problems encountered are more extensive than those listed in the GUIDELINES. Miscellaneous problems that may occur can be grouped as to physical, chemical and biological characteristics. Each of these will be discussed only to the extent needed to point out the problem.

Physical characteristics: The physical characteristics of sewage effluent include the total suspended solids, colour, temperature and odours. The total suspended solids include floating and suspended solids and dissolved organic substances. They may clog the soil pores, coat the land surface and reduce water penetration and aeration. The degree of problem due to organic content is dependent on the extent of treatment given to the sewage prior to use. Use of secondary treatment effluent presents very few problems due to suspended solids. Drying between irrigations and cultivation are the usual field practices used. The organic material can be beneficial to the soil if managed without aeration and odour problems. The management necessary will need to be evaluated on a site-by-site basis.

Colour has no effect on the use of a water for irrigation but can be an indication that organic material is present. Temperature is not thought to be a problem since sewage effluent is usually of a fairly normal temperature.

Odours are indicators of lack of aeration and anaerobic decompositions of organic matter. Strong odour may be obnoxious and indicative of operational problems but normal secondary effluent usually has little odour problem. Primary effluent use, however, may create strong odours and residents in the area of use may object, thus limiting its use to isolated areas.

Chemical characteristics: The chemical characteristics of sewage vary with the source of water, the sewage system characteristics and the type of discharge into the system. The chemical characteristics of importance to irrigated agriculture can be evaluated by the GUIDELINES of Table 1 and the recommended concentrations for trace elements presented in Table 11.

In effluents which receive considerable industrial wastes, trace element toxicity may be a problem. Copper, zinc, cadmium and boron content are sometimes high enough to be of concern. Others of importance include arsenic, chromium, lead, manganese, mercury and nickel. These are covered in Table 11 and should be assessed prior to approval for use for irrigation.

The trace element contamination in the effluent may act as a source of certain needed trace elements on deficient soils. Zinc and other deficiencies are sometimes corrected by use of sewage effluent.

Biological characteristics: Biological characteristics are concerned with bacteria, viruses, and other disease causing organisms. Raw sewage can be expected to be teeming with all sorts of micro-organisms, some of which may be pathogenic or disease causing. The degree of disinfection will depend upon the treatment used, the intended use and the health requirements in the area. The Public Health Service will usually decide the treatment needed for each of the various uses of the effluent. Effluent, though, has been extensively used for golf courses, parks, forage crops and processed crops such as cotton and sugar beets.

10.4 Water Quality and Environmental Concerns

Water quality affects agriculture but agriculture also affects water quality. Agriculture does certain things to water which, from an environmental and pollution standpoint, must be considered as polluting and which may need to be controlled to the fullest extent possible. Such things as animal wastes (manures), pesticides, fertilizer nutrients, salts and sediment coming from runoff or seepage from agricultural lands can each be a pollutant if, in some way, they enter and degrade the quality of a surface stream, lake, reservoir, estuary or an underground water supply - degrade it for some particular essential use or for some specific user of water. Almost all of these pollution problems related to agriculture involve water and improved water management may be the only key to control of agricultural pollution.

There are many other users of water besides agriculture. Each user has a need for both a certain quantity of water and a certain quality. These quality demands may be very different from one user to the next. The domestic user would like a high sodium, soft water; agriculture needs a high calcium, hard water. In several countries there are designated governmental agencies whose business it is to oversee the quality aspects of the "waters of the state" in order to assure that each of the many essential uses of water is protected as to both present and future quality needs. Where such a use is considered absolutely essential or beneficial to the total needs of the people, such a use is termed a "beneficial" use with quality rights that must be protected. Each water supply or water body has its designated "beneficial" uses and will very often have specific quality objectives that must be adhered to. A typical grouping of beneficial uses in the USA for which the quality of water is to be protected usually includes: (1) fish and wildlife; (2) aesthetics and recreation; (3) agriculture; (4) domestic and municipal; and (5) industrial.

There may be no established priority of use. The demands of fish and wildlife for water of certain temperature, oxygen content, low salinity and freedom from excessive pesticides or heavy metals are sometimes considered equal to the quality demands of people, agriculture or industry. One cannot be sacrificed for the demands of the others. Such equality may not be possible or desirable in every country or area situation. The intent, however, should be not just to prevent further quality degradation of the water resource, but both to protect and enhance the quality if at all possible.

In the USA, waste disposal into water bodies is not considered a "protected" beneficial use and the present programme calls for sewage effluent to be reclaimed, recycled or otherwise utilized. It can then be used to supplement and extend the available water supplies and will not degrade the quality of receiving waters for the designated beneficial uses.

Agriculture, too, must upgrade its waste disposal practices. To be specific, here are some pollution abatement measures that are now being enforced in the State of California, USA - an irrigated area in which at least 85% of all the developed water supply is used by agriculture. The first pollution abatement requirement has been placed on the animal industry - there shall be no runoff of polluted waters ("brown water") to surface streams from areas such as dairies, feedlots, poultry houses or from manure storage areas In addition, there are attempts to restrict indiscriminate use or disposal of manures in some areas because of the pollution hazard. A second measure requires that any agricultural enterprise having a discharge of wastes from a pipeline, ditch or drainage canal must register the discharge with the State and must monitor it as to quantity (volume) and quality characteristics. This monitoring is for quality characteristics such as sediment load (total suspended solids), salinity (electrical conductivity) and any other pollutants that may be shown to be of importance in the discharge (nitrogen, phosphorous, pesticides, etc.). The purpose of the initial monitoring is to obtain data from which decisions may be made as to the necessity for control and ways to control the pollutants in the discharge.

As regards control of pollution coming from these discharges, a first and obvious possible solution that has been proposed is to establish a "no discharge" policy. Under such a "no discharge" policy, no waste waters or return-flow waters could be discharged off the farm. Waste waters or water diverted or pumped for use would have to be used. There would be no surface discharges from pipes, canals or drainage ditches to surface streams, lakes or estuaries. A second possible solution might be to require that all discharges of waste waters be diluted to the point of acceptability before discharge. A salty drainage water for example, with ECw = 6 mmhos/cm, might need to be diluted with 5 volumes of good quality water before it would meet an ECw = 1 mmhos/cm quality requirement for discharge. Such great volumes of water as would be required for dilution purposes are normally not available. A third possible solution would be to disallow discharge of any "usable" waste waters but allow discharge of "unusable" waters. Under this sort of policy, if the water has a use, it must be used; if it has no further use, it could be discharged. The pollution problem then would be to find an acceptable place to which such unusable waters could be discharged.

Each of the above three approaches offers a solution to the discharge of wastes from agriculture and each may be acceptable under certain circumstances. The acceptability, however, for a specific location may change over a period of time. Dilution might be acceptable as long as adequate water was available but when surpluses were no longer available, the "no discharge of usable waters" policy might be more acceptable but would probably require a suitable system to be available to accept, transport and dispose of all unusable waters.

In addition to the previously mentioned pollution sources, the pollution of underground water supplies from wastes carried in diffuse sources, such as downward percolating (below-crop) drainage waters from agriculture, is also of considerable concern and is being studied as to possible means for control. At present, however, there seems to be no practical way to require routine monitoring of pollutants that may be moving in soil water below crops. We believe, however, that the best practical control of these diffuse sources of pollutants lies in improved and more efficient water management to reduce percolation losses to a reasonable minimum in which use is based on crop demand for water (ET), the leaching requirement for salinity control (LR) and the efficiency achievable with the system of irrigation and distribution system used.

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APPENDIX A

PRECAUTIONS FOR SAMPLING

This is intended to be a very brief non-technical discussion to obtain more reliable water samples for analysis.

A laboratory analysis is no better than the sample submitted for analysis. The sample should be as representative of the conditions of use as it is reasonably possible to make it.

1) Sample bottles should be clean. If possible rinse a clean bottle, at least three times with the water to be sampled. If samples are to be analysed for boron, plastic bottles (not glass) should be used.

2) Size of sample: one quart or one litre is usually ample.

3) A representative sample. Take time to think about the reasons for the sample. Get a sample or series of samples that will be representative of the conditions of use. For surface waters, decide where to take the sample - surface, below the surface, near the bottom, mid-stream or edge. In taking samples representative of the water diverted for irrigation, will one sample be adequate or are differences expected in quality due to flow rate, drainage return-flow fluctuations, etc. that indicate a series of samples will be needed to show changes. If a series is necessary, over what time interval - one day, one week, one month, one year, or several years? A choice should be made based on types and numbers of samples needed to be representative of true conditions.

For well water pumped from the underground sampling is simpler. Be sure the pump has been delivering water for at least 30 minutes. If a new well, a sample taken after surging or well development and after several hours delivery at designed capacity should be more representative than samples taken earlier.

4) Handling and storage. Samples should be kept cool until analysed. If samples cannot be analysed immediately storage near 4°C is ideal. Samples for nitrates, ammonia or organic substances will need to be kept frozen or near freezing (4°C). This is to prevent utilization or depletion of these constituents from the sample by growth of organisms (bacteria, algae, etc.). Freezing is a very satisfactory method of holding samples prior to analysis but remember that water expands on freezing and the container must be less than full to allow for expansion.

APPENDIX B

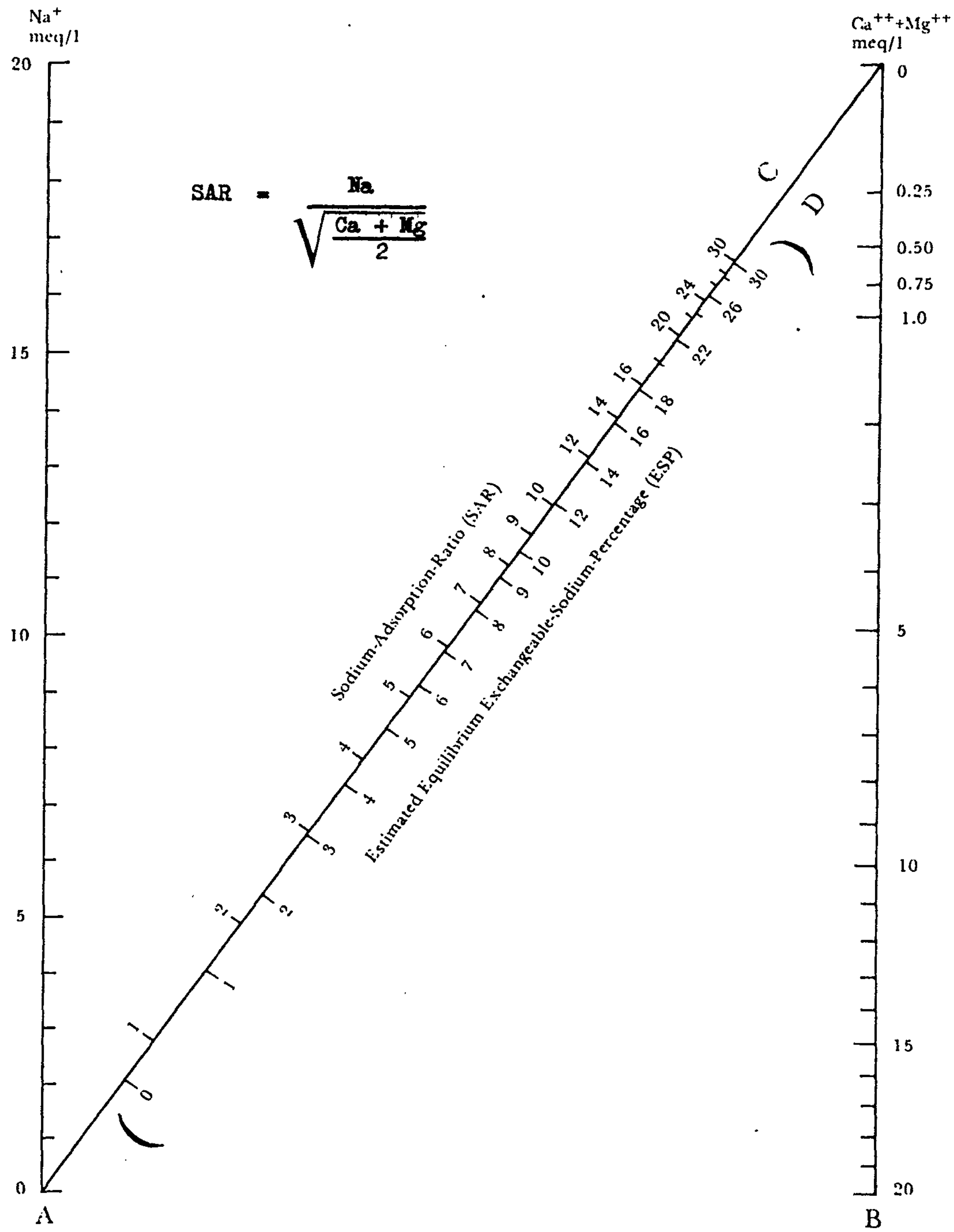
The SAR can be obtained from the nomogram on the next page, where

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

This SAR value is then used to obtain the adjusted SAR of the irrigation water from the following equation:

$$adj.SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \left[1 + (8.4 - pHc)\right]$$

The adj. SAR calculation procedure is given in Table 3 of the main document.



Nomogram for Determining the SAR Value of Irrigation Water and for Estimating the Corresponding ESP Value of a Soil that is at Equilibrium with the Water (USDA, 1954).

APPENDIX C

The average salinity of the crop root zone (ECe) varies with the salinity of the irrigation water (ECw) and the leaching fraction (LF). If it is assumed that the crop responds to the average salinity of the root zone and water uptake from each quarter of the root zone is 40-30-20-10%, the average soil salinity affecting yield can be calculated. The following two tables present the results of such a calculation.

TABLE - Average Soil Salinity (ECe) of the Crop Root Zone as Affected by Quality of Water Applied (ECw) and Leaching Fraction (LF)

Quality of Water (ECw)	Average Soil Salinity (ECe)				
	LF.05	LF.10	LF.16	LF.20	LF.30
0.1	0.32	0.21	0.15	0.13	0.10
0.2	0.65	0.41	0.31	0.27	0.21
0.4	1.30	0.82	0.61	0.53	0.42
0.7	2.27	1.44	1.07	0.93	0.73
1.0	3.25	2.05	1.53	1.33	1.04
2.0	6.50	4.11	3.06	2.66	2.08
4.0	13.00	8.21	6.11	5.33	4.15
7.0	22.75	14.37	10.70	9.32	7.27
10.0	-	20.53	15.28	13.31	10.39
20.0	-	-	-	26.63	20.77
40.0	Doubtful that agronomic crops can be grown				

These calculated averages are based on the following assumptions:

1) 40% of crop water uptake comes from 0 to 25% depth of root zone, 30% from 25 to 50% depth, 20% from 50 to 75% depth, and 10% from the lower 75 to 100% depth.

2) Crop responds to average salinity of root zone.

3) Irrigations will be on "as needed" basis with up to 50% of available soil water used by crop before irrigation water is again applied. For "high frequency irrigations", a weighted average salinity based on average salinity of soil water taken up by crop might be more realistic.

4) Since salinity concentration effects are nearly additive, the above table can be used for estimating effects of any quality of water (ECw) for a given LF.

TABLE - Average Soil Salinity (ECe) of the Crop Root Zone as Affected by Leaching Fraction (LF) and Quality of Water (ECw)

LF	Applied % of ET	Average Soil Salinity (ECe)			
		ECw = 1	ECw = 2	ECw = 3	ECw = 4
0	100.00	-	-	-	-
.01	101.01	11.51	23.02	34.53	46.03
.02	102.04	6.43	12.86	19.29	25.72
.03	103.09	4.70	9.39	14.09	18.78
.04	104.17	3.80	7.61	11.41	15.21
.05	105.26	3.25	6.50	9.75	13.00
.10	111.11	2.05	4.11	6.16	8.21
.16	117.65	1.53	3.06	4.58	6.11
.20	125.00	1.33	2.65	3.99	5.33
.25	133.33	1.16	2.32	3.48	4.64
.30	142.86	1.04	2.08	3.12	4.15
.35	153.85	0.95	1.89	2.84	3.78
.40	166.67	0.87	1.74	2.61	3.49
.45	181.82	0.81	1.62	2.43	3.24
.50	200.00	0.75	1.52	2.28	3.04
.60	250.00	0.68	1.36	2.04	2.72
.70	333.33	0.62	1.24	1.86	2.48
.80	500.00	0.57	1.14	1.72	2.29
.90	1000.00	0.53	1.07	1.60	2.13

These calculated averages are based on the following assumptions:

1) 40% of crop water uptake comes from 0 to 25% depth of root zone, 30% from 25 to 50% depth, 20% from 50 to 75% depth, and 10% from the lower 75 to 100% depth.

2) Crop responds to average salinity of root zone.

3) Irrigations will be on "as needed" basis with up to 50% of available soil water used by crop before irrigation water is again applied. For "high frequency irrigations", a weighted average salinity based on average salinity of soil water taken up by crop might be more realistic.