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IRRIGATION AND DRAINAGE PAPER 29

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water quality for agriculture

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FOOD AND AGRICULTURE ORGANIZATION
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RIGATION AND DRAINAGE PAPER 29

water quality for agriculture

by

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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
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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 ≅ 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 ≅ 10 x EC in millimhos/cm

OP = -0.36 x EC in millimhos/cm

mg/l ≅ 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.

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).

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.

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

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 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.

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.

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.

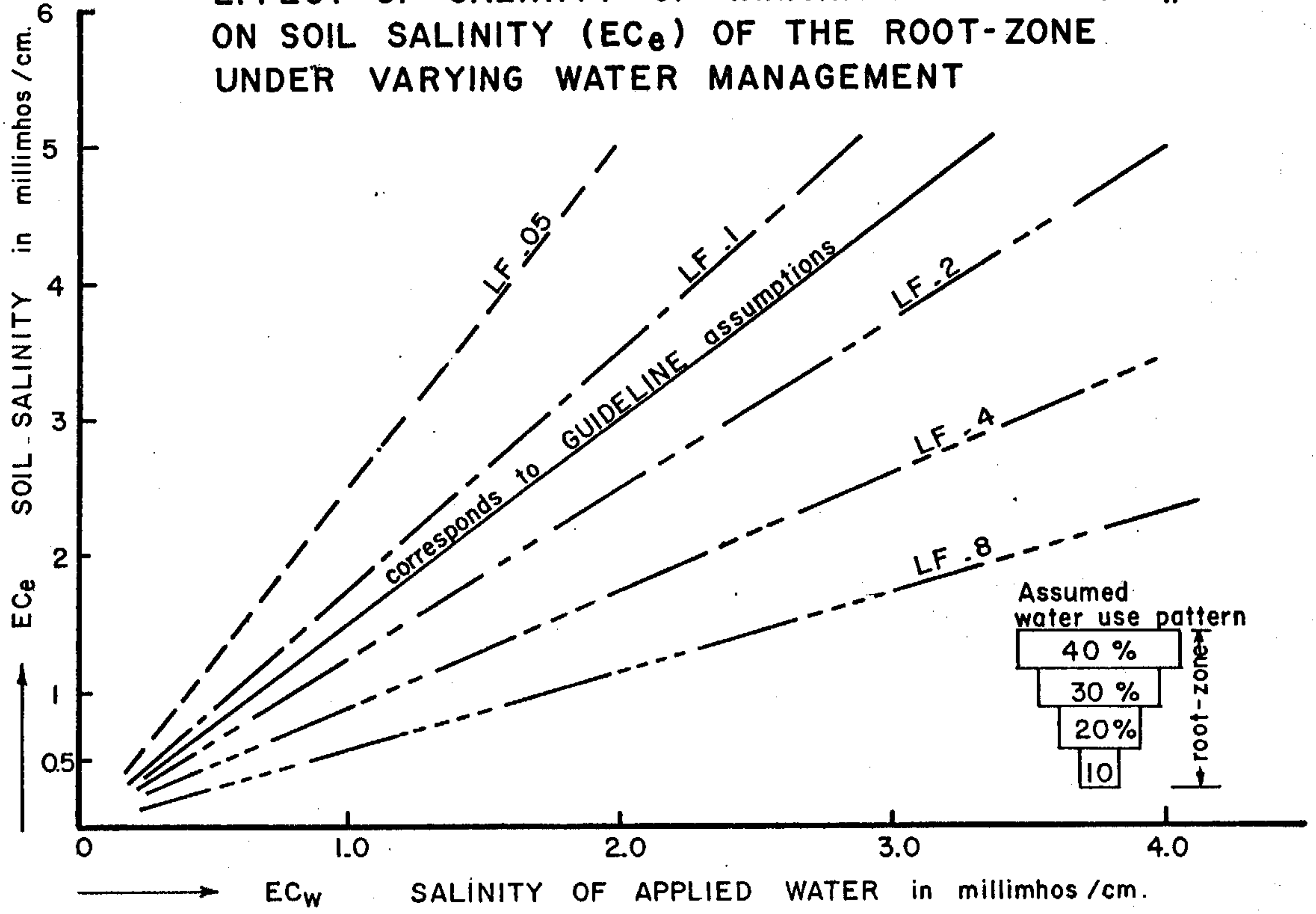
If by leaching a long term salt balance is achieved, the average soil salinity of the root zone will be closely associated with the quality of the irrigation water applied as well as with the fraction of water moving through the root zone. The crop primarily responds to this average salinity and any 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. 2

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



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 ECsw= 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 ECsw = 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 ECsw = 3 mmhos/cm, 20 days supply at ECsw = 15 mmhos/cm and a 10 days supply at ECsw = 30 mmhos/cm. This illustrates why the common practice of irrigating more often when using saline water is needed.

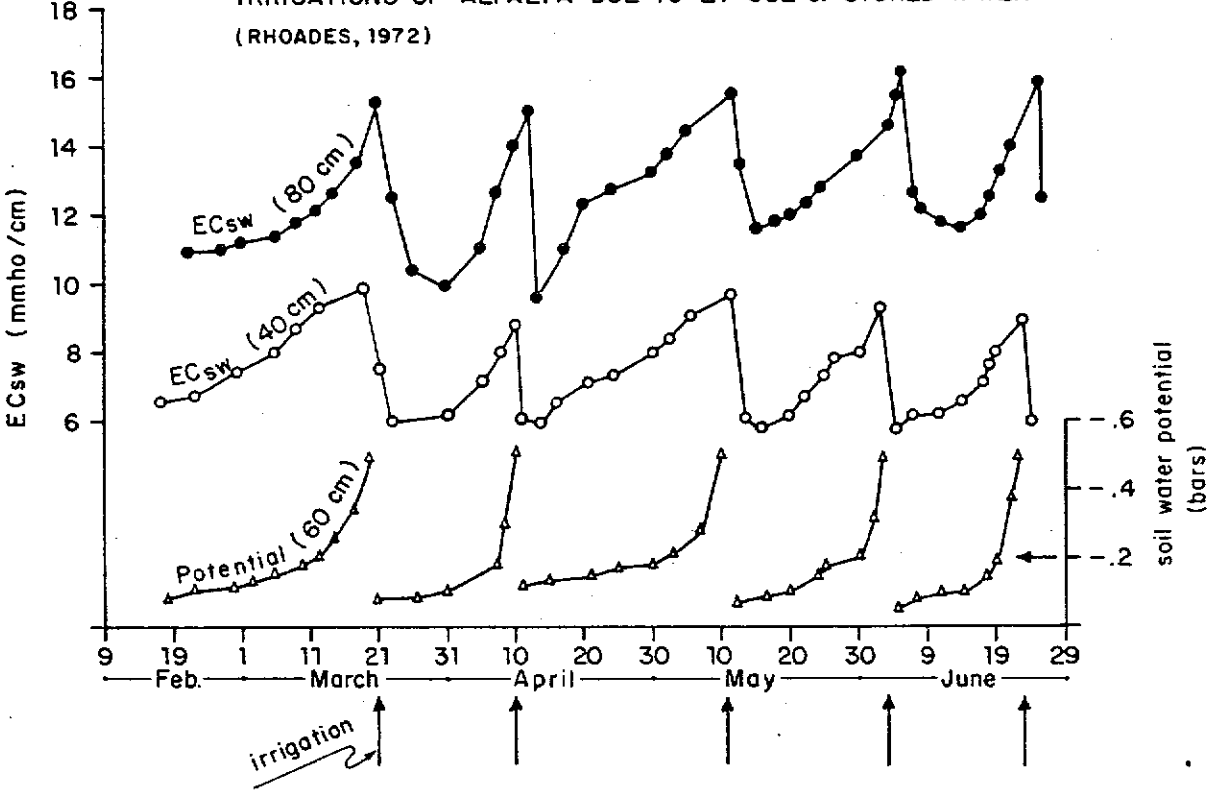
Since salinity (osmotic potential) and soil water (soil water potential) in the root zone are not uniform throughout, the plant roots are exposed to various levels of water availability due to differences in total potential. The plant will integrate the different total potentials throughout the root 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.

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

- 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).

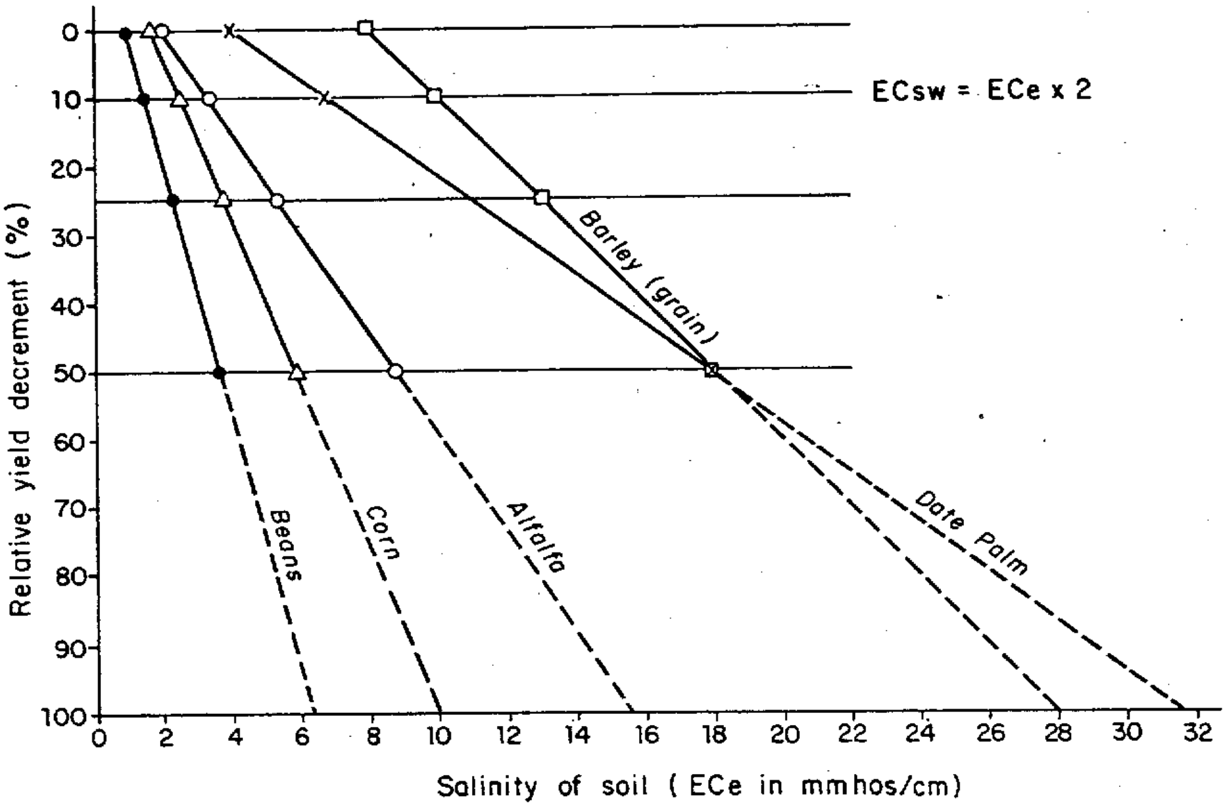
If water is taken or supplied on a "rotational basis" (fixed interval) increasing the frequency of irrigation may not be possible and other practices will need to be considered.

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

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 continued

CROP	0%		10%		25%		50%		MAXIMUM
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	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%		10%		25%		50%		MAXIMUM
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	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%		10%		25%		50%		MAXIMUM
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	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.

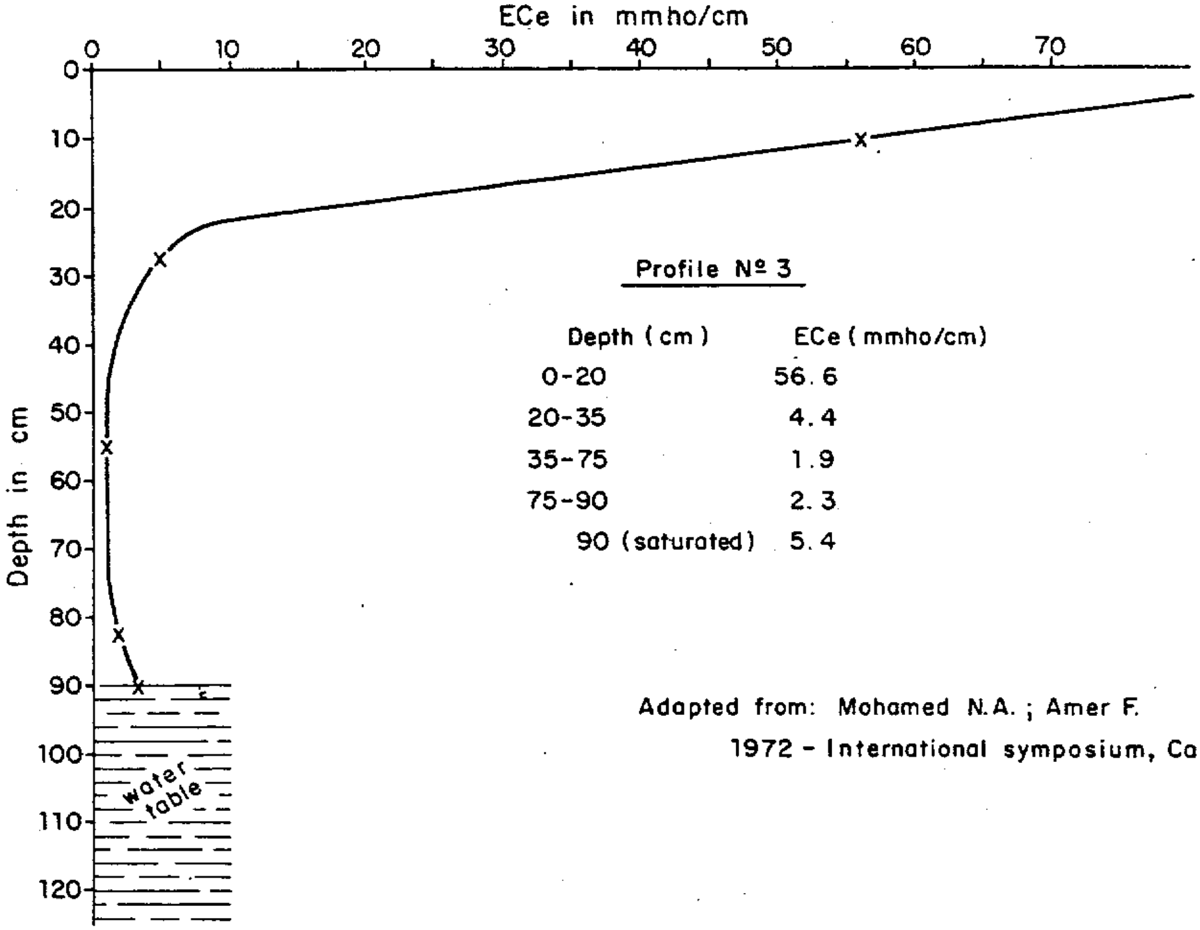
8/ Average for Boer, Wilman, Sand, and Weeping varieties. Lehman appears about 50% more tolerant.

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).

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

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:

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.

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

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.

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

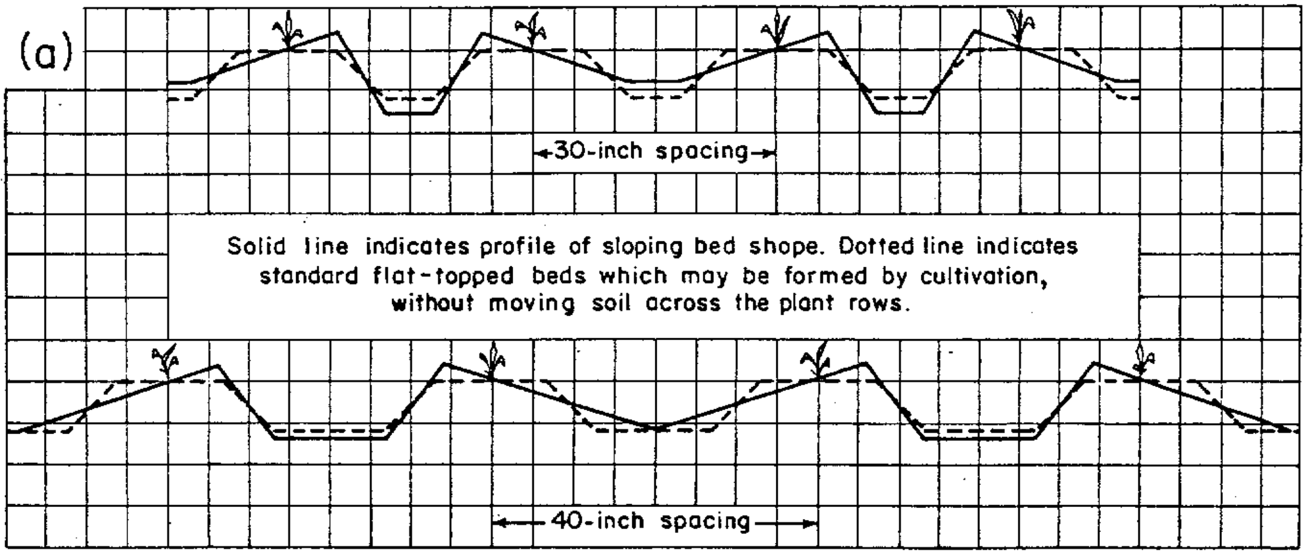
Obtaining a satisfactory stand of furrow irrigated crops on saline soils or when using poorer quality water is a particularly serious problem. Growers sometimes compensate by planting two or three times as much seed as normal. In other cases, appropriate adjustments in planting procedures are made to 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.

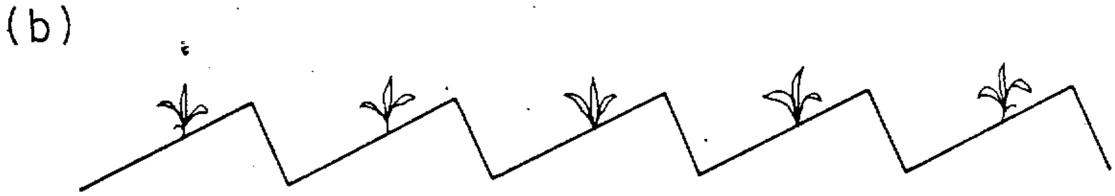
There are other alternatives. Alternate furrow irrigation may help. If the beds are wetted from both sides, the salts accumulate in the top and centre of the bed (Figs. 9a and 9d) but if alternate furrows are irrigated, the salt can be moved beyond the single seed row (Fig. 9b). The salts may still accumulate but the extent will be reduced. The

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.

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).

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

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

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.

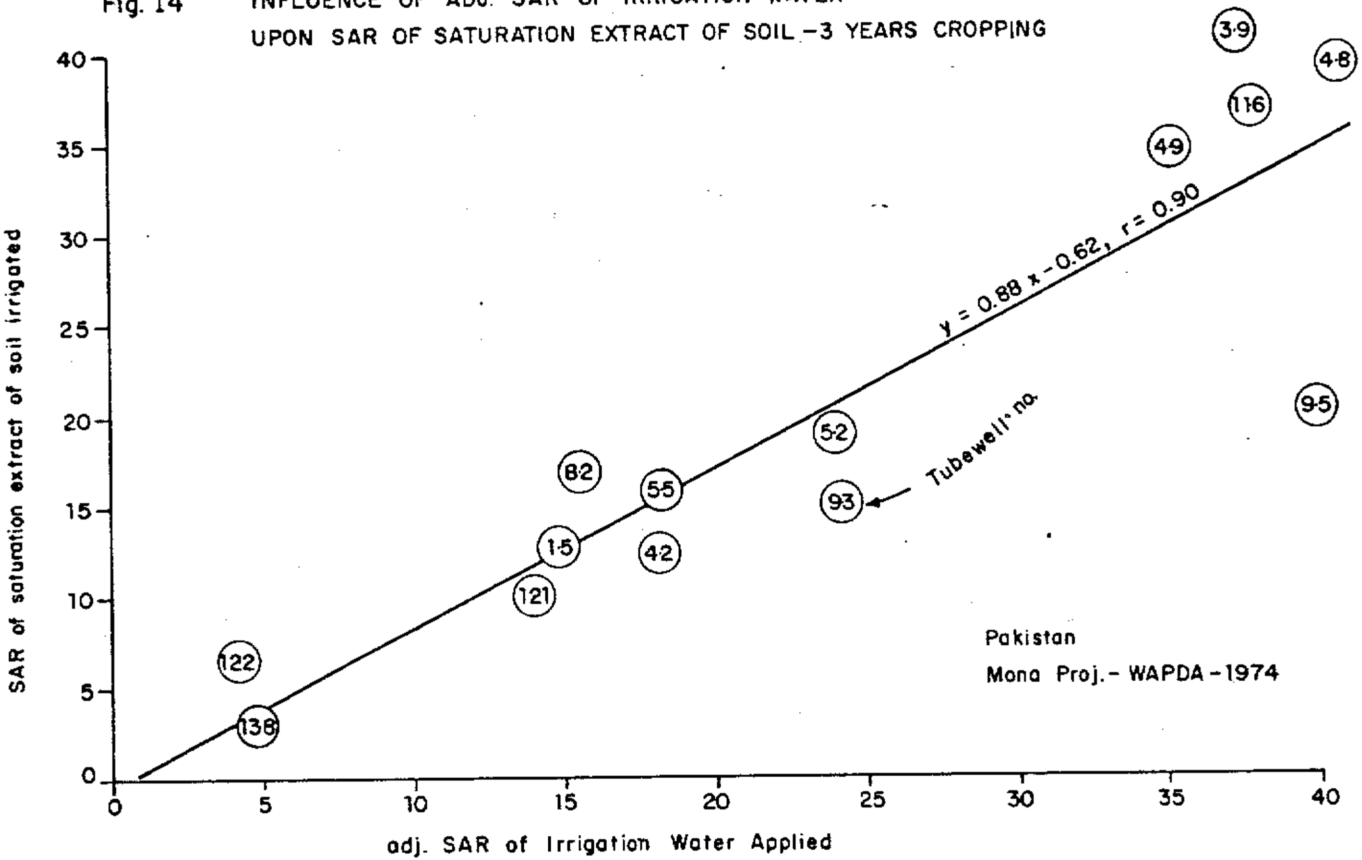
The most commonly used method to evaluate the potential has been the Sodium Adsorption Ratio (SAR) according to the equation:

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

where Na = Sodium in meq/l

Ca + Mg = Calcium plus magnesium in meq/l

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



7.2 Permeability Problem Evaluation

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).

Tigris River at Baghdad, Iraq

Low salinity effects: 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.

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

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

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

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 gypsum 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?

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 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.

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.

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

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.

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).

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.

}.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.

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.

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 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

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.

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

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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.

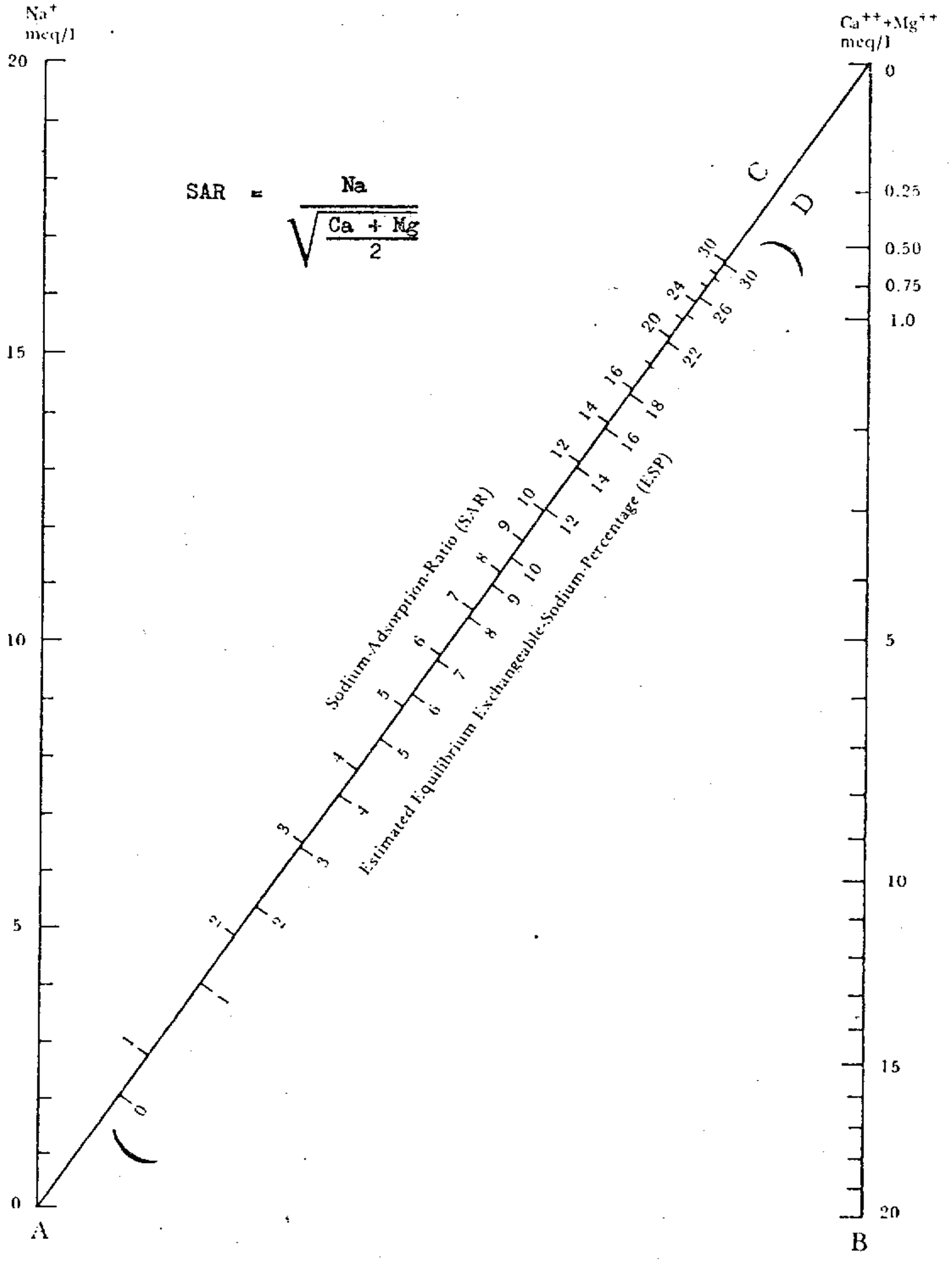
1) Sample bottles should be clean. If possible rinse a clean bottle, at least three times with the water to be sampled. If samples are to be analysed for boron, plastic bottles (not glass) should be used.

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.



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).

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.