GROUNDWATER INFORMATION SHEET

Salinity

This groundwater information sheet provides general information regarding a specific constituent of concern (COC). The information provided herein relates to wells (groundwater sources) used for public drinking water, not water served at the tap.

"Salinity" is a measure of the amount of dissolved particles and ions in water. There are several different ways to measure salinity; the two most frequently used analyses are described below:

- Total Dissolved Solids (TDS): A measure of all dissolved substances in water, including organic and suspended particles that can pass through a very small filter. TDS is measured in a laboratory and reported as milligrams per liter (mg/L).
- Electrical Conductivity (EC): The ability of an electric current to pass through water is proportional to the amount of dissolved salts in the water – specifically, the amount of charged (ionic) particles. EC is a measure of the concentration of dissolved ions in water, and is reported in micromhos per centimeter (µmhos/cm) or microSiemens per centimeter (µS/cm) (µmho is equivalent to a µS). EC is measured in a laboratory or with an inexpensive field meter. It also is referred to as specific conductance and specific conductivity.

"Salinity" can include many different ions; however, relatively few make up most of the dissolved salts/minerals in water. The most common are: chloride, sodium, nitrate, calcium, magnesium, bicarbonate, and sulfate. The concentration of boron, bromide, iron, and other trace ions can be locally important.

Approximate Total Dissolved Solids (TDS) Values in Natural Waters

Natural Water	TDS (mg/L)
Precipitation	10
Pristine Freshwater Lakes and Rivers	10 to 200
Amazon River	40
State Water Project Deliveries	275
Lakes Impacted by Road Salt Application	400
Agricultural Impact to Sensitive Crops	500
Colorado River Water	700
Average Seawater	35,000
Brines	>50,000
Groundwater	100 to >50,000

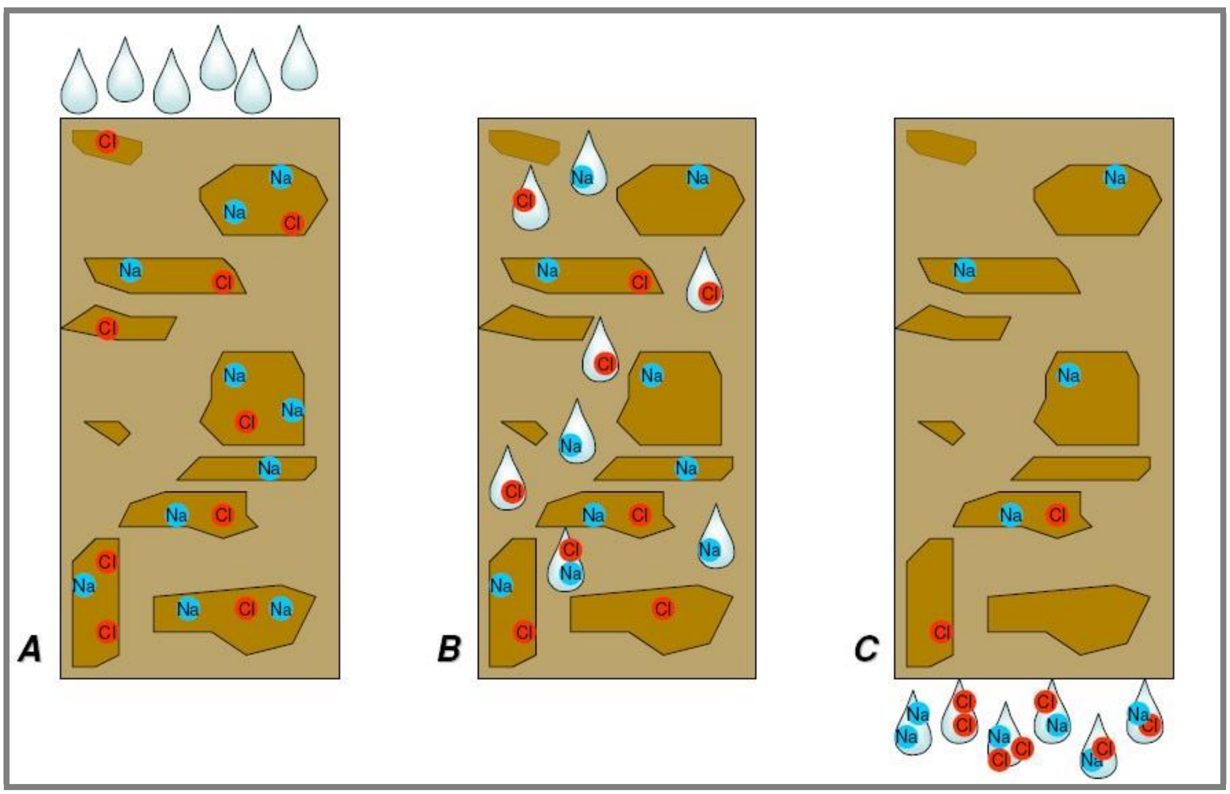
The clarity of water is unrelated to salinity (TDS). For example, visibility in the ocean can be hundreds of feet, even though ocean water has a very high salinity (TDS of 35,000 mg/L). On the other hand, water with low visibility like the Mississippi River can have low TDS (~200 mg/L) because the particles that obscure visibility are not dissolved, and can be easily filtered from the water. The amount of dissolved material in natural waters is a complex function of climate, land-use patterns, human activity in the watershed, and geologic formations (rocks and soils) of the hydrologic basin.

Adverse Effects

High concentrations of salts can damage crops, affect plant growth, degrade drinking water, damage home or industrial equipment and can be a health threat. Most salts do not naturally degrade, and can be persistent in groundwater. The economic impact of increased salinity in groundwater and surface water can result in fallowed farmland, unsuitable drinking water, and other environmental issues.

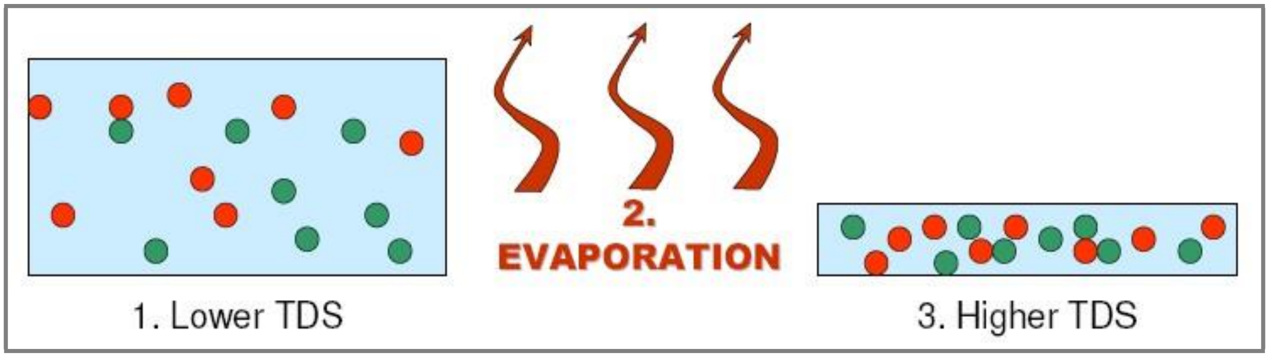
Sources of Salt

Salts enter groundwater through dissolution of soil, rock, and organic material. A schematic illustrating how dissolution occurs is shown below. Salinity will increase with time as more minerals in contact with groundwater will dissolve.



Dissolution of Natural Materials: Water is introduced to the soil from irrigation or rain (A). As the water percolates downwards it dissolves ionic and non-ionic particles from minerals in the soil column (B). The water that leaves the soil to the underlying groundwater is enriched in salts (C).

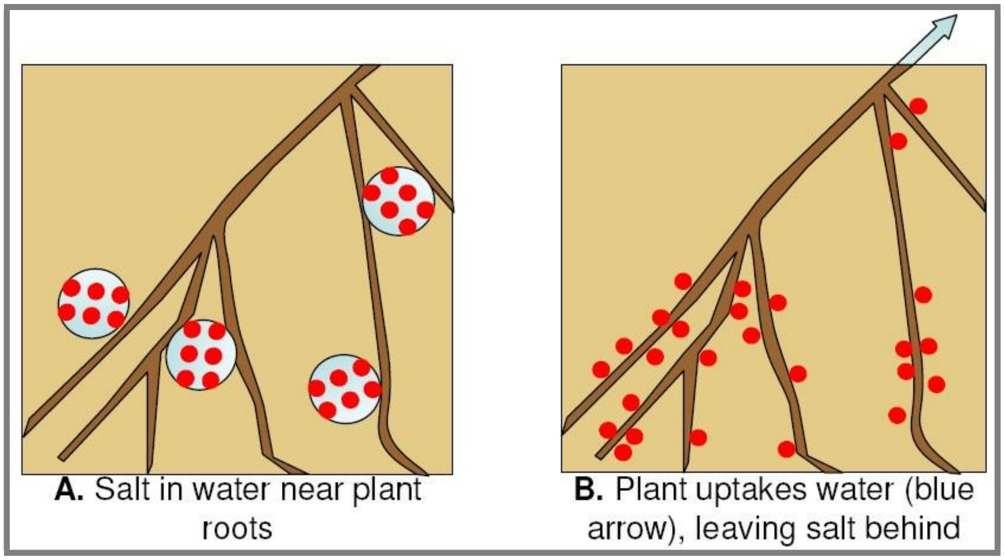
The concentration of salts in surface and groundwater can increase in several ways. Increased dissolution can increase salinity levels. Evaporative enrichment is the process of increasing salinity levels in surface or groundwater by removing water via evaporation. For example, irrigation water is often applied to crops during the summer when evaporation rates are highest. As water molecules evaporate into the atmosphere, salts remain behind in the irrigation water. This irrigation water can percolate into the underlying groundwater. If the groundwater is later pumped and used for additional irrigation, the evaporation cycle is repeated and salinity levels can increase. Dryland salinity affects soils when groundwater is brought to the surface by capillary action; evaporation removes water and leaves salt at the soil surface.



Evaporative Enrichment: As water evaporates, salts will remain behind. As a result, the concentration of salts in water with a relatively low starting salinity (TDS) can increase due to evaporation. Irrigation can result in increases in salinity through the evaporative process.

Water uptake by plants can also increase soil salinity. Water percolating through the ground has salts dissolved in it. Plant roots work by taking in water while excluding salts and other non-nutrients. The excluded salts will gradually build up around the roots, and must be periodically "flushed" from the root zone to maintain plant health. In natural systems, the types of plants found in a specific environment are adapted for naturally-occurring soil salinities. In many agricultural areas, salts are flushed from the soil by applying irrigation water. The salts that are flushed from the soil either enter groundwater or are discharged to surficial drains.

Human activities can also affect salinity levels in ground and surface water. Application of synthetic fertilizers, manures, and wastewater treatment facilities can all contribute salt to surface and groundwater. Nitrogen is a necessary nutrient for plant growth and nitrogen fertilizers are typically in the form of the salt, nitrate. If excess nitrate fertilizer is applied to a field, the nitrate not used by plants can dissolve and move to groundwater. Manure from confined animal facilities is enriched in nutrients and other salts, and can also increase salinity levels in receiving waters. Domestic wastewater is typically enriched in salts due to household activities such as washing and water softening. Most water treatment facilities cannot remove salt. As a result, discharges from these facilities can increase surface and groundwater salinity.



Plants Increase Soil Salinity: Soil pore water used by plants contains dissolved solids and other salts (A). Water uptake by roots will exclude salts and dissolved solids. Over time, as water is moved upwards through the roots to the rest of the plant, salts will build up in the soil surrounding the roots (B). Salts must be periodically flushed from the soil; otherwise, rising soil salinities may cause the plant to die.

Summary of Salinity Sources:

- <u>Agriculture:</u> Evaporation of irrigation water will remove water and leave salts behind. More salt can be dissolved from soil as irrigation water percolates downward. Plants can naturally increase soil salinity as they uptake water and exclude salts. Application of synthetic fertilizers can increase nitrate concentrations in surface and groundwater. Manure from confined animal facilities is enriched in nutrients and other salts, and can also increase salinity levels in receiving waters.

- <u>Municipal:</u> Detergents, water softeners, and industrial processes all use salts. Wastewater discharged to Publicly Owned Treatment Works (POTWs) and septic systems is often more salty than the original source water. Discharges from POTWs and septic systems can increase the salinity of receiving waters. Overwatering of lawns and residential use can also contribute to salinity.

- <u>Industrial:</u> Many industrial processes can increase salinity in process wastewater. Cooling towers, power plants, food processors, and canning facilities can contribute to salinity.

- <u>Natural:</u> Groundwater contains naturally-occurring salts from dissolving rocks and organic material. Some rocks dissolve very easily; groundwater in these areas can naturally be of very high salinity.

Drinking Water Standards for Salinity

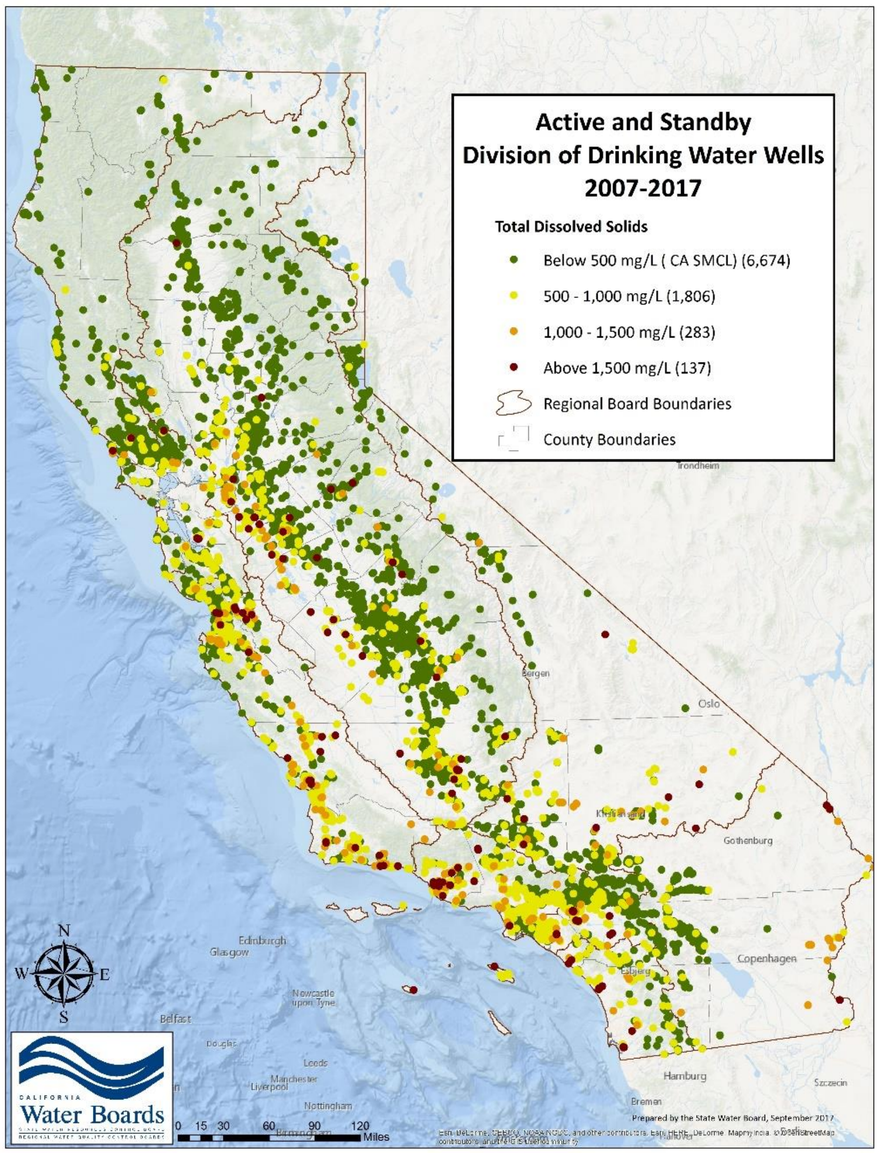
The California State Water Resources Control Board (SWRCB) established EC and TDS secondary maximum contaminant level (SMCL) drinking water standards for public water supplies. SMCLs are ranges set by SWRCB for taste and odor thresholds; for TDS, the SMCL is 500 mg/L (recommended) and the upper SMCL is 1,000 mg/L. For EC, the SMCL is 900 µS/cm (recommended), and the upper SMCL is 1,600 µS/cm. EC and TDS also have short-term SMCLs that are generally allowed only under rare circumstances at 2,200 µS/cm and 1,500 mg/L, respectively. A map of TDS in California's active and standby public wells measured between 2007 and 2017 is shown below.

TDS in Groundwater, 2007-2017

Map shows TDS concentrations from active and standby public water supply wells, between 2007 and 2017 (8,900 well sampled). Wells that had TDS concentrations:

- above short term public drinking water standards (137 wells), are shown in red
- concentrations above upper limit public drinking water standards (283 wells), are shown in orange
- above recommended public drinking water standards (1,806 wells), are shown in yellow
- equal or below recommended public drinking water standards (6,674 wells) are shown in green

Data source: GeoTracker GAMA, 2007 -2017.



<u>Nitrate: A Unique Salt</u>

Nitrate is formed naturally when nitrogen-containing organic compounds are broken down in the presence of oxygen. Nitrate is also produced in an industrial process of manufacturing synthetic fertilizers. High levels of nitrate in groundwater are associated with agricultural activity, septic systems, confined animal facilities, and wastewater treatment facilities. Nitrate is also one of the few salts that can be removed from water through a naturally-occurring process (denitrification). Denitrification is defined as the reduction of nitrate to nitrogen-containing gases such as nitric oxide, nitrous oxide, and nitrogen gas. Denitrification relies on microbial activity to break apart nitrogen-containing elements.

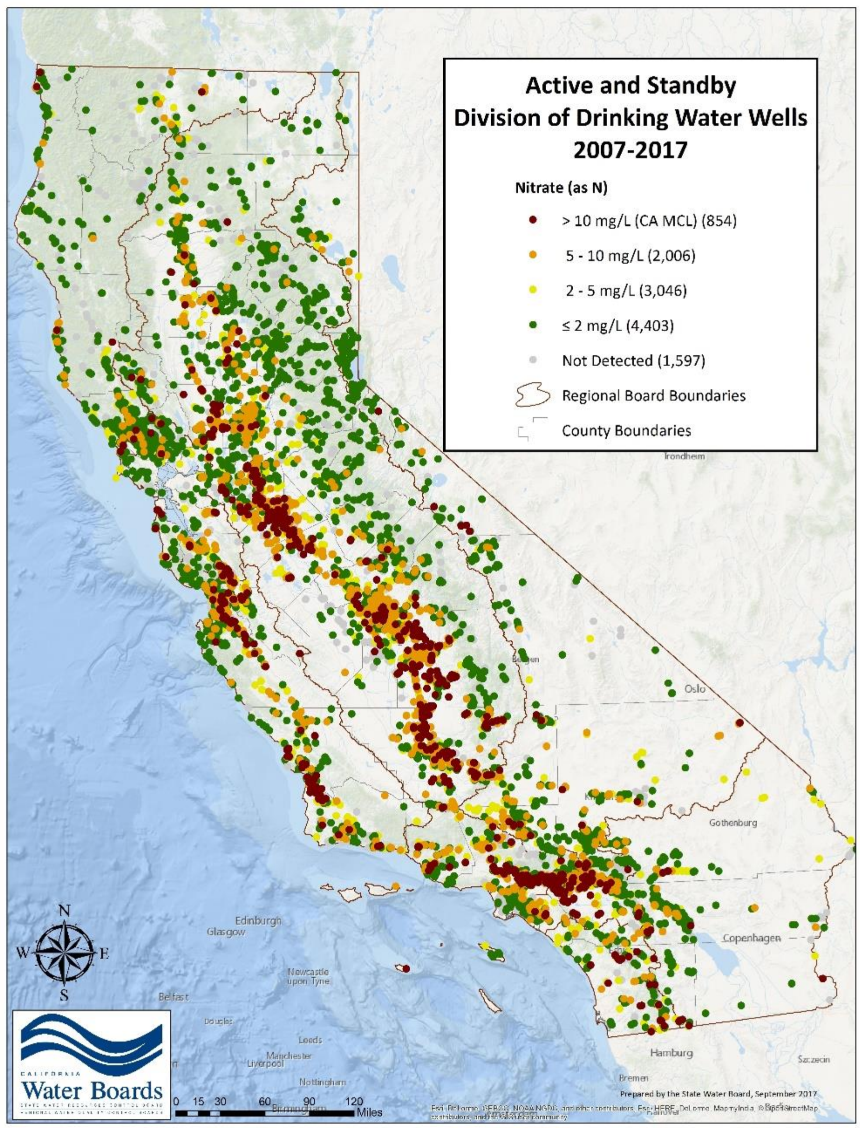
Nitrate in drinking water is a health concern. Methemoglobinemia, or "blue baby syndrome," can affect infants when elevated nitrate levels in drinking water cause a decrease in the oxygen carrying capacity of blood. The current state drinking water standard, 10 mg/L as Nitrogen, is specifically designed to protect infants. High levels of nitrate in drinking water may be unhealthy for pregnant women. Livestock can also be sensitive to high levels of nitrate in their drinking water.

<u>Nitrate in Groundwater, 2007-2017</u>

Map shows nitrate concentrations from active and standby public water supply wells, between 2007 and 2017. Wells that had nitrate concentrations:

- Above the MCL (10 mg/L) at least once, are shown in red (854 wells).

Data source: GeoTracker GAMA: 2007-2017.



Water Softeners

Water with high concentrations of calcium and magnesium is referred to as 'hard water.' Hard water, which can clog pipes and reduce the lathering action of soaps, may be treated using a water softener that exchanges magnesium and calcium ions for sodium or potassium ions. In order for the water softener to function properly, the exchange resin must be periodically recharged using highly saline brine. The brine used in the regeneration process is discharged to municipal sewage systems or a septic leachfield. Wide-spread use of water softeners has been known to significantly increase salinity levels in wastewater sent to water treatment facilities. As of August 2014, more than 25 communities in the state have banned or greatly restricted the use of salt-based water softeners.

Seawater Intrusion

In some locations, groundwater overdraft (excessive pumping) has caused the natural groundwater gradient to reverse and has allowed seawater to intrude coastal aquifers that historically contained only fresh water. Seawater intrusion can be detrimental to drinking water and irrigation wells, and render some areas unsuitable for continued agriculture. To prevent additional seawater intrusion, some communities have installed subsurface barriers and injection wells to restore or at least lower salinity of groundwater.

Closing

Public water works, industrial activities, food processors, and dairies are important parts of the economy and society but also can all increase salt loads to the State's waters. The following is a list of efforts to address salinity issues:

- National Pollutant Discharge Elimination System (NDPES) and Waste Discharge Requirements (WDR) regulatory programs manage salt impacts to surface water and groundwater.

- Institution of preventative measures by local agencies, such as requiring more efficient water softeners and managing lawn fertilizer application.

- Reducing salt loads from imported irrigation water.

- Development of technical advances in irrigated water and fertilizer application methods.

- Disposal of salts through brine lines, deep injection wells, lined landfills, and evaporation ponds.

- Limiting the use of salt for road de-icing in sensitive areas.

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EASTERN MUNICIPAL
WATER DISTRICT
SINCE 1950

02/15/2008
E08021512-01
DEJONG DAIRY
Station ID: 12836
SUBBASE-MENIFEE

Parm Sym	Methodref	Result	Units
Total Dissolved Solids	SM 2540C	2410	mg/L
pH	EPA 150.1	6.5	units
Bicarbonate (HCO3)	SM 2320B	420	mg/L
Carbonate (CO3)	SM 2320B	<3.	mg/L
Hydroxide (OH)	SM 2320B	<3.	mg/L
Total Alkalinity as CaCO3	SM 2320B	340	mg/L
Chloride	EPA 300.0	800	mg/L
Fluoride	EPA 300.0	0.3	mg/L
Nitrate as N	EPA 300.0	5.2	mg/L
Sulfate	EPA 300.0	480	mg/L
Total Organic Carbon	SM 5310C	0.7	mg/L
Ammonia as N	SM 4500 NH3 C	<2.0	mg/L
Electrical Conductance	SM 2510B	3750	umhos/cm
Total Inorganic Nitrogen	CALCULATION FOR TIN	5.5	mg/L
Boron	EPA 200.7	0.2	mg/L
Calcium	EPA 200.7	410	mg/L
Hardness	EPA 200.7	1500	mg/L
Magnesium	EPA 200.7	120	mg/L
Potassium	EPA 200.7	8.8	mg/L
Silica	EPA 200.7	64.	mg/L
Sodium	EPA 200.7	240	mg/L
Copper	EPA 200.7	<10	ug/L
Iron	EPA 200.7	1300	ug/L
Manganese	EPA 200.7	6.5	ug/L
Zinc	EPA 200.7	21.	ug/L
Nitrite as N	SM 4500NO2-B	0.02	mg/L

Mailing Address: Post Office Box 8300 Perris, CA 92572-8300 Telephone: (951) 928-3777 Fax: (951) 928-6177
Location: 2270 Trumble Road Perris, CA 92570 Internet: www.emwd.org

EASTERN MUNICIPAL WATER DISTRICT
SINCE 1950

RES DEV-AB3030

ABACHERLI DAIRY

Collect Date: 09/20/2012

Lab No. E120920031

Method Desc	Cmp Name	Result	Units	Run Date	Analyst
ICP Metals, EPA 200.7	Boron	360	ug/L	09/25/2012	AR
ICP Metals, EPA 200.7	Copper	25	ug/L	09/25/2012	AR
ICP Metals, EPA 200.7	Iron	16400	ug/L	09/25/2012	AR
ICP Metals, EPA 200.7	Manganese	72	ug/L	09/25/2012	AR
ICP Metals, EPA 200.7	Zinc	2980	ug/L	09/25/2012	AR
ICP Metals, EPA 200.7	Calcium	320	mg/L	09/25/2012	AR
ICP Metals, EPA 200.7	Magnesium	92	mg/L	09/25/2012	AR
ICP Metals, EPA 200.7	Silica	50	mg/L	09/25/2012	AR
ICP Metals, EPA 200.7	Sodium	360	mg/L	09/25/2012	AR
ICP Metals, EPA 200.7	Hardness	1180	mg/L	09/25/2012	AR
ICP Metals, EPA 200.7	Potassium	12	mg/L	09/25/2012	AR
pH (Lab), SM 4500H-B	pH, Laboratory	6.6	pH unit	09/20/2012	LP
Alk Spec-L, SM 2320B	Alkalinity, Total as CaCO3	210	mg/L	09/20/2012	LP
Alk Spec-L, SM 2320B	Hydroxide (OH)	<3	mg/L	09/20/2012	LP
Alk Spec-L, SM 2320B	Carbonate (CO3)	<3	mg/L	09/20/2012	LP
Alk Spec-L, SM 2320B	Bicarbonate (HCO3)	250	mg/L	09/20/2012	LP
Ammonia, EPA 350.1	Ammonia as N	<3.0	mg/L	09/21/2012	DW
Ammonia, EPA 350.1	Total Inorganic Nitrogen	9.3	mg/L	09/21/2012	DW
NO2 NO3 NOX, EPA 353.2	Nitrite as N	<0.1	mg/L	09/21/2012	DW
NO2 NO3 NOX, EPA 353.2	NOX	8.8	mg/L	09/21/2012	DW
NO2 NO3 NOX, EPA 353.2	Nitrate as N	8.8	mg/L	09/21/2012	DW
NO2 NO3 NOX, EPA 353.2	Nitrate (NO3)	39	mg/L	09/21/2012	DW
TDS, SM 2540C	Total Dissolved Solids	2500	mg/L	09/23/2012	CG
TOC, SM 5310C	Total Organic Carbon (TOC)	2.4	mg/L	09/25/2012	SD
Anions, EPA 300.0	Chloride	750	mg/L	09/26/2012	MK
Anions, EPA 300.0	Fluoride	0.27	mg/L	09/26/2012	MK
Anions, EPA 300.0	Sulfate	620	mg/L	09/26/2012	MK
Conductivity, SM 2510B	EC - Specific Conductance	4410	umhos/cm	09/20/2012	LP

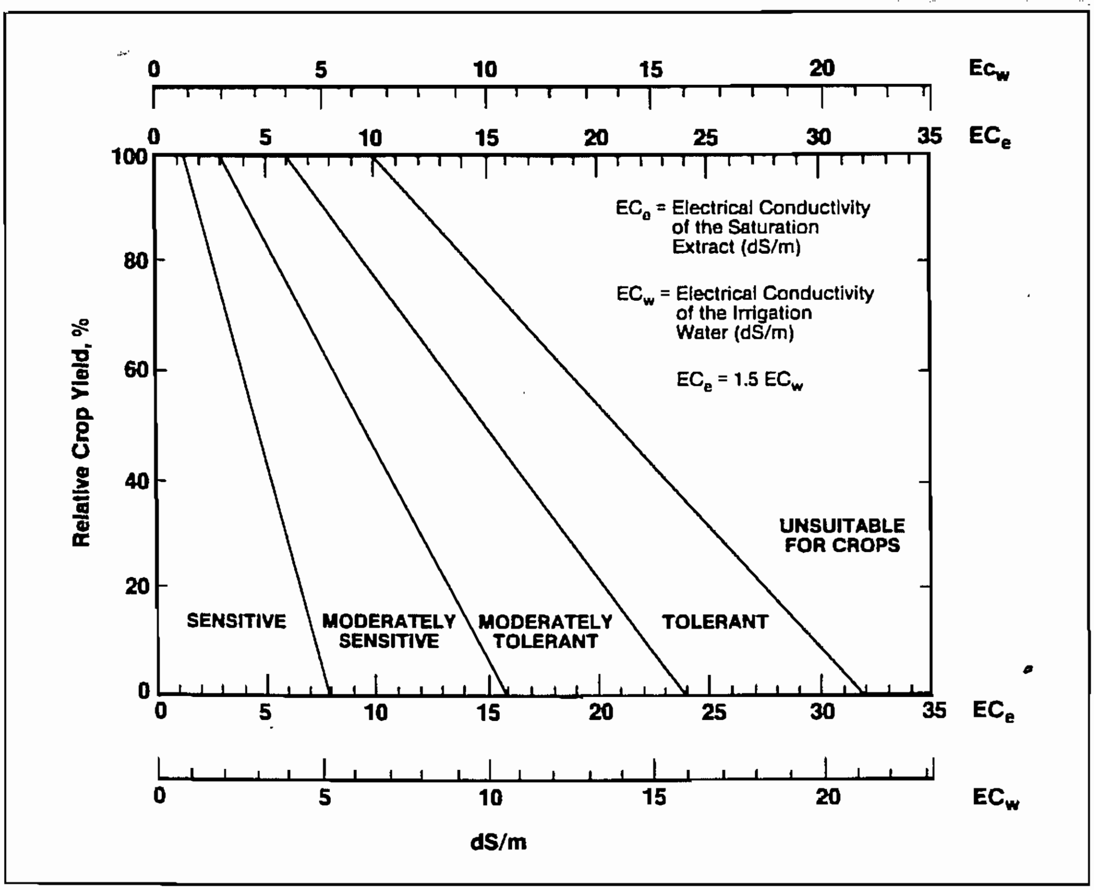
Kenneth Marshall, Lab Manager

Mailing Address: Post Office Box 8300 Perris, CA 92572-8300 Telephone: (951) 928-3777 Fax: (951) 928-6143
Location: 2270 Trumble Road Perris, CA 92570 Internet : www.emwd.org

Water quality for agriculture

FAO IRRIGATION AND DRAINAGE PAPER

29 Rev.1



FOOD AND AGRICULTURE ORGANIZATION

Water quality for agriculture

FAO IRRIGATION AND DRAINAGE PAPER

29 Rev. 1

by

R.S. Ayers
Soil and Water Specialist (Emeritus)
University of California
Davis, California, USA

and

D.W. Westcot
Senior Land and Water Resources Specialist
California Regional Water Quality Control Board
Sacramento, California, USA

FOOD AND AGRICULTURE ORGANIZATION OF THE

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PREFACE

Water Quality for Agriculture was first published in 1976 as Irrigation and Drainage Paper 29. Although many of the basic concepts of salinity control and dealing with poor quality water remain the same, new data and experience have prompted us to revise the 1976 paper in order to keep the user up-to-date.

The document is now presented as a field guide for evaluating the suitability of a water for irrigation. Included are suggestions for obtaining maximum utilization of an existing or potential water supply. Guideline values given identify a potential problem water based on possible restrictions in use related to 1) salinity, 2) rate of water infiltration into the soil, 3) a specific ion toxicity, or 4) to some other miscellaneous effects. Discussions and examples are given along with possible management alternatives to deal with these potential problems.

This paper is intended to provide guidance to farm and project managers, consultants and engineers in evaluating and identifying potential problems related to water quality. It discusses possible restrictions on the use of the water and presents management options which may assist in farm or project management, planning and operation. The guidelines and discussions are based on reported experiences gained from many farm areas throughout the world, mostly in arid and semi-arid areas. A vast majority of the data has come from agriculture in the Western United States, therefore, caution and a critical attitude should be taken when applying the guidelines to specific local conditions. The guidelines can indicate potential problems and possible restrictions on use of the water but the true suitability of a given water depends on the specific conditions of use and on the management capability of the user. The guidelines should be useful in placing water quality effects in perspective with the other factors affecting crop production, the ultimate goal being to obtain maximum production per unit of available water.

Salinity is discussed from the standpoint of a reduction in soil-water availability to the crop. Recent research findings on plant response to salinity within the root zone have been incorporated into the guidelines to improve their predictive capability. Updated crop tolerance values have also become available and are included. A method is presented for calculating the leaching requirement for the crop considering the quality of water available. Values calculated by this procedure, if adopted, represent an appreciable water saving as compared to most older procedures.

A water infiltration problem related to water quality is usually associated with both the salinity and sodium content of the water. A procedure is presented to evaluate the potential of a water to cause an infiltration problem based on a combination of its salinity (EC_w) and sodium adsorption ratio (SAR).

A specific ion toxicity is discussed as to the concentration of boron, sodium or chloride and their effect on yield of sensitive crops. Other less frequently encountered problems are discussed as miscellaneous problems. Tables showing recommended maximum concentrations of trace elements for irrigation water and for toxic substances in drinking water for livestock are also presented.

ACKNOWLEDGEMENTS

These guidelines are based on various preceding guidelines developed and used in irrigated agriculture in the Western United States. The format follows that used by the staff of the University of California, USA. Many of the basic data and the concepts of saline water use and management have been developed or proposed by the US Salinity Laboratory and the authors would like to express their grateful appreciation for this help, particularly to Drs. G.J. Hoffman, E.V. Maas, J.D. Rhoades, D.L. Suarez, and the Laboratory Director, J. van Schilfgaarde.

Drs. R.L. Branson and J.D. Oster (University of California), Dr. J. Van Hoorn (Wageningen), Mr. J.D. Doorenbos (Ministry of Agriculture, The Netherlands), and staff of the Land and Water Development Division (FAO) have been particularly helpful with suggestions and draft reviews. Thanks are also due to: Chrissi Smith-Redfern, Hazel Tonkin, Charlene Arora and Mary Westcot.

The paper is dedicated to the field person who must make decisions on the effective use of irrigation water. This paper attempts to take the solution and prevention of water quality problems to the field. The ultimate goal is that of maximum food production from the available supply of water.

NOTE:

In running text where symbols are used, e.g. ECdw, for mechanical reasons they have been typed level on the line. However, they appear correctly in the equations where greater flexibility is possible e.g. EC_{dw}.

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1. WATER QUALITY EVALUATION

1.1 INTRODUCTION

Irrigated agriculture is dependent on an adequate water supply of usable quality. Water quality concerns have often been neglected because good quality water supplies have been plentigul and readily available. This situation is now changing in many areas. Intensive use of nearly all good quality supplies means that new irrigation projects and old projects seeking new or supplemental supplies must rely on lower quality and less desirable sources. To avoid problems when using these poor quality water supplies, there must be sound planning to ensure that the quality of water available is put to the best use.

The objective of this paper is to help the reader to a better understanding of the effect of water quality upon soil and crops and to assist in selecting suitable alternatives to cope with potential water quality related problems that might reduce production under prevailing conditions of use.

Conceptually, water quality refers to the characteristics of a water supply that will influence its suitability for a specific use, i.e. how well the quality meets the needs of the user. Quality is defined by certain physical, chemical and biological characteristics. Even a personal preference such as taste is a simple evaluation of acceptability. For example, if two drinking waters of equally good quality are available, people may express a preference for one supply rather than the other; the better tasting water becomes the preferred supply. In irrigation water evaluation, emphasis is placed on the chemical and physical characteristics of the water and only rarely are any other factors considered important.

Specific uses have different quality needs and one water supply is considered more acceptable (of better quality) if it produces better results or causes fewer problems than an alternative water supply. For example, good quality river water which can be used successfully for irrigation may, because of its sediment load, be unacceptable for municipal use without treatment to remove the sediment. Similarly, snowmelt water of excellent quality for municipal use may be too corrosive for industrial use without treatment to reduce its corrosion potential.

The ideal situation is to have several supplies from which to make a selection, but normally only one supply is available. In this case, the quality of the available supply must be evaluated to see how it fits the intended use. Most of the experience in using water of different qualities has been gained from observations and detailed study of problems that develop following use. The cause and effect relationship between a water constituent and the observed problem then results in an evaluation of quality or degree of acceptability. With sufficient reported experiences and measured responses, certain constituents emerge as indicators of quality-related problems. These characteristics are then organized into guidelines related to suitability for use. Each new set of guidelines builds upon the previous set to improve the predictive capability. Numerous such guidelines have become available covering many types of use.

There have been a number of different water quality guidelines related to irrigated agriculture. Each has been useful but none has been entirely satisfactory because of the wide variability in field conditions. Hopefully, each new set of guidelines has improved our predictive capability. The guidelines presented in this paper have relied heavily on previous ones but are modified to give more practical procedures for evaluating and managing water quality-related problems of irrigated agriculture. They are an updated version of those in the 1976 edition of this paper. Changes from the 1976 edition are discussed in the appropriate sections of the paper.

1.2 WATER QUALITY PROBLEMS

Water used for irrigation can vary greatly in quality depending upon type and quantity of dissolved salts. Salts are present in irrigation water in relatively small but significant amounts. They originate from dissolution or weathering of the rocks and soil, including dissolution of lime, gypsum and other slowly dissolved soil minerals. These salts are carried with the water to wherever it is used. In the case of irrigation, the salts are applied with the water and remain behind in the soil as water evaporates or is used by the crop.

The suitability of a water for irrigation is determined not only by the total amount of salt present but also by the kind of salt. Various soil and cropping problems develop as the total salt content increases, and special management practices may be required to maintain acceptable crop yields. Water quality or suitability for use is judged on the potential severity of problems that can be expected to develop during long-term use.

The problems that result vary both in kind and degree, and are modified by soil, climate and crop, as well as by the skill and knowledge of the water user. As a result, there is no set limit on water quality; rather, its suitability for use is determined by the conditions of use which affect the accumulation of the water constituents and which may restrict crop yield. The soil problems most commonly encountered and used as a basis to evaluate water quality are those related to salinity, water infiltration rate, toxicity and a group of other miscellaneous problems.

WATER QUALITY-RELATED PROBLEMS IN IRRIGATED AGRICULTURE

SALINITY

Salts in soil or water reduce water availability to the crop to such an extent that yield is affected.

WATER INFILTRATION RATE

Relatively high sodium or low calcium content of soil or water reduces the rate at which irrigation water enters soil to such an extent that sufficient water cannot be infiltrated to supply the crop adequately from one irrigation to the next.

SPECIFIC ION TOXICITY

Certain ions (sodium, chloride, or boron) from soil or water accumulate in a sensitive crop to concentrations high enough to cause crop damage and reduce yields.

MISCELLANEOUS

Excessive nutrients reduce yield or quality; unsightly deposits on fruit or foliage reduce marketability; excessive corrosion of equipment increases maintenance and repairs.

1.2.1 Salinity

A salinity problem exists if salt accumulates in the crop root zone to a concentration that causes a loss in yield. In irrigated areas, these salts often originate from a saline, high water table or from salts in the applied water. Yield reductions occur when the salts accumulate in the root zone to such an extent that the crop is no longer able to extract sufficient water from the salty soil solution, resulting in a water stress for a significant period of time. If water uptake is appreciably reduced, the plant slows its rate of growth. The plant symptoms are similar in appearance to those of drought, such as wilting, or a darker, bluish-green colour and sometimes thicker, waxier leaves. Symptoms vary with the growth stage, being more noticeable if the salts affect the plant during the early stages of growth. In some cases, mild salt effects may go entirely unnoticed because of a uniform reduction in growth across an entire field.

Salts that contribute to a salinity problem are water soluble and readily transported by water. A portion of the salts that accumulate from prior irrigations can be moved (leached) below the rooting depth if more irrigation water infiltrates the soil than is used by the crop during the crop season. Leaching is the key to controlling a water quality-related salinity problem. Over a period of time, salt removal by leaching must equal or exceed the salt additions from the applied water to prevent salt building up to a damaging concentration. The amount of leaching required is dependent upon the irrigation water quality and the salinity tolerance of the crop grown.

Salt content of the root zone varies with depth. It varies from approximately that of the irrigation water near the soil surface to many times that of the applied water at the bottom of the rooting depth. Salt concentration increases with depth due to plants extracting water but leaving salts behind in a greatly reduced volume of soil water. Each subsequent irrigation pushes (leaches) the salts deeper into the root zone where they continue to accumulate until leached. The lower rooting depth salinity will depend upon the leaching that has occurred.

Following an irrigation, the most readily available water is in the upper root zone - a low salinity area. As the crop uses water, the upper root zone becomes depleted and the zone of most readily available water changes toward the deeper parts as the time interval between irrigations is extended. These lower depths are usually more salty. The crop does not respond to the extremes of low or high salinity in the rooting depth but integrates water availability and takes water from wherever it is most readily available. Irrigation timing is thus important in maintaining a high soil-water availability and reducing the problems caused when the crop must draw a significant portion of its water from the less available, higher salinity soil-water deeper in the root zone. For good crop production, equal importance must be given to maintaining a high soil-water availability and to leaching accumulated salts from the rooting depth before the salt concentration exceeds the tolerance of the plant.

For crops irrigated infrequently, as is normal when using surface methods and conventional irrigation management, crop yield is best correlated with the average root zone salinity, but for crops irrigated on a daily, or near daily basis (localized or drip irrigation) crop yields are better correlated with the water-uptake weighted root zone salinity (Rhoades 1982). The differences are not great but may become important in the higher range of salinity. In this paper, discussions are based on crop response to the average root zone salinity.

In irrigated agriculture, many salinity problems are associated with or strongly influenced by a shallow water table (within 2 metres of the surface). Salts accumulate in this water table and frequently become an important additional source of salt that moves upward into the crop root zone. Control of an existing shallow water table is thus essential to salinity control and to successful long-term irrigated agriculture. Higher salinity water requires appreciable extra water for leaching, which adds greatly to a potential water table (drainage) problem and makes long-term irrigated agriculture nearly impossible to achieve without adequate drainage. If drainage is adequate, salinity control becomes simply good management to ensure that the crop is adequately supplied with water at all times and that enough leaching water is applied to control salts within the tolerance of the crop.

1.2.2 Water Infiltration Rate

An infiltration problem related to water quality occurs when the normal infiltration rate for the applied water or rainfall is appreciably reduced and water remains on the soil surface too long or infiltrates too slowly to supply the crop with sufficient water to maintain acceptable yields. Although the infiltration rate of water into soil varies widely and can be greatly influenced by the quality of the irrigation water, soil factors such as structure, degree of compaction, organic matter content and chemical make-up can also greatly influence the intake rate.

The two most common water quality factors which influence the normal infiltration rate are the salinity of the water (total quantity of salts in the water) and its sodium content relative to the calcium and magnesium content. A high salinity water will increase infiltration. A low salinity water or a water with a high sodium to calcium ratio will decrease infiltration. Both factors may operate at the same time. Secondary problems may also develop if irrigations must be prolonged for an extended period of time to achieve adequate infiltration. These include crusting of seedbeds, excessive weeds, nutritional disorders and drowning of the crop, rotting of seeds and poor crop stands in low-lying wet spots. One serious side effect of an infiltration problem is the potential to develop disease and vector (mosquito) problems.

An infiltration problem related to water quality in most cases occurs in the surface few centimetres of soil and is linked to the structural stability of this surface soil and its low calcium content relative to that of sodium. When a soil is irrigated with a high sodium water, a high sodium surface soil develops which weakens soil structure. The surface soil aggregates then disperse to much smaller particles which clog soil pores. The problem may also be caused by an extremely low calcium content of the surface soil. In some cases, water low in salt can cause a similar problem but this is related to the corrosive nature of the low salt water and not to the sodium content of the water or soil. In the case of the low salt water, the water dissolves and leaches most of the soluble minerals, including calcium, from the surface soil.

1.2.3 Toxicity

Toxicity problems occur if certain constituents (ions) in the soil or water are taken up by the plant and accumulate to concentrations high enough to cause crop damage or reduced yields. The degree of damage depends on the uptake and the crop sensitivity. The permanent, perennial-type crops (tree crops) are the more sensitive. Damage often occurs at relatively low ion concentrations for sensitive crops. It is usually first evidenced by marginal leaf burn and interveinal chlorosis. If the accumulation is great enough, reduced yields result. The more tolerant annual crops are not sensitive at low concentrations but almost all crops will be damaged or killed if concentrations are sufficiently high.

The ions of primary concern are chloride, sodium and boron. Although toxicity problems may occur even when these ions are in low concentrations, toxicity often accompanies and complicates a salinity or water infiltration problem. Damage results when the potentially toxic ions are absorbed in significant amounts with the water taken up by the roots. The absorbed ions are transported to the leaves where they accumulate during transpiration. The ions accumulate to the greatest extent in the areas where the water loss is greatest, usually the leaf tips and leaf edges. Accumulation to toxic concentrations takes time and visual damage is often slow to be noticed. The degree of damage depends upon the duration of exposure, concentration by the toxic ion, crop sensitivity, and the volume of water transpired by the crop. In a hot climate or hot part of the year, accumulation is more rapid than if the same crop were grown in a cooler climate or cooler season when it might show little or no damage.

Toxicity can also occur from direct absorption of the toxic ions through leaves wet by overhead sprinklers. Sodium and chloride are the primary ions absorbed through leaves, and toxicity to one or both can be a problem with certain sensitive crops such as citrus. As concentrations increase in the applied water, damage develops more rapidly and becomes progressively more severe.

1.2.4 Miscellaneous

Several other problems related to irrigation water quality occur with sufficient frequency for them to be specifically noted. These include high nitrogen concentrations in the water which supplies nitrogen to the crop and may cause excessive vegetative growth, lodging, and delayed crop maturity; unsightly deposits on fruit or leaves due to overhead sprinkler irrigation with high bicarbonate water, water containing gypsum, or water high in iron; and various abnormalities often associated with an unusual pH of the water. A special problem faced by some farmers practising irrigation is deterioration of equipment due to water-induced corrosion or encrustation. This problem is most serious for wells and pumps, but in some areas, a poor quality water may also damage irrigation equipment and canals. In areas where there is a potential risk from diseases such as malaria, schistosomiasis and lymphatic filariasis, disease vector problems must be considered along with other water quality-related problems. Vector problems (mosquitoes) often originate as a secondary trouble related to a low water infiltration rate, to the use of wastewater for irrigation, or to poor drainage. Suspended organic as well as inorganic sediments cause problems in irrigation systems through clogging of gates, sprinkler heads and drippers. They can cause damage to pumps if screens are not used to exclude them. More commonly, sediments tend to fill canals and ditches and cause costly dredging and maintenance problems. Sediment also tends to reduce further the water infiltration rate of an already slowly permeable soil.

1.3 APPROACH TO EVALUATING WATER QUALITY

The prediction that a water quality-related problem will occur requires evaluation of the potential of the water to create soil conditions that may restrict its use or that may require the use of special management techniques to maintain acceptable yields. There are a number of procedures available for this evaluation but regardless of which one is used, emphasis should focus on relating the potential problem to the field situation since solutions to water quality problems usually must be implemented at the farm level rather than at the project level. The evaluation must therefore be done in terms of specific local conditions of use and the farm management capability of the water user.

This approach is the same as in the 1976 edition of this paper and similar guidelines are proposed for evaluating the potential of an irrigation water to create soil or crop problems. The guidelines are followed by suggestions on management alternatives to overcome these potential problems. This approach is often referred to as a problem-solving approach and emphasizes long-term effects on irrigated agriculture rather than short-term, because of the large investments now needed in irrigated agriculture.

The four problem categories previously discussed - **salinity, infiltration, toxicity** and **miscellaneous** - are used for evaluation. Water quality problems, however, are often complex and a combination of problems may affect crop production more severely than a single problem in isolation. The more complex the problem, the more difficult it is to formulate an economical management programme for solution.

If problems do occur in combination, they are more easily understood and solved if each factor is considered individually. Therefore, the guidelines and discussion which follow treat each problem and its solution separately, so that a number of factors are evaluated for each of the problem areas, such as:

* the type and concentration of salts causing the problem;
* the soil-water-plant interactions that may cause the loss in crop yield;
* the expected severity of the problem following long-term use of the water;
* the management options that are available to prevent, correct, or delay the onset of the problem.

1.4 WATER QUALITY GUIDELINES

Guidelines for evaluation of water quality for irrigation are given in Table 1. They emphasize the long-term influence of water quality on crop production, soil conditions and farm management, and are presented in the same format as in the 1976 edition but are updated to include recent research results. This format is similar to that of the 1974 University of California Committee of Consultant's Water Quality Guidelines which were prepared in cooperation with staff of the United States Salinity Laboratory.

The guidelines are practical and have been used successfully in general irrigated agriculture for evaluation of the common constituents in surface water, groundwater, drainage water, sewage effluent and wastewater. They are based on certain assumptions which are given immediately following the table. These assumptions must be clearly understood but should not become rigid prerequisites. A modified set of alternative guidelines can be prepared if actual conditions of use differ greatly from those assumed.

Ordinarily, no soil or cropping problems are experienced or recognized when using water with values less than those shown for 'no restriction on use'. With restrictions in the slight to moderate range, gradually increasing care in selection of crop and management alternatives is required if full yield potential is to be achieved. On the other hand, if water is used which equals or exceeds the values shown for severe restrictions, the water user should experience soil and cropping problems or reduced yields, but even with cropping management designed especially to cope with poor quality water, a high level of management skill is essential for acceptable production. If water quality values are found which approach or exceed those given for the severe restriction category, it is recommended that before initiating the use of the water in a large project, a series of pilot farming studies be conducted to determine the economics of the farming and cropping techniques that need to be implemented.

Table 1 is a management tool. As with many such interpretative tools in agriculture, it is developed to help users such as water agencies, project planners, agriculturalists, scientists and trained field people to understand better the effect of water quality on soil conditions and crop production. With this understanding, the user should be able to adjust management to utilize poor quality water better. However, the user of Table 1 must guard against drawing unwarranted conclusions based only on the laboratory results and the guideline interpretations as these must be related to field conditions and must be checked, confirmed and tested by field trials or experience.

The guidelines are a first step in pointing out the quality limitations of a water supply, but this alone is not enough; methods to overcome or adapt to them are also needed. Therefore, in subsequent sections, management alternatives are presented and several examples are given to illustrate how the guidelines can be used.

The guidelines do not evaluate the effect of unusual or special water constituents sometimes found in wastewater, such as pesticides and organics. However, suggested limits of trace element concentrations for normal irrigation water are given in Section 5.5. As irrigation water supplies frequently serve as a drinking water source for livestock, salinity and trace element drinking water limitations for livestock are presented in Section 6.

It is beyond the scope of this publication to go into drinking water standards, but this aspect should, nevertheless, be considered during the planning of an irrigation scheme. This is important, because irrigation supplies are also commonly used, either intentionally or unintentionally, as human drinking water. The World Health Organization (WHO) or a local health agency should be consulted for more specific information.

Laboratory determinations and calculations needed to use the guidelines are given in Table 2 and Figure 1, along with the symbols used. Analytical procedures for the laboratory determinations are given in several publications: USDA Handbook 60 (Richards 1954), Rhoades and Clark 1978, FAO Soils Bulletin 10 (Dewis and Freitas 1970), and Standard Methods for Examination of Waters and Wastewaters (APHA 1980). The method most appropriate for the available equipment, budget and number of samples should be used. Analytical accuracy within ±5 percent is considered adequate.

Table 1 GUIDELINES FOR INTERPRETATIONS OF WATER QUALITY FOR IRRIGATION[1]

Potential Irrigation Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Salinity *(affects crop water availability)*[2]				
EC_w	dS/m	< 0.7	0.7 - 3.0	> 3.0
(or)				
TDS	mg/l	< 450	450 - 2000	> 2000
Infiltration *(affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)*[3]				
SAR = 0 - 3 and EC_w =		> 0.7	0.7 - 0.2	< 0.2
= 3 - 6 =		> 1.2	1.2 - 0.3	< 0.3
= 6 - 12 =		> 1.9	1.9 - 0.5	< 0.5
= 12 - 20 =		> 2.9	2.9 - 1.3	< 1.3
= 20 - 40 =		> 5.0	5.0 - 2.9	< 2.9
Specific Ion Toxicity *(affects sensitive crops)*				
Sodium (Na)[4]				
surface irrigation	SAR	< 3	3 - 9	> 9
sprinkler irrigation	me/l	< 3	> 3	
Chloride (Cl)[4]				
surface irrigation	me/l	< 4	4 - 10	> 10
sprinkler irrigation	me/l	< 3	> 3	
Boron (B)[5]	mg/l	< 0.7	0.7 - 3.0	> 3.0
Trace Elements (see Table 21)				
Miscellaneous Effects *(affects susceptible crops)*				
Nitrogen (NO_3 - N)[6]	mg/l	< 5	5 - 30	> 30
Bicarbonate (HCO_3) *(overhead sprinkling only)*	me/l	< 1.5	1.5 - 8.5	> 8.5
pH			Normal Range 6.5 - 8.4	

[1] Adapted from University of California Committee of Consultants 1974.

[2] ECw means electrical conductivity, a measure of the water salinity, reported in deciSiemens per metre at 25°C (dS/m) or in units millimhos per centimetre (mmho/cm). Both are equivalent. TDS means total dissolved solids, reported in milligrams per litre (mg/l).

[3] SAR means sodium adsorption ratio. SAR is sometimes reported by the symbol RNa. See Figure 1 for the SAR calculation procedure. At a given SAR, infiltration rate increases as water salinity increases. Evaluate the potential infiltration problem by SAR as modified by ECw. Adapted from Rhoades 1977, and Oster and Schroer 1979.

[4] For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use the values shown. Most annual crops are not sensitive; use the salinity tolerance tables (Tables 4 and 5). For chloride tolerance of selected fruit crops, see Table 14. With overhead sprinkler irrigation and low humidity (< 30 percent), sodium and chloride may be absorbed through the leaves of sensitive crops. For crop sensitivity to absorption, see Tables 18, 19 and 20.

[5] For boron tolerances, see Tables 16 and 17.

[6] NO_3-N means nitrate nitrogen reported in terms of elemental nitrogen (NH_4-N and Organic-N should be included when wastewater is being tested).

Table 1 (cont.)

Assumptions in the Guidelines

The water quality guidelines in Table 1 are intended to cover the wide range of conditions encountered in irrigated agriculture. Several basic assumptions have been used to define their range of usability. If the water is used under greatly different conditions, the guidelines may need to be adjusted. Wide deviations from the assumptions might result in wrong judgements on the usability of a particular water supply, especially if it is a borderline case. Where sufficient experience, field trials, research or observations are available, the guidelines may be modified to fit local conditions more closely.

The basic assumptions in the guidelines are:

Yield Potential: Full production capability of all crops, without the use of special practices, is assumed when the guidelines indicate no restrictions on use. A "restriction on use" indicates that there may be a limitation in choice of crop, or special management may be needed to maintain full production capability. A "restruction on use" does not indicate that the water is unsuitable for use.

Site Conditions: Soil texture ranges from sandy-loam to clay-loam with good internal drainage. The climate is semi-arid to arid and rainfall is low. Rainfall does not play a significant role in meeting crop water demand or leaching requirement. (In a monsoon climate or areas where precipitation is high for part or all of the year, the guideline restrictions are too severe. Under the higher rainfall situations, infiltrated water from rainfall is effective in meeting all or part of the leaching requirement.) Drainage is assumed to be good, with no uncontrolled shallow water table present within 2 metres of the surface.

Methods and Timing of Irrigations: Normal surface or sprinkler irrigation methods are used. Water is applied infrequently, as needed, and the crop utilizes a considerable portion of the available stored soil-water (50 percent or more) before the next irrigation. At least 15 percent of the applied water percolates below the root zone (leaching fraction [LF]≥15 percent). The guidelines are too retrictive for specialized irrigation methods, such as localized drip irrigation, which results in near daily or frequent irrigations, but are applicable for subsurface irrigation if surface applied leaching satisfies the leaching requirements.

Water Uptake by Crops: Different crops have different water uptake patterns, but all take water from wherever it is most readily available within the rooting depth. On average about 40 percent is assumed to be taken from the upper quarter of the rooting depth, 30 percent from the second quarter, 20 percent from the third quarter, and 10 percent from the lowest quarter. Each irrigation leaches the upper root zone and maintains it at a relatively low salinity. Salinity increases with depth and is greatest in the lower part of the root zone. The average salinity of the soil-water is three times that of the applied water and is representative of the average root zone salinity to which the crop responds. These conditions result from a leaching fraction of 15-20 percent and irrigations that are timed to keep the crop adequately watered at all times.

Salts leached from the upper root zone accumulate to some extent in the lower part but a salt balance is achieved as salts are moved below the root zone by sufficient leaching. The higher salinity in the lower root zone becomes less important if adequate moisture is maintained in the upper, "more active" part of the root zone and long-term leaching is accomplished.

Restriction on Use: The "Restriction on Use" shown in Table 1 is divided into three degrees of severity: none, slight to moderate, and severe. The divisions are somewhat arbitrary since change occurs gradually and there is no clearcut breaking point. A change of 10 to 20 percent above or below a guideline value has little significance if considered in proper perspective with other factors affecting yield. Field studies, research trials and observations have led to these divisions, but management skill of the water user can alter them. Values shown are applicable under normal field conditions prevailing in most irrigated areas in the arid and semi-arid regions of the world.

Table 2 LABORATORY DETERMINATIONS NEEDED TO EVALUATE COMMON IRRIGATION WATER QUALITY PROBLEMS

Water parameter	Symbol	Unit[1]	Usual range in irrigation water	
SALINITY				
Salt Content				
Electrical Conductivity	EC_w	dS/m	0 - 3	dS/m
(or)				
Total Dissolved Solids	TDS	mg/l	0 - 2000	mg/l
Cations and Anions				
Calcium	Ca^{++}	me/l	0 - 20	me/l
Magnesium	Mg^{++}	me/l	0 - 5	me/l
Sodium	Na^{+}	me/l	0 - 40	me/l
Carbonate	CO_3^{--}	me/l	0 - .1	me/l
Bicarbonate	HCO_3^{-}	me/l	0 - 10	me/l
Chloride	Cl^{-}	me/l	0 - 30	me/l
Sulphate	SO_4^{--}	me/l	0 - 20	me/l
NUTRIENTS[2]				
Nitrate-Nitrogen	NO_3-N	mg/l	0 - 10	mg/l
Ammonium-Nitrogen	NH_4-N	mg/l	0 - 5	mg/l
Phosphate-Phosphorus	PO_4-P	mg/l	0 - 2	mg/l
Potassium	K^{+}	mg/l	0 - 2	mg/l
MISCELLANEOUS				
Boron	B	mg/l	0 - 2	mg/l
Acid/Basicity	pH	1-14	6.0 - 8.5	
Sodium Adsorption Ratio[3]	SAR	$(me/l)^{1/2}$	0 - 15	

[1] dS/m = deciSiemen/metre in S.I. units (equivalent to 1 mmho/cm = 1 millimmho/centimetre)

mg/l = milligram per litre ≃ parts per million (ppm).

me/l = milliequivalent per litre (mg/l ÷ equivalent weight = me/l); in SI units, 1 me/l = 1 millimol/litre adjusted for electron charge.

[2] NO_3 -N means the laboratory will analyse for NO_3 but will report the NO_3 in terms of chemically equivalent nitrogen. Similarly, for NH_4-N, the laboratory will analyse for NH_4 but report in terms of chemically equivalent elemental nitrogen. The total nitrogen available to the plant will be the sum of the equivalent elemental nitrogen. The same reporting method is used for phosphorus.

[3] SAR is calculated from the Na, Ca and Mg reported in me/l (see Figure 1).

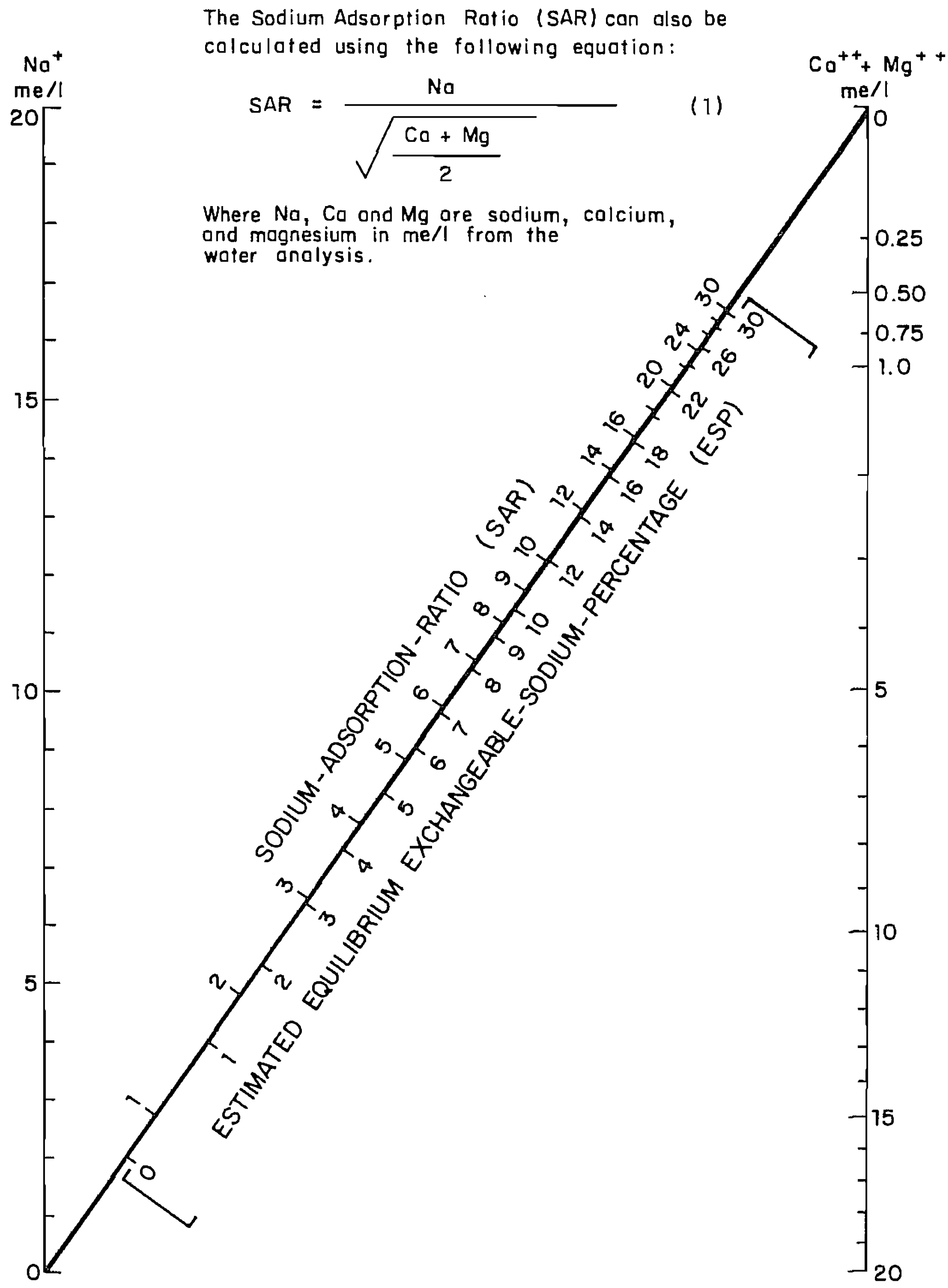


Fig. 1 Nomogram for determining the SAR value of irrigation water and for estimating the corresponding ESP value of a soil that is at equilibrium with the water (Richards 1954)

2. SALINITY PROBLEMS

2.1 INTRODUCTION

Irrigation water contains a mixture of naturally occurring salts. Soils irrigated with this water will contain a similar mix but usually at a higher concentration than in the applied water. The extent to which the salts accumulate in the soil will depend upon the irrigation water quality, irrigation management and the adequacy of drainage. If salts become excessive, losses in yield will result. To prevent yield loss, salts in the soil must be controlled at a concentration below that which might affect yield.

Most water used for irrigation is of good to excellent quality and is unlikely to present serious salinity constraints. Salinity control, however, becomes more difficult as water quality becomes poorer. As water salinity increases, greater care must be taken to leach salts out of the root zone before their accumulation reaches a concentration which might affect yields. Alternatively, steps must be taken to plant crops tolerant to the expected root zone salinity. The frequency of leaching depends on water quality and the crop sensitivity to salinity.

The intent of this chapter is to illustrate the effect of water quality on the build-up of soil salinity and show how the latter can reduce the soil-water available to the crop. This is followed by a discussion of how leaching, crop selection and other management techniques are used to make salinity control easier and allow greater use of more saline water in irrigated agriculture. Emphasis will be on how to manage intermediate quality water with slight to moderate restrictions on use, as shown in Table 1. Such water could result in more severe problems if it is not properly managed. The same management techniques will apply to a poorer quality water, but as quality worsens the options for management become fewer.

2.2. BUILD-UP OF SOIL SALINITY

Salts are added to the soil with each irrigation. These salts will reduce crop yield if they accumulate in the rooting depth to damaging concentrations. The crop removes much of the applied water from the soil to meet its evapotranspiration demand (ET) but leaves most of the salt behind to concentrate in the shrinking volume of soil-water. At each irrigation, more salt is added with the applied water. A portion of the added salt must be leached from the root zone before the concentration affects crop yield. Leaching is done by applying sufficient water so that a portion percolates through and below the entire root zone carrying with it a portion of the accumulated salts. The fraction of applied water that passes through the entire rooting depth and percolates below is called the leaching fraction (LF).

$$\text{Leaching Fraction (LF)} = \frac{\text{depth of water leached below the root zone}}{\text{depth of water applied at the surface}} \qquad (2)$$

After many successive irrigations, the salt accumulation in the soil will approach some equilibrium concentration based on the salinity of the applied water and the leaching fraction. A high leaching fraction (LF = 0.5) results in less salt accumulation than a lower leaching fraction (LF = 0.1). If the water salinity (ECw) and the leaching fraction (LF) are known or can be estimated, both the salinity of the drainage water that percolates below the rooting depth and the average root zone salinity can be estimated. The salinity of the drainage water can be estimated from the equation:

$$EC_{dw} = \frac{EC_w}{LF} \qquad (3)$$

where: EC_{dw} = salinity of the drainage water percolating below the root zone (equal to salinity of soil-water, EC_{sw})

EC_w = salinity of the applied irrigation water

LF = leaching fraction

In Example 1, the leaching fraction and water quality are used to predict drainage water quality. The plant, however, is only exposed to this drainage water salinity at the lowest part of the root zone. The salinity in this lower portion of the root zone tends to be higher than in the upper portion due to its much lower leaching fraction. The crop responds, however, to the average root zone soil salinity and not to the extremes of either the upper or lower zones.

EXAMPLE 1 - CALCULATION OF CONCENTRATION OF DEEP PERCOLATION FROM THE BOTTOM OF THE ROOT ZONE

A crop is irrigated with water of an electrical conductivity (ECw) of 1 dS/m. The crop is irrigated to achieve a leaching fraction of 0.15 (assumes that 85 percent of the applied water is used by the crop or evaporates from the soil surface).

Given: EC_w = 1 dS/m

LF = 0.15

Explanation:

The concentration of the soil-water percolating below the root zone (ECsw) is equivalent to the concentration of the drainage water (ECdw) accumulating below the root zone. The salinity of the deep percolation from the bottom of the root zone (drainage water) can be estimated by using equation (3):

$$EC_{dw} = EC_{sw} = \frac{EC_w}{LF} \qquad (3)$$

$$EC_{dw} = \frac{1}{0.15} = 6.7 \text{ dS/m}$$

The salinity of the soil-water that is percolating from the bottom of the root zone (ECdw) will be approximately 6.7 dS/m.

Equation (3) can also be used to predict average soil-water salinity (ECsw) in the rooting depth if certain assumptions are made regarding water use within the root zone. The guidelines of Table 1 assume that 40, 30, 20 and 10 percent of the water used by the crop comes, respectively, from the upper to lower quarter of the rooting depth. This water use pattern closely fits conditions found under normal irrigation practices. An illustration is given in Example 2 where the above water use pattern is used to estimate average soil-water salinity (ECsw).

Example 2 shows that with a 15 percent leaching fraction and a 40-30-20-10 water use pattern the average soil-water salinity (ECsw) is approximately 3.2 times more concentrated than the applied irrigation water. At a leaching fraction of 20 percent, the average ECsw is 2.7 times the salinity of the applied irrigation water (ECw). The guidelines of Table 1 were developed assuming a 15-20 percent leaching fraction range which results in an average soil-water salinity (ECsw) approximately 3 times that of the applied water. The soil-water salinity (ECsw) is the average root zone salinity to which the plant is exposed. It is difficult to measure. Salinity measurement is normally done on a saturation extract of the soil and referred to as the soil salinity (ECe). This soil salinity, (ECe), is approximately equal to one-half of the soil-water salinity (ECsw). As a general rule of thumb, at a 15-20 percent leaching fraction, salinity of the applied water (ECw) can be used to predict or estimate soil-water salinity (ECsw) or soil salinity (ECe) using the following equations:

$$EC_{sw} = 3\ EC_w \qquad (4)$$

$$EC_e = 1.5\ EC_w \qquad (5)$$

$$EC_{sw} = 2\ EC_e \qquad (6)$$

If irrigation practices result in greater or less leaching than the 15-20 percent LF assumed in the guidelines of Table 1, a more correct concentration factor can be calculated using a new estimated average leaching fraction and the procedure illustrated in Example 2. Table 3 lists concentration factors for a wide range of leaching fractions (LF = 0.05 to 0.80). The predicted average soil salinity (ECe) is estimated by multiplying the irrigation water salinity (ECw) by the appropriate concentration factor for the estimated leaching fraction (see equation (8) in Table 3). These predicted average soil salinities reflect changes due to long-term water use and not short-term changes that may occur within a season or between irrigations. Figure 2 illustrates typical soil salinity profiles that can be identified and are typical of salinity distribution in the crop root zone after several years of irrigation with one water source and closely similar leaching fractions.

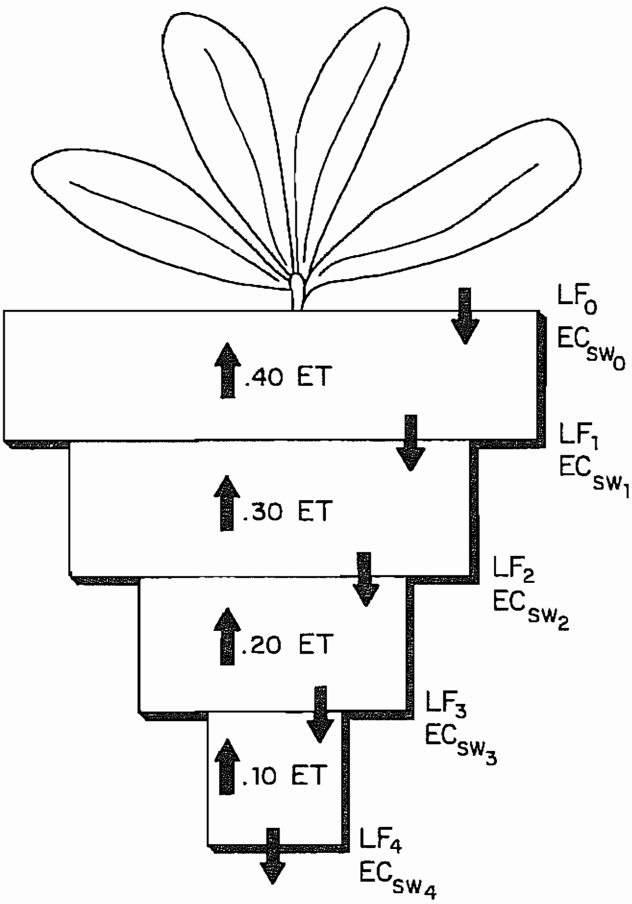
2.3 SALINITY EFFECTS ON CROPS

The primary objective of irrigation is to provide a crop with adequate and timely amounts of water, thus avoiding yield loss caused by extended periods of water stress during stages of crop growth that are sensitive to water shortages. However, during repeated irrigations, the salts in the irrigation water can accumulate in the soil, reducing water available to the crop and hastening the onset of a water shortage. Understanding how this occurs will help suggest ways to counter the effect and reduce the probability of a loss in yield.

The plant extracts water from the soil by exerting an absorptive force greater than that which holds the water to the soil. If the plant cannot make sufficient internal adjustment and exert enough force, it is not able to extract sufficient water and will suffer water stress. This happens when the soil becomes too dry. Salt in the soil-water increases the force the plant must exert to extract water and this additional force is referred to as the osmotic effect or osmotic

EXAMPLE 2 - DETERMINATION OF AVERAGE ROOT ZONE SALINITY

The average root zone salinity can be calculated using the average of five points in the rooting depth. The following procedure can be used to estimate the average root zone salinity to which the crop responds.



ASSUMPTIONS

1. Applied water salinity (EC_w) = 1 dS/m.

2. Crop water demand (ET) = 1000 mm/season.

3. The crop water use pattern is 40-30-20-10. This means the crop will get 40 percent of its ET demand from the upper quarter of the root zone, 30 percent from the next quarter, 20 percent from the next, and 10 percent from the lowest quarter. Crop water use will increase the concentration of the soil-water which drains into the next quarter (EC_{sw}) of the root zone.

4. Desired leaching fraction (LF) = 0.15. The leaching fraction of 0.15 means that 15 percent of the applied irrigation water entering the surface percolates below the root zone and 85 percent replaces water used by the crop to meet its ET demand and water lost by surface evaporation.

EXPLANATION

1. Five points in the root zone are used to determine the average root zone salinity. These five points are soil-water salinity at (1) the soil surface, (ECsw0); (2) bottom of the upper quarter of the root zone, (ECsw1); (3) bottom of the second quarter depth, (ECsw2); (4) bottom of the third quarter, (ECsw3) and (5) bottom of the fourth quarter or the soil-water draining from the root zone (ECsw4) which is equivalent to the salinity of the drainage water (ECdw).

2. With a LF of 0.15, the applied water (AW) needed to meet both the crop ET and the LF is determined from the following equation:

$$AW = \frac{ET}{1 - LF} = 1176 \text{ mm of water} \qquad (7)$$

3. Since essentially all the applied water enters and leaches through the soil surface, effectively removing any accumulated salts, the salinity of the soil water at the surface (ECsw0) must be very close to the salinity of the applied water as shown using equation (3) and assuming LF0 = 1.0.

$$EC_{dw_0} = EC_{sw_0} = \frac{EC_w}{LF_0} = \frac{1}{1} = 1 \text{ dS/m} \qquad (3)$$

4. The salinity of the soil-water draining from the bottom of each root zone quarter is found by determining the leaching fraction for that quarter using equation (2) and then determining the soil-water salinity using equation (3).

$$LF = \frac{\text{Water leached}}{\text{Water applied}} \qquad EC_{sw} = \frac{EC_w}{LF}$$

For the bottom of the first quarter:

$$LF_1 = \frac{1176-.40(1000)}{1176} = 0.66 \qquad EC_{sw_1} = \frac{EC_w}{LF_1} = 1.5 \text{ dS/m}$$

--- at the bottom of the second quarter:

$$LF_2 = \frac{1176-.40(1000)-.30(1000)}{1176} = 0.40 \qquad EC_{sw_2} = \frac{EC_w}{LF_2} = 2.5 \text{ dS/m}$$

--- at the bottom of the third quarter:

$$LF_3 = \frac{1176-.40(1000)-.30(1000)-.20(1000)}{1176} = 0.23 \qquad EC_{sw_3} = \frac{EC_w}{LF_3} = 4.3 \text{ dS/m}$$

--- at the bottom of the root zone (fourth quarter):

$$LF_4 = \frac{1176-.40(1000)-.30(1000)-.20(1000)-.10(1000)}{1176} = 0.15 \qquad EC_{sw_4} = \frac{EC_w}{LF_4} = 6.7 \text{ dS/m}$$

5. The average soil-water salinity of the root zone is found by taking the average of the five root zone salinities found above:

$$EC_{sw} = \frac{EC_{sw_0} + EC_{sw_1} + EC_{sw_2} + EC_{sw_3} + EC_{sw_4}}{5}$$

$$EC_{sw} = \frac{1.0 + 1.5 + 2.5 + 4.3 + 6.7}{5} = 3.2 \text{ dS/m}$$

6. This calculation shows that the soil-water draining below the root zone will be 3.2 times as concentrated as the applied water.

Table 3 CONCENTRATION FACTORS (X) FOR PREDICTING SOIL SALINITY (ECe)[1] FROM IRRIGATION WATER SALINITY (ECw) AND THE LEACHING FRACTION (LF)

Leaching Fraction (LF)	Applied Water Needed (Percent of ET)	Concentration Factor [2] (X)
0.05	105.3	3.2
0.10	111.1	2.1
0.15	117.6	1.6
0.20	125.0	1.3
0.25	133.3	1.2
0.30	142.9	1.0
0.40	166.7	0.9
0.50	200.0	0.8
0.60	250.0	0.7
0.70	333.3	0.6
0.80	500.0	0.6

[1] The equation for predicting the soil salinity expected after several years of irrigation with water of salinity ECw is:

$$EC_e\ (dS/m) = EC_w\ (dS/m) \cdot X \qquad (8)$$

[2] The concentration factor is found by using a crop water use pattern of 40-30-20-10. The procedure is shown in example 2.

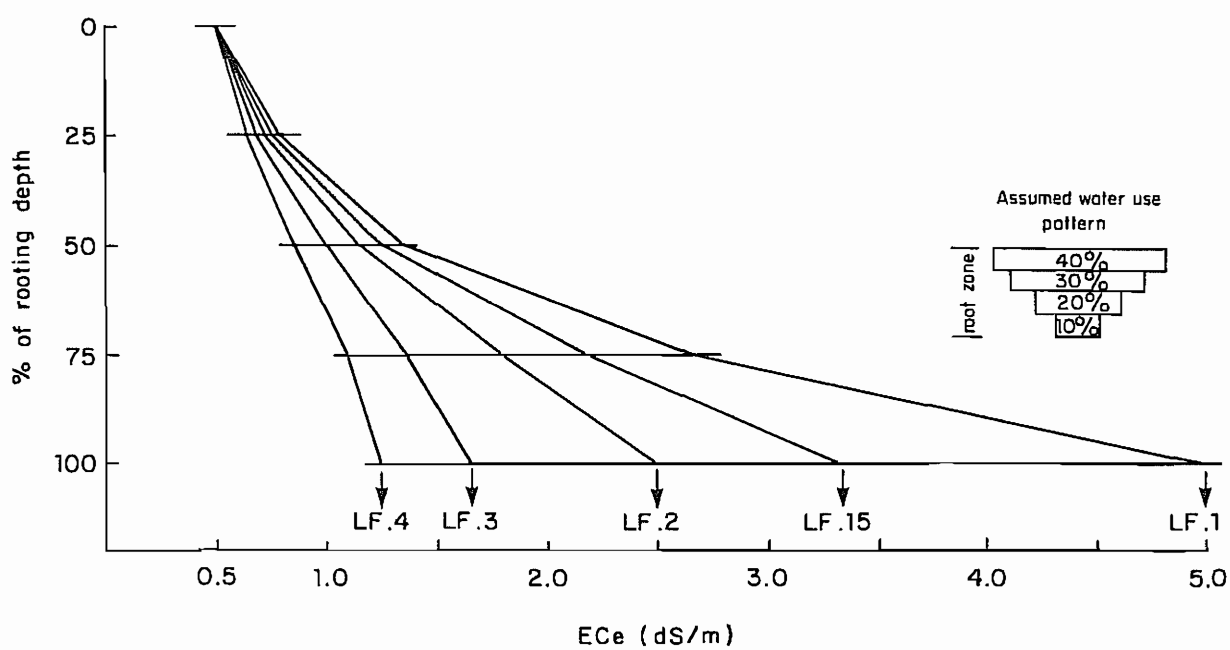


Fig. 2 Salinity profile expected to develop after long-term use of water of EC_w = 1.0 dS/m at various leaching fractions (LF)

potential. For example, if two otherwise identical soils are at the same water content but one is salt-free and the other is salty, the plant can extract and use more water from the salt-free soil than from the salty soil. The reasons are not easily explained. Salts have an affinity for water. If the water contains salt, more energy per unit of water must be expended by the plant to absorb relatively salt-free water from a relatively salty soil-water solution.

For all practical purposes, the added energy required to absorb water from the salty soil (osmotic potential) is additive to the energy required to absorb water from a salt-free soil (soil-water potential). The cumulative effect is illustrated in Figure 3 and results in an important reduction in water available to the crop as salinity increases. Salinity effects are closely analogous to those of drought as both result in water stress and reduced growth. Stunting, leaf damage and necrosis or obvious injury to the plant are only noticeable after prolonged exposure to relatively high salinity.

The previous discussion showed how the concentration of salts in the soil varied with leaching fraction and depth in the root zone and resulted in an increase in concentration as the leaching fraction decreases or with increasing depth in the root zone. As the soil dries, the plant is also exposed to a continually changing water availability in each portion of the rooting depth since the soil-water content (soil-water potential) and soil-water salinity (osmotic potential) are both changing as the plant uses water between irrigations. The plant absorbs water but most of the salt is excluded and left behind in the root zone in a shrinking volume of soil-water. Figure 4 shows that following an irrigation, the soil salinity is not constant with depth. Following each irrigation, the soil-water content at each depth in the root zone is near the maximum, and the concentration of dissolved salts is near the minimum. Each changes, however, as water is used by the crop between irrigations.

The plant exerts its absorptive force throughout the rooting depth and takes water from wherever most readily available (the least resistance to absorption). Usually this is the upper root zone, the area most frequently replenished by irrigation and rainfall. Since more water passes through this upper root zone, it is more thoroughly leached and the osmotic or salinity effects are much less than at greater depths. Between irrigations, the upper root zone dries more rapidly than the lower because of the proliferation of roots in this zone which extract the readily available soil moisture. The plant must then meet more of its water demand from increasingly greater depths as the upper soil-water is depleted. Both the soil moisture at depth and the soil moisture remaining in the upper portions have a higher soil-water salinity and thus a greater osmotic potential. As the plant depletes the soil-water, a water extraction pattern develops. The extraction pattern of 40, 30, 20 and 10 percent for the upper to lower quarters of the root zone is assumed in the guidelines in Table 1. This closely fits water extraction patterns under normal irrigation practices and is assumed throughout this paper.

The pattern for water uptake is closely related to the frequency of irrigation. With infrequent irrigations, as assumed for the guidelines in Table 1, the typical extraction pattern is 40-30-20-10, but for more frequent irrigations the water uptake pattern is skewed towards greater uptake from the upper root zone and less from the lower and the crop rooting depth tends to be at shallower depths. A typical extraction pattern might be 60-30-7-3. Whatever the frequency, irrigations must be timed to supply adequate water and prevent crop moisture stress between irrigations, especially if soil salinity is also affecting water availability.

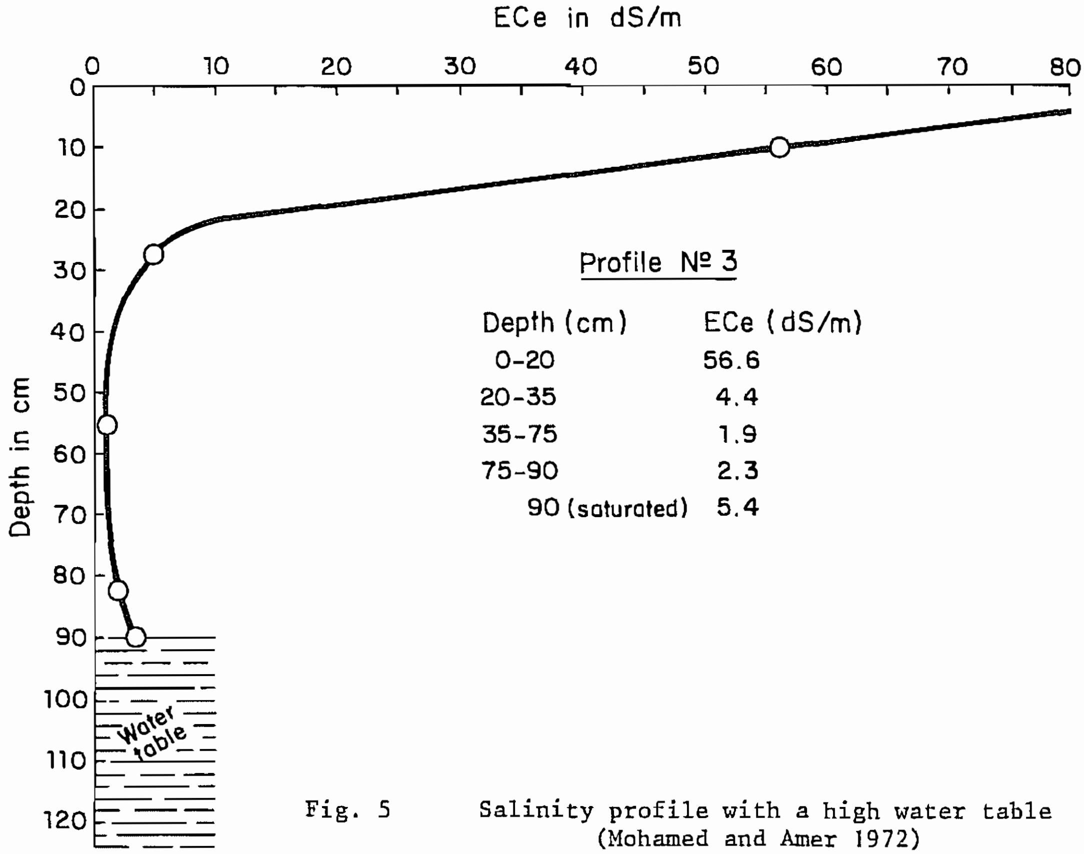


Fig. 5 Salinity profile with a high water table (Mohamed and Amer 1972)

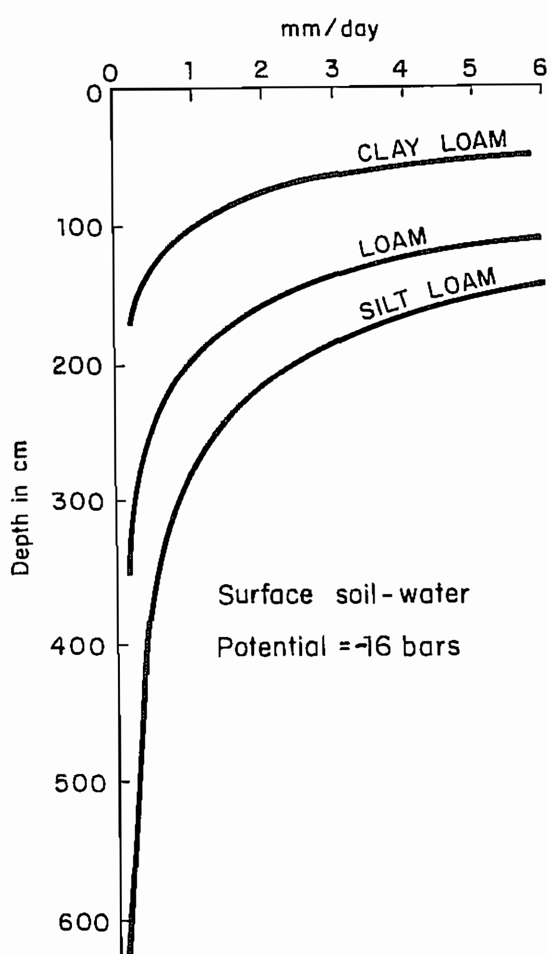


Fig. 6

Relation between capillary flow velocity and depth of water table (Van Hoorn 1979) reclamation, the permanent cropping pattern will be determined by water quality. In a few instances, an alternative water supply may be available for periodic use or can be blended with a poorer water supply to diminish a quality-related hazard. These alternatives, including drainage, leaching, cropping changes and cultural practices, will be discussed in more detail in the following sections.

2.4.1 Drainage

Salinity problems encountered in irrigated agriculture are very frequently associated with an uncontrolled water table within one to two metres of the ground surface (Figure 5). In most soils with a shallow water table, water rises into the active root zone by capillarity and, if the water table contains salts, it becomes a continual source of salts to the root zone as water is used by the crop or evaporates at the soil surface. Salinization from this source can be rapid in irrigated areas in hot climates where portions of the land remain fallow for extended periods. The rate of soil salinity accumulation from an uncontrolled shallow water table will depend upon irrigation management, salt concentration and depth of the groundwater, soil type, and climatic conditions. Figure 6 shows that capillary rise from a shallow water table can represent a sizeable salt input into the root zone.

In arid and semi-arid climates, a salinity problem caused or complicated by poor drainage cannot be adequately controlled until the water table is stabilized and maintained at a safe depth - usually at least two metres. This requires open or tile drains or drainage wells to remove a part of the salty subsurface water and transport it to an acceptable salt-sink for safe disposal. When drainage is adequate, salinity related directly to water quality and irrigation management becomes a problem only if the salts applied with the irrigation water are allowed to accumulate to a concentration which reduces yield. Effective salinity control, therefore, must include adequate drainage to control and stabilize the water table and leaching as needed to reduced the accumulated salts. A net downward flux of surface applied water to achieve the required leaching will then control the salinity. The guidelines in Table 1 and the remainder of the discussion in this paper assume that all salts accumulating in the crop root zone come from the applied water. This means drainage is adequate and salinity management is a significant part of irrigation management.

2.4.2 Salinity Control by Leaching

When the build-up of soluble salts in the soil becomes or is expected to become excessive, the salts can be leached by applying more water than that needed by the crop during the growing season. This extra water moves at least a portion of the salts below the root zone by deep percolation (leaching). Leaching is the key factor in controlling soluble salts brought in by the irrigation water. Over time, salt removal by leaching must equal or exceed the salt additions from the applied water or salts will build up and eventually reach damaging concentrations. The questions that arise are how much water should be used for leaching and when should leachings be applied?

i. The leaching requirement[1]

To estimate the leaching requirement, both the irrigation water salinity (ECw) and the crop tolerance to soil salinity (ECe) must be known. The water salinity can be obtained from laboratory analysis while the ECe should be estimated from appropriate crop tolerance data given in the tables in Section 2.4.3 of this paper. These tables give an acceptable ECe value for each crop appropriate to the tolerable degree of yield loss (usually 10 percent or less).

The necessary leaching requirement (LR) can be estimated from Figure 7 for general crop rotations. For more exact estimates for a particular crop, the leaching requirement equation (9) (Rhoades 1974; and Rhoades and Merrill 1976) should be used:

$$LR = \frac{EC_w}{5\,(EC_e) - EC_w} \qquad (9)$$

where: LR = the minimum leaching requirement needed to control salts within the tolerance (ECe) of the crop with ordinary surface methods of irrigation

EC_w = salinity of the applied irrigation water in dS/m

EC_e = average soil salinity tolerated by the crop as measured on a soil saturation extract. Obtain the ECe value for the given crop and the appropriate acceptable yield from Table 4. It is recommended that the ECe value that can be expected to result in at least a 90 percent or greater yield be used in the calculation. (Figure 7 was developed using ECe values for the 100 percent yield potential.) For water in the moderate to high salinity range (>1.5 dS/m), it might be better to use the ECe value for maximum yield potential (100 percent) since salinity control is critical to obtaining good yields.

The total annual depth of water that needs to be applied to meet both the crop demand and leaching requirement can be estimated from equation (7).

$$AW = \frac{ET}{1 - LR} \qquad (7)$$

where: AW = depth of applied water (mm/year)
ET = total annual crop water demand (mm/year)
LR = leaching requirement expressed as a fraction (leaching fraction)

---

[1] In many texts, the Terms 'leaching fraction (LF)' and 'leaching requirement (LR)' are used interchangeably. They both refer to that portion of the irrigation which should pass through the root zone to control salts at a specific level. While LF indicates that the value be expressed as a fraction, LR can be expressed either as a fraction or percentage of irrigation water.

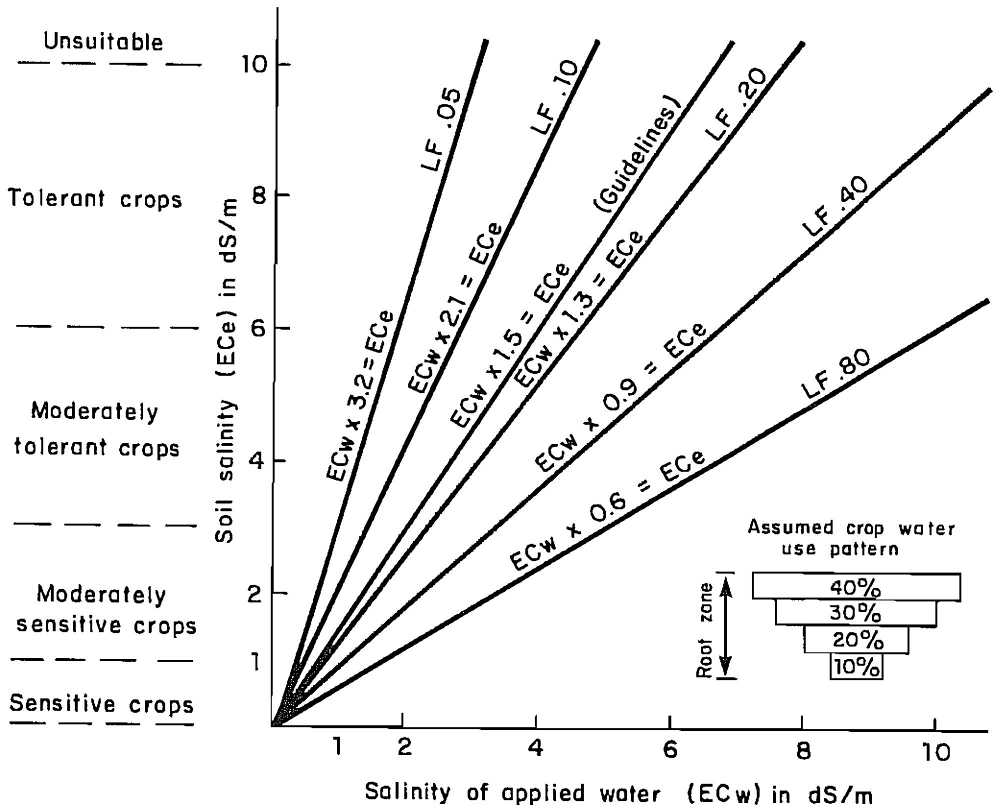


Fig. 7 Effect of applied water salinity (EC_w) upon root zone soil salinity (EC_e) at various leaching fractions (LF)

ii. Timing of leachings

It takes time to accumulate salts in the root zone to a concentration that reduces yield. Most irrigation water is of such good quality that, without leaching, two or more years of irrigation will be required before salinity accumulates sufficiently to affect yield. Further, the later in the growing season the salts reach damaging concentrations, the less will be their effect. This suggests that if salts are low enough at the start of the irrigation season, efficiency of water use during the growing season can be 100 percent (no leaching) without loss of yield due to salinity. For the next season, rainfall, dormant season and pre-plant irrigations, singly or in combination, can be used to replenish deep soil moisture and leach soils free enough of accumulated salts to allow efficient water use again during the next growing season. It is often difficult to supply both essential crop water and leaching water during the hot summer season. The key factor to remember is that leaching is not needed until accumulating salinity is expected to exceed crop tolerance and reduce yield.

The timing of leachings does not appear to be critical provided crop tolerance is not exceeded for extended or critical periods of time. This certainly does not mean that leaching is relatively unimportant. The leaching requirement must be satisfied to prevent excessive salt accumulation. Leaching can be done at each irrigation, each alternate irrigation or less frequently, such as seasonally or at even longer intervals, as necessary to keep salinity below the threshold above which yields may be unacceptably reduced. In many instances, the usual inefficiencies of water application satisfy the leaching requirement and additional leaching is wasteful of water (see Example 3). Where low leaching fractions (< 0.10) are needed, as with good quality water, inefficiencies in irrigation water application will almost always apply sufficient extra water to accomplish leaching. In other instances, particularly with higher salinity water, meeting the leaching requirement is difficult and requires large amounts of water, possibly adding to a drainage problem. It can be assumed that an appreciable portion of the total deep percolation losses from normal irrigation practices is useful in controlling salinity.

EXAMPLE 3 – LEACHING REQUIREMENT CALCULATION

A maize crop is irrigated by furrow irrigation. The crop is planted in a uniform loam soil and river water, which has an ECw = 1.2 dS/m, is used for irrigation. The crop evapotranspiration (ET) is 800 mm/season. The irrigation application efficiency is 0.65. Therefore the total amount of water that must be applied to meet crop ET demand is 800 mm/0.65 = 1230 mm/season. How much additional water must be applied for leaching?

Given:

EC_w = 1.2 dS/m

EC_e = 2.5 dS/m (from Table 4 for maize at a 90 percent yield potential)

EC_e = 1.7 dS/m (from Table 4 for maize at a 100 percent yield potential)

Explanation: The leaching requirement can be calculated using equation (9) and substituting the appropriate ECe value for the desired yield potential (from Table 4).

$$LR = \frac{EC_w}{5(EC_e) - EC_w} = \frac{1.2}{5(2.5) - 1.2} = 0.10 \text{ (for a 90 percent yield potential)} \qquad (9)$$

$$LR = \frac{1.2}{5(1.7) - 1.2} = 0.16 \text{ (for a 100 percent yield potential)}$$

The actual amount of water to be applied to supply both crop ET and leaching (long-term salt control) can be found by using equation (7).

$$AW = \frac{ET}{1 - LR} = \frac{800}{1 - 0.10} = 890 \text{ mm/season} \qquad (7)$$

Since a 1230 mm depth of applied water is needed to ensure that the maize crop is adequately irrigated to meet the 800 mm ET demand and, since this 1230 mm is in excess of the calculated depth of 890 mm required to meet both crop ET demand and the leaching requirement, the question arises whether the losses in excess of ET are deep percolation losses and whether these losses may be satisfying the leaching requirement. Water losses due to deep percolation are often greatly in excess of the leaching fraction of 0.15 assumed in the crop tolerance tables (Table 4) as being typical of efficient irrigated agriculture. If, in this example, the losses are due to deep percolation, no additional leaching to control salinity is necessary since the required leaching fraction of 0.10 or 0.16, as calculated above, will be satisfied by irrigation inefficiency (losses) during water application.

Rainfall must be considered in estimating the leaching requirement. Rainfall that enters the soil is effective in meeting both crop ET and the leaching requirement. Rainfall that infiltrates into the soil (effective rainfall) replaces ET losses. If in excess of ET, it becomes drainage water and will satisfy part or all of the leaching needed to control salts. The advantage of rainfall in accomplishing all or part of the leaching is that it uniformly applies an almost salt-free water (ECw < 0.05 dS/m). Leaching is further enhanced if the rate of rainfall is below the infiltration rate of the soil. If the total amount of rainfall infiltrated is sufficient, it will reduce the average salinity used for the applied water (ECw) in calculating the leaching requirement (LR) and thus reduce proportionately the required leaching. Figure 8 shows how rainfall quickly reduces the salinity in the crop root zone.

In low rainfall years or low rainfall areas, precipitation may not be adequate to refill the soil to its water holding capacity, in which case no leaching occurs to reduce accumulated salinity other than to move the salts from the upper part of the root zone deeper into the soil. The upper portions of the rooting depth will then reflect the very low salinity levels of the rainfall which can enhance germination.

In areas where rainfall occurs in the cooler months or winter season, it may be possible to enhance winter leaching even in a dry year. It is recommended that a heavy autumn or early winter irrigation be given to refill the soil profile with water before the rains. Winter rains will then complete the soil-water replenishment and accomplish all or part of the required leaching with low-salt water. If the rewetting or leaching is still not complete by crop planting time, the deep percolation losses from extended early season irrigations may accomplish the soil rewetting and salt leaching. Figure 9 shows how winter rains have leached salts from citrus plantings in Cyprus.

The leaching requirement can be calculated (Equation 9) but we can only make estimates of the amount of leaching that is actually taking place. Soil and crop monitoring are useful tools to determine the need for leaching. Considerable variation occurs from one cropping season to the next; therefore, monitoring should stress long-term trends and changes in soil salinity.

Several studies, field trials and observations suggest procedures that might increase the efficiency of leaching and reduce the amount of water needed. These will not be covered in detail here but will be mentioned as they apply to many irrigation situations:

- leach during the cool season instead of the warm to increase the efficiency and ease of leaching since the ET losses are lower;
- use more salt tolerant crops which require a lower LR and thus a lower total water demand;
- use tillage to slow overland water flow and reduce the number of surface cracks which bypass flow through large pores and decrease efficiency in leaching;
- use sprinkler irrigation at an application rate below the soil infiltration rate which favours unsaturated flow which is appreciably more efficient than saturated flow

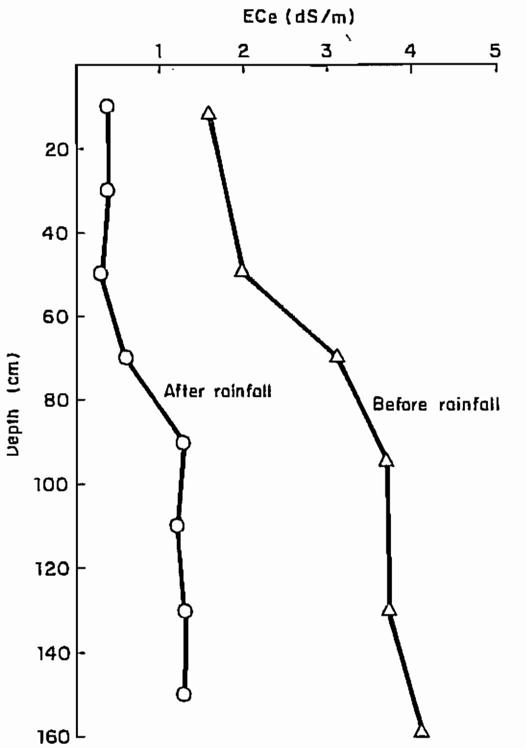


Fig. 8 Soil salinity (EC_e) of a sandy-loam soil before and after 150 mm of rainfall (Aziz 1968)

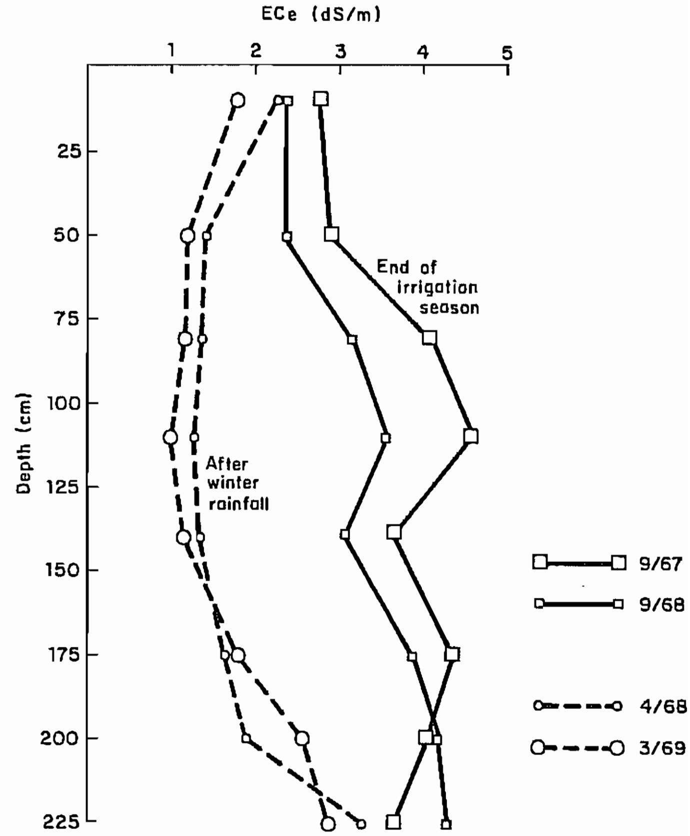


Fig. 9 Soil salinity (EC_e) profiles at the end of the irrigation season and after winter rainfall in citrus plantings (Stylianou 1970)

for leaching. More irrigation time but less water is required than for continuous ponding (Oster **et al.** 1972);

- use alternate ponding and drying instead of continuous ponding. More efficient in leaching (Oster **et al.** 1972) and uses less water but the time required to leach is greater. May have drawbacks in areas with a high water table which allows secondary salinization between pondings;
- where possible, schedule leachings at periods of low crop water use or postpone leachings until after the cropping season;
- avoid fallow periods particularly during hot summers where rapid secondary soil salinization from high water tables can occur;
- if infiltration rates are low, consider pre-planting irrigations or off-season leaching to avoid excessive water applications during the crop season;

use an irrigation before the start of the rainy season if total rainfall is normally expected to be insufficient to do a complete leaching. Rainfall is often the most efficient leaching method because it provides high quality water at relatively low rates of application.

iii. Monitoring

A good irrigation management plan strives to apply sufficient water to meet the crop water demand plus the leaching requirement without wastage. Both the crop water demand and leaching requirement can be estimated and the depth of applied water needed can be calculated. In many instances, however, estimates of depth of applied water (flow rate, duration and area covered) are inaccurate or not available, making estimates of effectiveness of leaching for salinity control unreliable. Existing conditions and reliable estimates of past management can be determined with a reasonable degree of certainty by means of soil samples, analysed for salinity. From the soil samples an apparent leaching fraction as well as an average root zone salinity resulting from past irrigation practices can be determined.

The following procedure is suggested:

a. Estimate the probable depth of rooting of the last crop grown - from observation (pit, hole, soil samples, etc.), or from past experience. Depth estimate should include 75 to 85 percent of the observed root zone.

b. Take representative soil samples from each quarter depth of root zone and analyse each quarter depth separately for ECe by the soil paste extraction method of the US Salinity Laboratory (USDA 1954).

c. Plot by a graph similar to that of Figure 2 for the soil depth and salinity representative of each quarter depth of root zone and compare this curve with the curves depicting the various typical leaching fractions (LF = 0.1, 0.15, 0.2, 0.3, 0.4) in the graph. Then, estimate a leaching fraction for the site sampled based on the shape of the salinity profile.

d. From the ECe of the four soil samples (one from each quarter depth of the root zone) calculate the average root zone salinity and compare with the crop tolerance ECe values in Table 4 for the crops to be planted.

e. From the apparent leaching fraction and the average ECe of the root zone, make any necessary management decisions to adjust irrigations to increase or decrease the leaching fraction in order to stay close to the tolerance of the preferred crop. Alternatively, change the crop to agree more closely with the existing salinity conditions.

2.4.3 Crop Tolerance to Salinity

All plants do not respond to salinity in a similar manner; some crops can produce acceptable yields at much greater soil salinity than others. This is because some are better able to make the needed osmotic adjustments enabling them to extract more water from a saline soil. The ability of the crop to adjust to salinity is extremely useful. In areas where a build-up of soil salinity cannot be controlled at an acceptable concentration for the crop being grown, an alternative crop can be selected that is both more tolerant of the expected soil salinity and can produce economical yields.

There is an 8 to 10-fold range in salt tolerance of agricultural crops. This wide range in tolerance allows for a much greater use of moderately saline water much of which was previously thought to be unusable. It also greatly expands the acceptable range of water salinity (ECw) considered suitable for irrigation.

The relative salt tolerance of most agricultural crops is known well enough to give general salt tolerance guidelines. Tolerances for many common field, vegetable, forage and tree crops are given in Table 4. This table has been updated from the 1976 edition and gives the latest tolerance values for crops grown under semi-arid irrigated agriculture. Where insufficient data exist to give numerical values for tolerance, a relative rating has been assigned to the crop, based on field experience, limited data or observations. For comparative purposes, relative tolerance ratings are listed in Table 5 for a large number of crops, including many of those given in Table 4. General groupings for tolerance are shown in the schematic diagram in Figure 10. The relative tolerance ratings, even if based on a limited amount of data, are useful for comparisons among crops.

The relative crop tolerance ratings were considered in setting the degrees of 'restriction on use' in the guidelines of Table 1. For example, the tolerance data of Table 4 indicate that a full yield potential should be obtainable for nearly all crops when using a water which has a salinity less than 0.7 dS/m. The guidelines of Table 1 indicate that water of this salinity would have no restriction on use. For the salinity listed in the slight to moderate range, a full yield potential is still possible but care must be taken to achieve the required leaching fraction in order to maintain soil salinity within the tolerance of the crop. For higher salinity water and sensitive crops, increasing the leaching to satisfy a leaching requirement greaster than 0.25-0.30 may not be practical because of the excessive amount of water required. In such a case, consideration must be given to changing to a more tolerant crop that will require less leaching to control salts within crop tolerance. As the water salinity (ECw) increases within the slight to moderate range, production of the more sensitive crops may be restricted due to an inability to achieve the high leaching fraction needed, especially when grown on the heavier, more clayey soil types. If the salinity of the applied water exceeds 3.0 dS/m, as shown in Table 1 for a severe restriction on use, the water may still be usable but its use may need to be restricted to more permeable soils and more salt tolerant crops where the high leaching fractions are more easily achieved.

The salt tolerance data of Table 4 are used in the calculation of the leaching requirement. Figure 7 can also be used to estimate the leaching requirement if crop tolerance grouping and water salinity are known, as discussed in the previous section. If the exact cropping patterns or rotations are not known for a new area, the leaching requirement must be based on the least tolerant of the crops adapted to the area. In those instances where soil salinity cannot be maintained within acceptable limits of preferred sensitive crops, changing to more tolerant crops will raise the area's production potential. In case of doubt as to the effect of the water salinity on crop production, a pilot study should be undertaken to demonstrate the feasibility for irrigation and the outlook for economic success.

Table 4 CROP TOLERANCE AND YIELD POTENTIAL OF SELECTED CROPS AS INFLUENCED BY IRRIGATION WATER SALINITY (EC_w) OR SOIL SALINITY (EC_e)[1]

Y I E L D P O T E N T I A L[2]

FIELD CROPS	100% EC_e	100% EC_w	90% EC_e	90% EC_w	75% EC_e	75% EC_w	50% EC_e	50% EC_w	0% "maximum"[3] EC_e	0% "maximum"[3] EC_w
Barley *(Hordeum vulgare)*[4]	8.0	5.3	10	6.7	13	8.7	18	12	28	19
Cotton *(Gossypium hirsutum)*	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18
Sugarbeet *(Beta vulgaris)*[5]	7.0	4.7	8.7	5.8	11	7.5	15	10	24	16
Sorghum *(Sorghum bicolor)*	6.8	4.5	7.4	5.0	8.4	5.6	9.9	6.7	13	8.7
Wheat *(Triticum aestivum)*[4,6]	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13
Wheat, durum *(Triticum turgidum)*	5.7	3.8	7.6	5.0	10	6.9	15	10	24	16
Soybean *(Glycine max)*	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0	10	6.7
Cowpea *(Vigna unguiculata)*	4.9	3.3	5.7	3.8	7.0	4.7	9.1	6.0	13	8.8
Groundnut (Peanut) *(Arachis hypogaea)*	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4
Rice (paddy) *(Oriza sativa)*	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6
Sugarcane *(Saccharum officinarum)*	1.7	1.1	3.4	2.3	5.9	4.0	10	6.8	19	12
Corn (maize) *(Zea mays)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Flax *(Linum usitatissimum)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Broadbean *(Vicia faba)*	1.5	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12	8.0
Bean *(Phaseolus vulgaris)*	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
VEGETABLE CROPS										
Squash, zucchini (courgette) *(Cucurbita pepo melopepo)*	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Beet, red *(Beta vulgaris)*[5]	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15	10
Squash, scallop *(Cucurbita pepo melopepo)*	3.2	2.1	3.8	2.6	4.8	3.2	6.3	4.2	9.4	6.3
Broccoli *(Brassica oleracea botrytis)*	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14	9.1
Tomato *(Lycopersicon esculentum)*	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13	8.4
Cucumber *(Cucumis sativus)*	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10	6.8
Spinach *(Spinacia oleracea)*	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15	10
Celery *(Apium graveolens)*	1.8	1.2	3.4	2.3	5.8	3.9	9.9	6.6	18	12
Cabbage *(Brassica oleracea capitata)*	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12	8.1
Potato *(Solanum tuberosum)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Corn, sweet (maize) *(Zea mays)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Sweet potato *(Impomoea batatas)*	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11	7.1
Pepper *(Capsicum annuum)*	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.6	5.8
Lettuce *(Lactuca sativa)*	1.3	0.9	2.1	1.4	3.2	2.1	5.1	3.4	9.0	6.0
Radish *(Raphanus sativus)*	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	8.9	5.9
Onion *(Allium cepa)*	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.4	5.0
Carrot *(Daucus carota)*	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.0	8.1	5.4
Bean *(Phaseolus vulgaris)*	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
Turnip *(Brassica rapa)*	0.9	0.6	2.0	1.3	3.7	2.5	6.5	4.3	12	8.0

Table 4 (continued)

Y I E L D   P O T E N T I A L

FORAGE CROPS	100% EC_e	100% EC_w	90% EC_e	90% EC_w	75% EC_e	75% EC_w	50% EC_e	50% EC_w	0% "maximum"[3] EC_e	0% "maximum"[3] EC_w
Wheatgrass, tall *(Agropyron elongatum)*	7.5	5.0	9.9	6.6	13	9.0	19	13	31	21
Wheatgrass, fairway crested *(Agropyron cristatum)*	7.5	5.0	9.0	6.0	11	7.4	15	9.8	22	15
Bermuda grass *(Cynodon dactylon)*[7]	6.9	4.6	8.5	5.6	11	7.2	15	9.8	23	15
Barley (forage) *(Hordeum vulgare)*[4]	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20	13
Ryegrass, perennial *(Lolium perenne)*	5.6	3.7	6.9	4.6	8.9	5.9	12	8.1	19	13
Trefoil, narrowleaf birdsfoot[8] *(Lotus corniculatus tenuifolium)*	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15	10
Harding grass *(Phalaris tuberosa)*	4.6	3.1	5.9	3.9	7.9	5.3	11	7.4	18	12
Fescue, tall *(Festuca elatior)*	3.9	2.6	5.5	3.6	7.8	5.2	12	7.8	20	13
Wheatgrass, standard crested *(Agropyron sibiricum)*	3.5	2.3	6.0	4.0	9.8	6.5	16	11	28	19
Vetch, common *(Vicia angustifolia)*	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12	8.1
Sudan grass *(Sorghum sudanense)*	2.8	1.9	5.1	3.4	8.6	5.7	14	9.6	26	17
Wildrye, beardless *(Elymus triticoides)*	2.7	1.8	4.4	2.9	6.9	4.6	11	7.4	19	13
Cowpea (forage) *(Vigna unguiculata)*	2.5	1.7	3.4	2.3	4.8	3.2	7.1	4.8	12	7.8
Trefoil, big *(Lotus uliginosus)*	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.6	5.0
Sesbania *(Sesbania exaltata)*	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	17	11
Sphaerophysa *(Sphaerophysa salsula)*	2.2	1.5	3.6	2.4	5.8	3.8	9.3	6.2	16	11
Alfalfa *(Medicago sativa)*	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16	10
Lovegrass *(Eragrostis sp.)*[9]	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14	9.3
Corn (forage) (maize) *(Zea mays)*	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15	10
Clover, berseem *(Trifolium alexandrinum)*	1.5	1.0	3.2	2.2	5.9	3.9	10	6.8	19	13
Orchard grass *(Dactylis glomerata)*	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18	12
Foxtail, meadow *(Alopecurus pratensis)*	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Clover, red *(Trifolium pratense)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, alsike *(Trifolium hybridum)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, ladino *(Trifolium repens)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, strawberry *(Trifolium fragiferum)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
FRUIT CROPS[10]										
Date palm *(Phoenix dactylifera)*	4.0	2.7	6.8	4.5	11	7.3	18	12	32	21
Grapefruit *(Citrus paradisi)*[11]	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8.0	5.4
Orange *(Citrus sinensis)*	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8.0	5.3
Peach *(Prunus persica)*	1.7	1.1	2.2	1.5	2.9	1.9	4.1	2.7	6.5	4.3
Apricot *(Prunus armeniaca)*[11]	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	5.8	3.8
Grape *(Vitus sp.)*[11]	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Almond *(Prunus dulcis)*[11]	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.8	6.8	4.5

Table 4 (continued)

Y I E L D   P O T E N T I A L

FRUIT CROPS [10]	100%		90%		75%		50%		0% "maximum" [3]	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Plum, prune *(Prunus domestica)* [11]	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.9	7.1	4.7
Blackberry *(Rubus sp.)*	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Boysenberry *(Rubus ursinus)*	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Strawberry *(Fragaria sp.)*	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4	2.7

1 Adapted from Maas and Hoffman (1977) and Maas (1984). These data should only serve as a guide to relative tolerances among crops. Absolute tolerances vary depending upon climate, soil conditions and cultural practices. In gypsiferous soils, plants will tolerate about 2 dS/m higher soil salinity (ECe) than indicated but the water salinity (ECw) will remain the same as shown in this table.

2 ECe means average root zone salinity as measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre (dS/m) at 25°C. ECw means electrical conductivity of the irrigation water in deciSiemens per metre (dS/m). The relationship between soil salinity and water salinity (ECe = 1.5 ECw) assumes a 15-20 percent leaching fraction and a 40-30-20-10 percent water use pattern for the upper to lower quarters of the root zone. These assumptions were used in developing the guidelines in Table 1.

3 The zero yield potential or maximum ECe indicates the theoretical soil salinity (ECe) at which crop growth ceases.

4 Barley and wheat are less tolerant during germination and seedling stage; ECe should not exceed 4-5 dS/m in the upper soil during this period.

5 Beets are more sensitive during germination; ECe should not exceed 3 dS/m in the seeding area for garden beets and sugar beets.

6 Semi-dwarf, short cultivars may be less tolerant.

7 Tolerance given is an average of several varieties; Suwannee and Coastal Bermuda grass are about 20 percent more tolerant, while Common and Greenfield Bermuda grass are about 20 percent less tolerant.

8 Broadleaf Birdsfoot Trefoil seems less tolerant than Narrowleaf Birdsfoot Trefoil.

9 Tolerance given is an average for Boer, Wilman, Sand and Weeping Lovegrass; Lehman Lovegrass seems about 50 percent more tolerant.

10 These data are applicable when rootstocks are used that do not accumulate Na^+ and Cl^- rapidly or when these ions do not predominate in the soil. If either ions do, refer to the toxicity discussion in Section 4.

11 Tolerance evaluation is based on tree growth and not on yield.

Table 5 RELATIVE SALT TOLERANCE OF AGRICULTURAL CROPS [1,2]

TOLERANT [3]

Fibre, Seed and Sugar Crops

Barley	*Hordeum vulgare*
Cotton	*Gossypium hirsutum*
Jojoba	*Simmondsia chinensis*
Sugarbeet	*Beta vulgaris*

Grasses and Forage Crops

Alkali grass, Nuttall	*Puccinellia airoides*
Alkali sacaton	*Sporobolus airoides*
Bermuda grass	*Cynodon dactylon*
Kallar grass	*Diplachne fusca*
Saltgrass, desert	*Distichlis stricta*
Wheatgrass, fairway crested	*Agropyron cristatum*
Wheatgrass, tall	*Agropyron elongatum*
Wildrye, Altai	*Elymus angustus*
Wildrye, Russian	*Elymus junceus*

Vegetable Crops

Asparagus	*Asparagus officinalis*

Fruit and Nut Crops

Date palm	*Phoenix dactylifera*

MODERATELY TOLERANT [3]

Fibre, Seed and Sugar Crops

Cowpea	*Vigna unguiculata*
Oats	*Avena sativa*
Rye	*Secale cereale*
Safflower	*Carthamus tinctorius*
Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Triticale	*X Triticosecale*
Wheat	*Triticum aestivum*
Wheat, Durum	*Triticum turgidum*

Grasses and Forage Crops

Barley (forage)	*Hordeum vulgare*
Brome, mountain	*Bromus marginatus*
Canary grass, reed	*Phalaris, arundinacea*
Clover, Hubam	*Melilotus alba*
Clover, sweet	*Melilotus*
Fescue, meadow	*Festuca pratensis*
Fescue, tall	*Festuca elatior*
Harding grass	*Phalaris tuberosa*
Panic grass, blue	*Panicum antidotale*
Rape	*Brassica napus*
Rescue grass	*Bromus unioloides*
Rhodes grass	*Chloris gayana*
Ryegrass, Italian	*Lolium italicum multiflorum*
Ryegrass, perennial	*Lolium perenne*
Sudan grass	*Sorghum sudanense*
Trefoil, narrowleaf birdsfoot	*Lotus corniculatus tenuifolium*
Trefoil, broadleaf birdsfoot	*Lotus corniculatus arvenis*
Wheat (forage)	*Triticum aestivum*
Wheatgrass, standard crested	*Agropyron sibiricum*

MODERATELY TOLERANT

Grasses and Forage Crops

Wheatgrass, intermediate	*Agropyron intermedium*
Wheatgrass, slender	*Agropyron trachycaulum*
Wheatgrass, western	*Agropyron smithii*
Wildrye, beardless	*Elymus triticoides*
Wildrye, Canadian	*Elymus canadensis*

Vegetable Crops

Artichoke	*Helianthus tuberosus*
Beet, red	*Beta vulgaris*
Squash, zucchini	*Cucurbita pepo melopepo*

Fruit and Nut Crops

Fig	*Ficus carica*
Jujube	*Ziziphus jujuba*
Olive	*Olea europaea*
Papaya	*Carica papaya*
Pineapple	*Ananas comosus*
Pomegranate	*Punica granatum*

MODERATELY SENSITIVE [3]

Fibre, Seed and Sugar Crops

Broadbean	*Vicia faba*
Castorbean	*Ricinus communis*
Maize	*Zea mays*
Flax	*Linum usitatissimum*
Millet, foxtail	*Setaria italica*
Groundnut/Peanut	*Arachis hypogaea*
Rice, paddy	*Oryza sativa*
Sugarcane	*Saccarum officinarum*
Sunflower	*Helianthus annuus*

Grasses and Forage Crops

Alfalfa	*Medicago sativa*
Bentgrass	*Agrostis stolonifera palustris*
Bluestem, Angleton	*Dichanthium aristatum*
Brome, smooth	*Bromus inermis*
Buffelgrass	*Cenchrus ciliaris*
Burnet	*Poterium sanguisorba*
Clover, alsike	*Trifolium hydridum*
Clover, Berseem	*Trifolium alexandrinum*
Clover, ladino	*Trifolium repens*
Clover, red	*Trifolium pratense*
Clover, strawberry	*Trifolium fragiferum*
Clover, white Dutch	*Trifolium repens*
Corn (forage) (maize)	*Zea mays*
Cowpea (forage)	*Vigna unguiculata*
Dallis grass	*Paspalum dilatatum*
Foxtail, meadow	*Alopecurus pratensis*
Grama, blue	*Bouteloua gracilis*
Lovegrass	*Eragrostis sp.*
Milkvetch, Cicer	*Astragalus cicer*
Oatgrass, tall	*Arrhenatherum, Danthonia*
Oats (forage)	*Avena sativa*

Table 5 (continued)

MODERATELY SENSITIVE

Grasses and Forage Crops	
Orchard grass	*Dactylis glomerata*
Rye (forage)	*Secale cereale*
Sesbania	*Sesbania exaltata*
Siratro	*Macroptilium atropurpureum*
Sphaerophysa	*Sphaerophysa salsula*
Timothy	*Phleum pratense*
Trefoil, big	*Lotus uliginosus*
Vetch, common	*Vicia angustifolia*
Vegetable Crops	
Broccoli	*Brassica oleracea botrytis*
Brussels sprouts	*B. oleracea gemmifera*
Cabbage	*B. oleracea capitata*
Cauliflower	*B. oleracea botrytis*
Celery	*Apium graveolens*
Corn, sweet	*Zea mays*
Cucumber	*Cucumis sativus*
Eggplant	*Solanum melongena esculentum*
Kale	*Brassica oleracea acephala*
Kohlrabi	*B. oleracea gongylode*
Lettuce	*Latuca sativa*
Muskmelon	*Cucumis melo*
Pepper	*Capsicum annuum*
Potato	*Solanum tuberosum*
Pumpkin	*Cucurbita peop pepo*
Radish	*Raphanus sativus*
Spinach	*Spinacia oleracea*
Squash, scallop	*Cucurbita pepo melopepo*
Sweet potato	*Ipomoea batatas*
Tomato	*Lycopersicon lycopersicum*
Turnip	*Brassica rapa*
Watermelon	*Citrullus lanatus*
Fruit and Nut Crops	
Grape	*Vitis sp.*

SENSITIVE[3]

Fibre, Seed and Sugar Crops	
Bean	*Phaseolus vulgaris*
Guayule	*Parthenium argentatum*
Sesame	*Sesamum indicum*
Vegetable Crops	
Bean	*Phaseolus vulgaris*
Carrot	*Daucus carota*
Okra	*Abelmoschus esculentus*
Onion	*Allium cepa*
Parsnip	*Pastinaca sativa*
Fruit and Nut Crops	
Almond	*Prunus dulcis*
Apple	*Malus sylvestris*
Apricot	*Prunus armeniaca*
Avocado	*Persea americana*
Blackberry	*Rubus sp.*
Boysenberry	*Rubus ursinus*
Cherimoya	*Annona cherimola*
Cherry, sweet	*Prunus avium*
Cherry, sand	*Prunus besseyi*
Currant	*Ribes sp.*
Gooseberry	*Ribes sp.*
Grapefruit	*Citrus paradisi*
Lemon	*Citrus limon*
Lime	*Citrus aurantiifolia*
Loquat	*Eriobotrya japonica*
Mango	*Mangifera indica*
Orange	*Citrus sinensis*
Passion fruit	*Passiflora edulis*
Peach	*Prunus persica*
Pear	*Pyrus communis*
Persimmon	*Diospyros virginiana*
Plum: Prume	*Prunus domestica*
Pummelo	*Citrus maxima*
Raspberry	*Rubus idaeus*
Rose apple	*Syzgium jambos*
Sapote, white	*Casimiroa edulis*
Strawberry	*Fragaria sp.*
Tangerine	*Citrus reticulata*

[1] Data taken from Maas (1984).

[2] These data serve only as a guide to the relative tolerances among crops. Absolute tolerances vary with climate, soil conditions and cultural practices.

[3] The relative tolerance ratings are defined by the boundaries in Figure 10. Detailed tolerances can be found in Table 4 and Maas (1984).

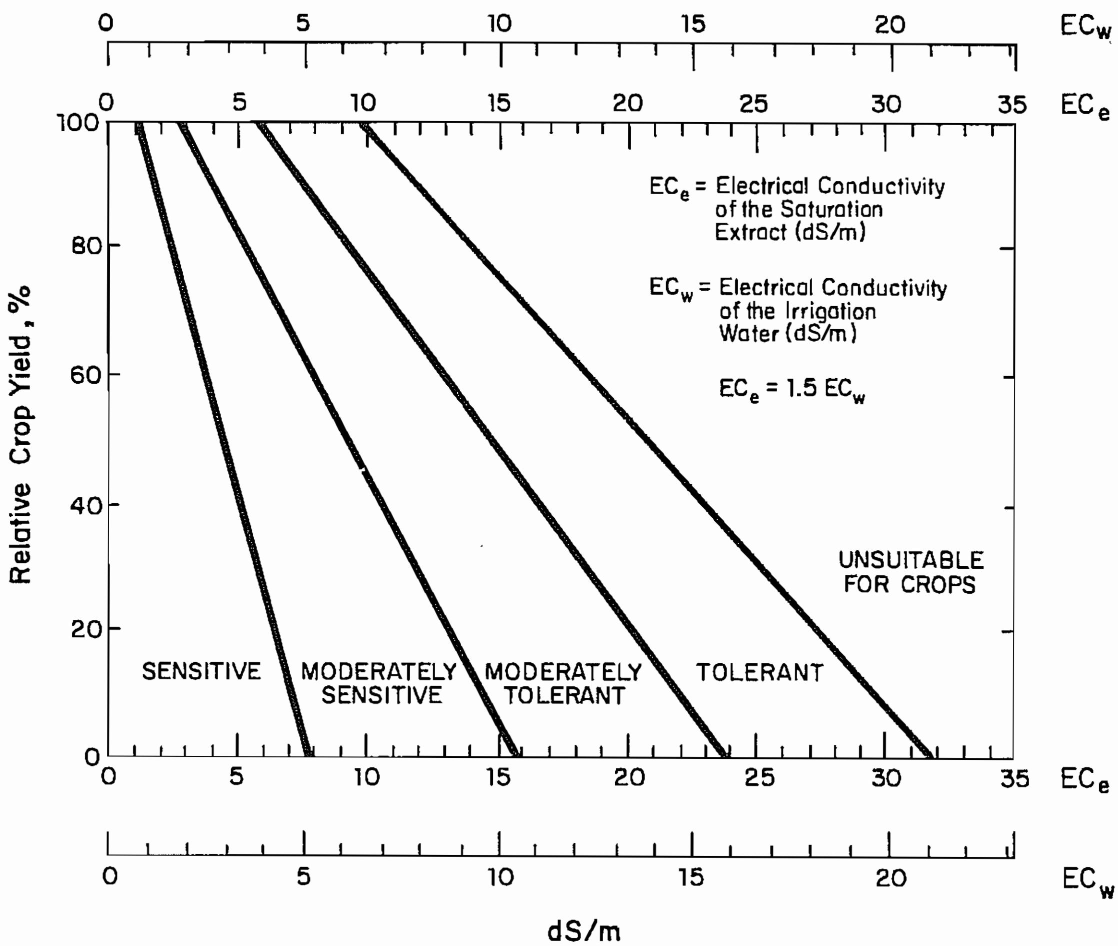


Fig. 10 Divisions for relative salt tolerance ratings of agricultural crops (Maas 1984)

i. Development of tolerance data

Numerical values for tolerance given in Table 4 were adapted from data of Maas and Hoffman (1977) and Maas (1984). These data indicate that plant growth rate decreases linearly as salinity increases above a critical threshold salinity at which growth rate first begins to decrease. This linear decrease in yield is in good agreement with field data throughout the usual range of salinity. Deviations from the linear decrease occur at yields considerably less than 50 percent of potential, at which level yields are commercially unacceptable anyway.

The following equation (Maas and Hoffman 1977) expresses the straight line salinity effect on yield and was used in the preparation of Table 4.

$$Y = 100 - b\,(EC_e - a) \qquad (10)$$

where:
- Y = relative crop yield (percent)
- EC_e = salinity of the soil saturation extract in dS/m
- a = salinity threshold value
- b = yield loss per unit increase in salinity

The values for (a) and (b) are given by Maas in his original paper but can also be determined from Table 4. The (a) value (the threshold soil salinity) is the ECe value for 100 percent yield potential in Table 4. The (b) value can be determined from Table 4 as follows:

$$b = \frac{100}{EC_e \text{ at } 0\% \text{ yield} - EC_e \text{ at } 100\% \text{ yield}} \qquad (11)$$

The ECe values of Table 4 for other than those associated with a 100 percent yield were calculated from the yield equation of Maas and Hoffman (1977) by rearranging equation (10) as follows:

$$EC_e = \frac{100 + ab - Y}{b} \qquad (12)$$

where ECe is the soil salinity associated with a designated percent yield, Y (see Example 4).

In Table 4 values are presented for the potential yields of 100, 90, 75, 50 and 0 percent. Table 4 also lists the applied irrigation water salinity (ECw) equivalent to the soil salinity (ECe) developed by the use of equation (5). This concentration factor from water salinity (ECw) to soil salinity of 1.5 is representative of a 15-20 percent leaching fraction. It was used in the development of the guidelines, and concentration factors for other leaching fractions are given in Table 3. The tolerance limits of Table 4 for water salinity assume that the soil salinity (ECe) results from accumulatin of salts coming from the applied irrigation water. If there is a source of salt other than the irrigation water, for example from a high water table, the concentration relationship between water salinity (ECw) and soil salinity (ECe) is not valid, but the ECe values given in Table 4 are still valid. It is again emphasized that the soil salinity (ECe) that is expected to develop following several years of use of a water assumes that the water is the primary source of soluble salts. If a water table is present, it is an additional salt source not considered in the fixed relationship ECe = 1.5 ECw.

If conditions of use consistently indicate a leaching fraction other than 0.15 to 0.20, the concentration factor (1.5 ECw = ECe), will also be different and the equivalent water salinity (ECw) of Table 4 can be changed and a new table prepared. However, this should only be done if well documented local experience confirms that the 1.5 concentration factor does not apply. The soil salinity values (ECe) presented in Table 4 for crop tolerance are believed to be the best available to date and should not be changed. They are supported by extensive and worldwide field research. Changing the leaching fraction to change the concentration factor is one of the options available for control of salinity. Table 3 presents concentration factors for various leaching fractions. These are useful to predict soil salinity (ECe) that is expected to result from use of water at any given salinity and leaching fraction, as explained in a previous section.

The majority of the yield data used by Maas and Hoffman (1977) to develop their linear equation (Equation 10) were for yields varying between 50 and 100 percent yield potential. Because the linear equation predicts these yields so well, it can be used to predict the approximate theoretical soil salinity (ECe) at which

EXAMPLE 4 - DETERMINATION OF YIELD POTENTIAL

For a cotton crop, from Table 4:

a = salinity threshold value (EC_e for 100 percent yield)

a = 7.7 dS/m

From equation (11) and Table 4:

$$b = \frac{100}{EC_e \text{ at } 0\% \text{ yield} - EC_e \text{ at } 100\% \text{ yield}} \quad (11)$$

where: b = slope of the yield loss line

b = 5.2 percent yield loss per 1 unit increase in soil salinity (EC_e)

Substituting a and b into equation (12) for yield (Y) at 100 percent,

$$EC_e = \frac{100 + ab - Y}{b} = 7.7 \text{ dS/m} \quad (12)$$

The following shows EC_e corresponding to indicated yield:

Potential Yield (percent)	EC_e (dS/m)
100	7.7
90	9.6
75	13
50	17
0	27

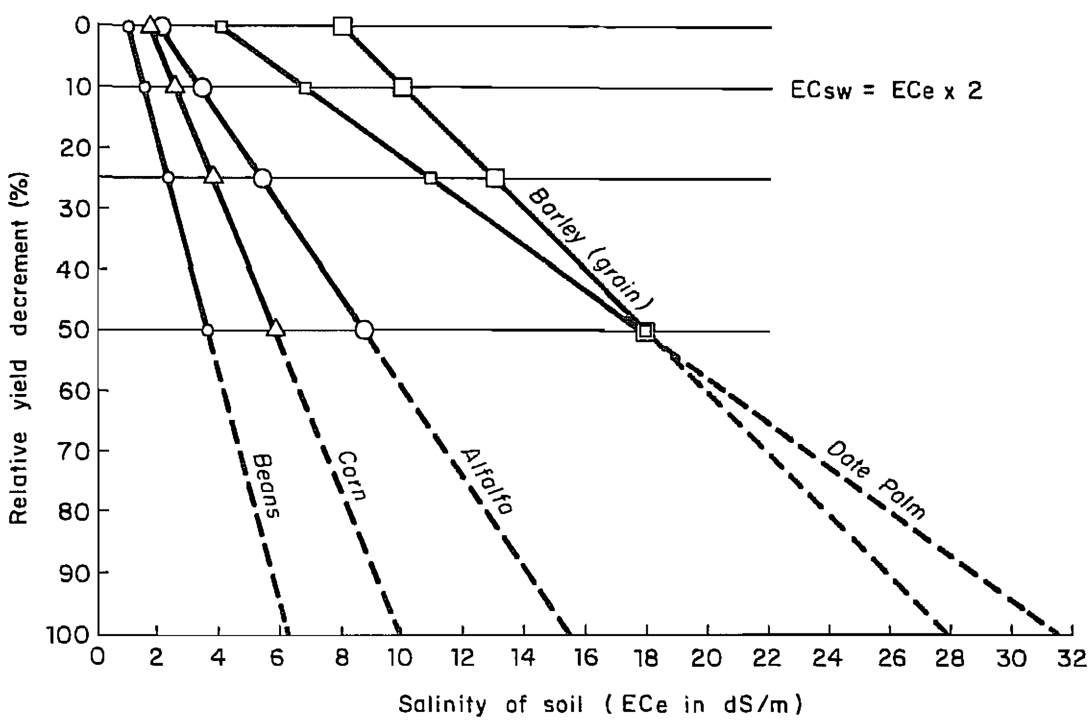


Fig. 11 Method of determining maximum EC_e

the plant is presumed to be unable to extract water, and growth ceases (yield in this case would be zero). The maximum ECe or the 0 percent yield predicted by this procedure are given in the last column of Table 4. Figure 11 illustrates this projection to the expected salinity for zero yield.

If the tolerance data are plotted in graphic form, crops with similar tolerances form groups. Boundaries and relative tolerance ratings can then be assigned to these groups. The schematic diagram in Figure 10 (Maas 1984) corresponds to the relative tolerance ratings given earlier for the crops in Table 5. The divisions, although arbitrary, are useful for general planning and for comparisons among crops. In those instances where sufficient data do not exist, a relative tolerance rating was assigned to the crop, based upon best judgement from field experience and observations (Maas 1984). According to the diagram in Figure 10, crop tolerances have been grouped as follows:

Relative crop salinity tolerance rating	Soil salinity (ECe) at which yield loss begins
Sensitive	< 1.3 dS/m
Moderately sensitive	1.3 - 3.0 dS/m
Moderately tolerant	3.0 - 6.0 dS/m
Tolerant	6.0 - 10.0 dS/m
Unsuitable for most crops (unless reduced yield is acceptable)	> 10.0 dS/m

If there are few crops in an area, it may be desirable to prepare separate guidelines for each specific crop or group of crops rather than use the broad guidelines given in Table 1. Guidelines for an individual crop can be more specific and are better aids to managers and cultivators for evaluating the suitability of the available water supply. An example of such a specific guideline is given in Table 6.

ii. Factors affecting tolerance

Crop production potential using a particular irrigation water can range from 100 percent down to zero but there are often factors other than water quality which affect yield. The tolerance values in Table 4 represent production potential when salinity is the only limiting factor. Such conditions, however, do not always exist. Other conditions may also limit production but the relative yield loss due to salinity will approximate those in Table 4 if salinity is the main limiting factor.

The soil salinity tolerances in Table 4 apply primarily to crops from late seedling stage to maturity. Tolerance during the germination and early seedling stage may be different and is only clearly defined for a few crops. Table 7 presents data for a few crops showing soil salinity that resulted in a 50 percent reduction in either yield or seedling emergence. In general, if the soil salinity in the surface soil (seeding area) is greater than 4 dS/m, it may inhibit or delay germination and early seedling growth. This slowed germination may then delay emergence, allowing soil crusting and disease problems to reduce the crop stand. Rainfall or pre-plant irrigations will often help to maintain low salinity, delay crusting and promote good emergence.

Table 6 GUIDELINES FOR INTERPRETING LABORATORY DATA ON WATER SUITABILITY FOR GRAPES [1]

Potential Irrigation Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe [2]
Salinity [3] *(affects water availability to crops)*				
EC_w	dS/m	< 1	1.0 - 2.7	> 2.7
Toxicity *(specific ions which affect growth of crop)*				
Sodium (Na^+) [4]	me/l	< 20	-	-
Chloride (Cl^-) [4]	me/l	< 4	4 - 15	> 15
Boron (B)	mg/l	< 1	1 - 3	> 3
Miscellaneous				
Bicarbonate (HCO_3^-) [5]	me/l	< 1.5	1.5 - 7.5	> 7.5
Nitrate-nitrogen (NO_3-N)	mg/l	< 5	5 - 30	> 30

1 Adapted from Neja **et al.** 1978

2 Special management practices and favourable soil conditions are required for successful production.

3 Assumes that rainfall and extra water applied owing to inefficiencies of normal irrigation will supply the crop needs plus about 15 percent extra for salinity control.

4 With overhead sprinkler irrigation, sodium or chloride in excess of 3 me/l under extreme drying conditions may result in excessive leaf absorption, leaf burn and crop damage. If overhead sprinklers are used for cooling by frequent on-off cycling, damage may occur even at lower concentrations.

5 Bicarbonate (HCO_3) in water applied by overhead sprinklers may cause white deposits on fruit and leaves which reduces market acceptability, but is not toxic to the plant.

Table 7 RELATIVE SALT TOLERANCE OF VARIOUS CROPS AT GERMINATION [1]

Crop		50 percent Emergence reduction (ECe in dS/m)
Barley	*(Hordeum vulgare)*	16 - 24
Cotton	*(Gossypium hirsutum)*	15.5
Sugarbeet	*(Beta vulgaris)*	6 - 12.5
Sorghum	*(Sorghum bicolor)*	13
Safflower	*(Carthamus tinctorius)*	12.3
Wheat	*(Triticum aestivum)*	14 - 16
Beet, red	*(Beta vulgaris)*	13.8
Alfalfa	*(Medicago sativa)*	8.2 - 13.4
Tomato	*(Lycopersicon lycopersicum)*	7.6
Rice	*(Oryza sativa)*	18
Cabbage	*(Brassica oleracea capitata)*	13
Muskmelon	*(Cucumis melo)*	10.4
Maize	*(Zea mays)*	21 - 24
Lettuce	*(Lactuca sativa)*	11.4
Onion	*(Allium cepa)*	5.6 - 7.5
Bean	*(Phaseolus vulgaris)*	8.0

1 Data taken from Maas (1984).

Rootstocks used for certain tree (citrus, almonds, stone-fruit) and vine crops (grapes) can appreciably influence salinity tolerance. Rootstocks differ in their ability to exclude salt, especially the toxic sodium and chloride ions. With a reduction in the amount absorbed, accumulation is reduced. This characteristic for exclusion has allowed selection of commercially acceptable rootstocks as well as varieties for improved production under saline conditions of soil or water.

Varietal differences also exist among cultivars of annual crops. The greatest differences in tolerance appear to be among selections from cultivars of the more salt tolerant crops. A few may be significantly more or less tolerant than indicated in Table 4. A careful screening of available varieties is essential if salinity of applied water makes tolerance critical.

Plant breeding and selection for salinity tolerance have only recently been undertaken to any appreciable extent. Initial results are promising and have stimulated new research in genetic salt tolerance, particularly among closely related varieties or strains within a variety. If successful, plant breeding and gene selection for salinity tolerance may greatly expand our ability to use more saline water suplies, but any new information on tolerance should be used with caution. Any new varieties developed, and having greater tolerance, should be judged on their own merits. A number of years (5-15 or more) will probably be needed before even a few new, more salt tolerant crops are commercially available and competitive in yield and quality with present varieties. The tolerances given in Table 4 are expected to remain valid for most of the crops for the foreseeable future.

Climate also affects crop tolerance to salinity and drought. In general, crops grown in cooler climates or during the cooler time of the year will have a higher tolerance to salinity then similar crops grown during warmer, drier periods. Since crop demand for water is less during the cooler periods, the effect of reduced water availability due to salinity is not so critical and a greater proportion of rainfall or applied water may be available to leach accumulated salts. In contrast, however, during periods of very high ET demand, as in summer months, under hot, dry conditions, water absorption by the plant roots may not be adequate due to both rapid depletion of soil water and increased salt concentration around the roots. Under these conditions, the plants may show earlier water stress than anticipated from normal bulk soil sampling and water stress may be critical during extended periods of hot dry winds. Climate appears to affect salt sensitive crops to a much greater extent than salt tolerant ones.

Fertilization has little effect on salt tolerance. If fertility is a limiting factor, proper fertilization will increase yields, but if fertilization is not limiting, additional fertilizer will not improve salt tolerance. Since fertilizers are for the most part soluble salts, timing and placement are important, and unless properly applied they may contribute to or cause a salinity problem.

2.4.4 Cultural Practices

The primary management options to control salinity were discussed in the preceding sections: adequate drainage, leaching to control salinity within the tolerance of the crop or, if this cannot be done, change to a more salt tolerant crop that requires less leaching for adequate salt control. These management practices are the ones most appropriate for long-term salinity control but there are separate cultural practices that can have a profound effect upon germination, early seedling growth and ultimately on yield of crop. Low yields are often the result of obtaining poor crop stands during the germination or early seedling stage of growth. These short-term cultural practices that aid in salinity control become more important as the irrigation water salinity increases, and are often done on an annual or continual basis. They include land smoothing for better water distribution, timing of irrigations to prevent crusting and water stress, placement of seed to avoid areas likely to be salinized, and care in selection of materials, rate and placement of fertilizers.

i. Land smoothing or grading

Salinity control is difficult if a field is not sufficiently graded to permit uniform water distribution. Salts accumulate in the high spots which have too little penetration and leaching (water runs off), while water accumulates in low-lying areas which causes waterlogging and potential drainage problems. Germination is often poor in high spots due to shortage of water and excessive salinity, while in low areas, similar poor crop stands may result from waterlogging and soil crusting. The most difficult problems occur with flood (border check or strip check) irrigation whereas sprinkler or localized (drip) irrigation require smoothing or grading only to the extent needed to prevent water from accumulating excessively in low areas.

Land smoothing (land planing) simply smooths the soil surface. Although a good practice, it does not grade a field and is not a substitute for land levelling to a set gradient or slope. Land smoothing is often an annual practice or is done every few years to ensure uniform water distribution when annual crops are changed. In contrast, land grading is usually a one-time practice where 'cuts' from one part of a field are transported to another area of the same field and spread as 'fill' to raise the level in that area. After this one-time field grading is done, land smoothing or a less extensive land grading is done to restore the field slope or gradient which may have changed slightly due to cropping, cultivations and irrigations.

Recent deep alluvial soils can be smoothed or graded with little risk of greatly damaging soil quality but the older, mature and layered alluvial or residual soils may be difficult to smooth, level or grade to a set slope without serious structural damage. Land grading causes a significant amount of soil compaction due to the weight of the heavy equipment and it is advisable to follow this operation with subsoiling, chiselling, or ploughing to break up the compaction and restore or improve water infiltration.

ii. Timing of irrigations

The timing of irrigations to prevent water stress will improve the chances for success when using higher salinity water. Irrigation timing may include increasing the frequency of irrigation, irrigating prior to a winter rainy season, and using pre-plant or other practices to aid in germinating the crop. The goal of irrigation timing is to reduce salinity and avoid water stress between irrigations.

Water stress between irrigations can often be eliminated by increasing the frequency of irrigations, thereby preventing excessive root zone depletion caused by too long an interval between irrigations. By decreasing the interval between irrigations, a higher soil-water availability is maintained.

Increasing the frequency of irrigations may not always produce the desired results. For example, with furrow and other flood methods, a change to more frequent irrigation may result in an unacceptable increase in depth of water applied, a corresponding decrease in water use efficiency and consequent drainage problems. These irrigation methods are generally less efficient because the depth of water applied per irrigation cannot be as easily adjusted as with sprinkler or drop. With the more efficient methods of irrigation, increased frequency may not greatly increase water use.

More frequent irrigations may not be practical except in areas where water can be taken on demand. A good knowledge of crop water demand as the season advances is necessary to determine proper frequency. The methods for estimating crop water demand (ET) and the periods of greatest sensitivity are discussed in Doneen (1971); Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979).

Salts from higher salinity irrigation water can accumulate rapidly in the top few centimetres of the soil due to surface evaporation during non-crop periods, particularly if a high water table is also present and the climate is hot and dry. The extent of accumulation is influenced by salinity of both the irrigation water and the water table, if present. Under such conditions, seed germination, seedling development and yield may be seriously reduced. A pre-plant leaching irrigation is often used to remove these surface salt concentrations.

If winter rainfall is insufficient to leach the accumulated salts from the topsoil, applying an irrigation before the onset of limited winter rains refills the upper soil with water and the winter rains may then be relied upon to provide sufficient water for leaching. Rainfall is excellent in quality and leaches salts out of the seed areas, thus eliminating germination problems. Late autumn or early winter irrigation is a good practice in a Mediterranean climate where winter rains may not provide all the necessary leaching. Winter plus pre-plant irrigations give the user of less than ideal quality water greater flexibility in timing of irrigations during the growing season.

When using water of moderate to high salinity ($ECw > 1.0$ dS/m) germination is often poor due to salts accumulating in the seed row, especially when crops are seeded on raised beds and furrow irrigated. A common practice among growers of lettuce, tomatoes and other sensitive annual crops is to use sprinklers to reduce salinity to obtain better germination, to lower surface soil temperatures and improve early seedling growth. Irrigations are applied one or more times each day for several days and for relatively short periods of time - 1 to 3 hours' duration. After 10 to 14 days the sprinklers are moved to another field and normal furrow or flood irrigations are applied as needed. One sprinkler system can be used for germination and early growth of several different fields in a season.

Overhead sprinklers cause problems for certain sensitive crops when chloride or sodium is relatively high. These concentrate as water evaporates between sprinkler rotations and are then absorbed in excessive amounts by the leaves wet by the sprinklers. These problems occur mostly with slowly rotating sprinkler heads and are aggravated by low rates of application. Sodium or chloride in the water in excess of about 3 me/l causes the problem. Similar problems can occur due to drift of spray from sprinklers applying moderately high salinity water. The toxicity usually appears as leaf burn (necrosis) on the leaf-edges and can be confirmed by leaf analysis for chloride and sodium. 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 very sensitive to low levels of sodium and chloride but all crops will be affected if the concentration is high enough. These problems are discussed in more detail in Section 4.3.

iii. Placement of seed

Salinity reduces or slows germination and it is often difficult to obtain a satisfactory stand of furrow irrigated crops on saline soils or when using moderately saline water. In some cases, growers plant two or three times as much seed as normal, hoping to offset the reduced germination. Increasing the amount of seed planted can give higher plant density (Table 8) but may also result in additional thinning costs; even then the plant population may not be uniform and increased yields cannot be assumed. A better alternative might be to make appropriate adjustments in planting procedures to ensure that the soil around the germinating seeds is sufficiently low in salinity. Suitable planting practices, bed shapes, and irrigation management can greatly enhance salt control during the critical germination period.

Table 8 EFFECT OF PLANTING RATES ON SEEDLING ESTABLISHMENT OF CROPS SPRINKLE-IRRIGATED WITH DIFFERENT QUALITY WATER IN ISRAEL[1]

Seeding rate (percent of acceptable field practice)	Onions		Carrots		Alfalfa	
	EC_w (dS/m)					
	1.0	4.0	1.0	4.0	1.0	4.0
100[2]	17	14	83	56	29	24
130	23	19	126	72	39	34
200	33	28	198	120	51	36

[1] Data taken from Pasternak (1975).

[2] Acceptable field practice in Israel.

With furrow irrigated crops planted on raised beds, water movement is from the furrow into the bed. Since water moves from the two furrows towards the centre of the bed, any salts present move with the water and tend to accumulate in the upper centre of the bed. Planting seeds in a single row in the centre of a raised bed places the seed exactly in the area where salts concentrate (Figure 12A), planting a double-row on a raised planting bed (Figure 12D) will place the two seed rows near each shoulder of the raised bed, away from the area of greatest salt accumulation. By this planting method, soil and water salts still concentrate near the centre of the bed but away from the seed rows and germination is likely to be better if salinity is a problem.

There are other planting alternatives. Alternate row irrigation may help. If the beds are wetted from both sides, the salts accumulate near the top or centre of the bed (Figures 12A and 12D) but if alternate rows are irrigated, the salt can be moved beyond the single seed row (Figure 12B). The salts may still accumulate, but to a lower concentration. Off-centre, single-row planting on the shoulder of the bed closest to the watered furrow (Figure 12E) has also been used and aids germination under salty soil conditions. Double-row planting with alternate row irrigation is not recommended as salts would accumulate in the second seed row from the wet furrow.

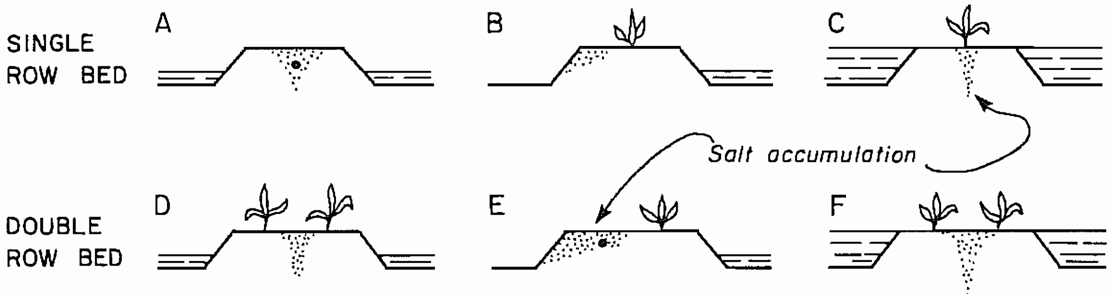


Fig. 12 Flat top beds and irrigation practice (Bernstein, Fireman and Reeve 1975)

With either single or double-row planting, if salts are a problem, increasing the depth of water in the furrow can also be an aid to improved germination (Figures 12C and 12F). 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 (Figure 13). Irrigation is continued until the wetting front has moved well past the seed row. A correct configuration for a single-row sloping bed that is easy to cultivate and convert back to a conventional raised bed is shown in Figure 14. This reshaping is usually done after germination and after the early growth period.

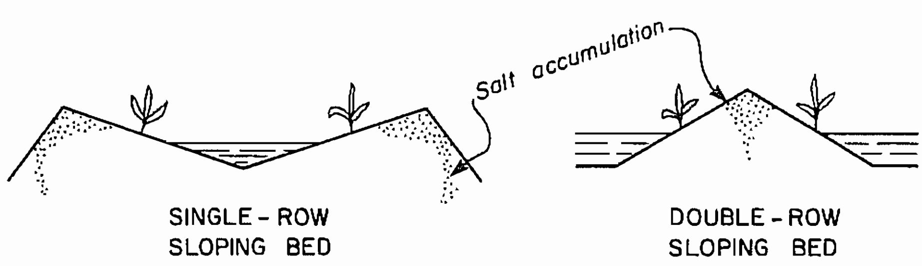


Fig. 13 Salinity control with sloping beds (Bernstein and Fireman 1957)

Another widely used modification of the single-row sloping bed is shown in Figure 15; it is used for both salinity and temperature control. The seeds are planted just above the water line in the furrow. For a crop planted in winter or early spring, a soil temperature a few degrees warmer is important; the sloping bed is oriented toward the south in the northern hemisphere. In hot climates, where cooler soil temperature is desired, reversing this slope (facing away from the sun) has been beneficial.

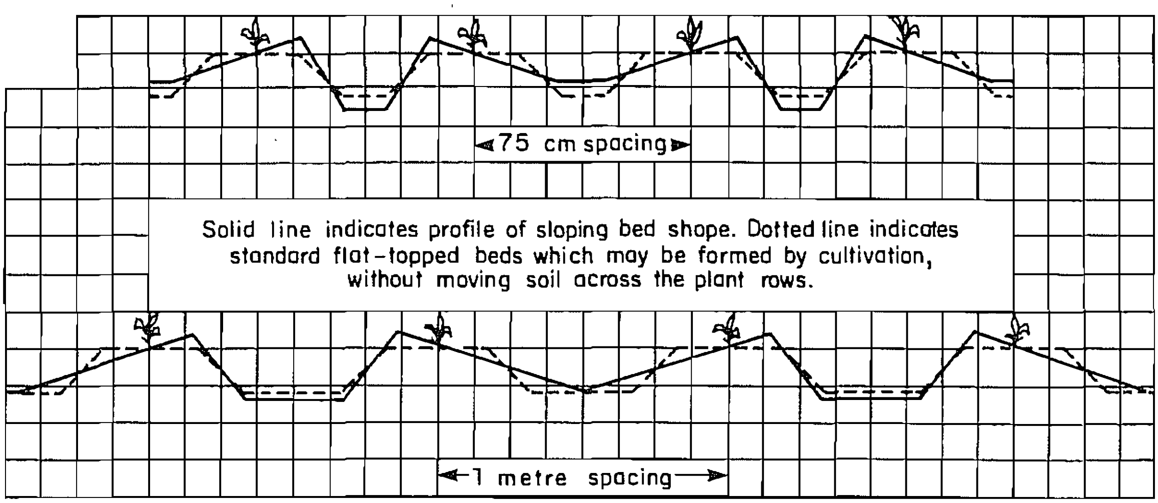


Fig. 14 Sloping seedbeds (Bernstein and Ayers 1955)

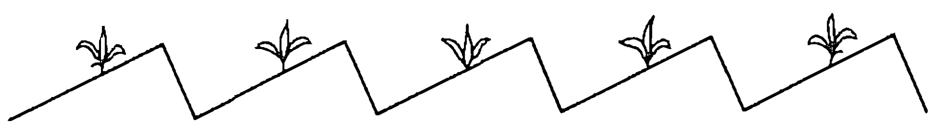
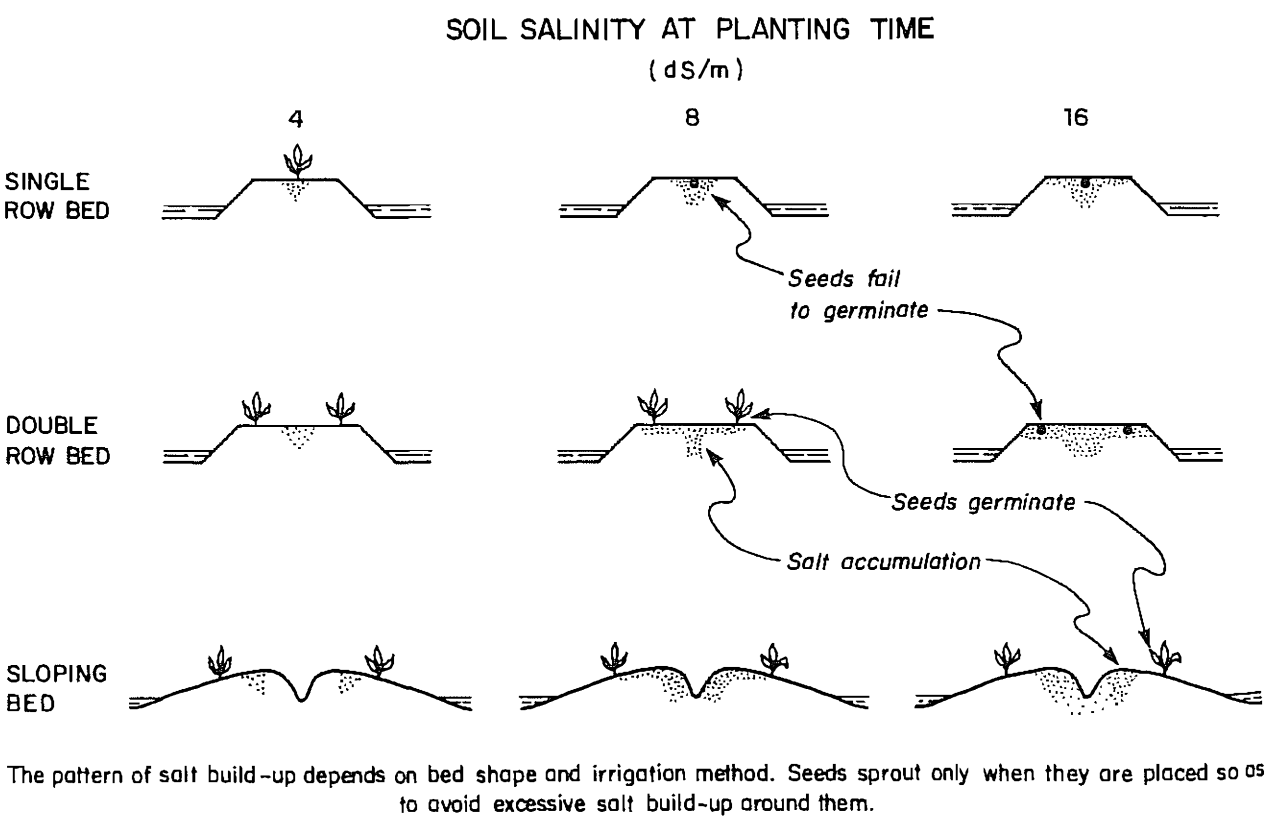


Fig. 15 Sloping seedbeds used for salinity and temperature control



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

Fig. 16 Bed shapes and salinity effects (Bernstein, Fireman and Reeve 1955)

For different soil salinities, the diagrams in Figure 16 show the effectiveness of modifying the shape of the planting beds. Actual response will depend on the initial soil salinity, the irrigation method, the irrigation water salinity, and the crop tolerance during germination. Since salinity slows germination of many crops, holding the water in the furrows for a longer period sometimes improves emergence by maintaining moist soils, reducing crusting, and it actually dilutes or reduces salinity.

The larger seeded crops, such as maize, are sometimes planted in the water furrow for improved germination under salty conditions. Grapes, too, are sometimes grown in the bottom of wide, flat furrows or at the bottom of wide, gently sloping V-shaped furrows. Much of the root zone then remains relatively low in salinity.

iv. Fertilization

Fertilizers, manures, and soil amendments include many soluble salts in high concentrations. If placed too close to the germinating seedling or to the growing plant, the fertilizer may cause or aggravate a salinity or toxicity problem. For example, an application of 50 kg per hectare of nitrogen (240 kg/ha of ammonium sulphate) would cause no salinity problem if spread uniformly over a 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 caused by the high salinity of the fertilizer placed too close to the seed.

Care, therefore, should be taken in placement as well as timing of fertilization. Seedlings are sensitive to salts and, while small, require little fertilization. A small amount of fertilizer can be applied at or before planting, and the remainder in one or more applications after crop emergence but before the main growth period. In addition, a fertilizer with a lower salt index can be considered. The lower the salt index of the fertilizer, the less danger there is of salt burn and damage to seedlings or young plants. Salt indices for various fertilizers are shown in Table 9.

Salt tolerance of a crop is generally considered to be unaffected by raising the level of soil fertility above that necessary to supply needed nutrients for optimum growth. However, if both salinity and low fertility are limiting yield, correction of either or both will improve yield. If, however, the fertility is adequate and the salinity is limiting, further increasing the fertility will not increase yield or improve the salt tolerance of the crop (Bernstein, Francois and Clark 1974).

2.4.5 Changing Methods of Irrigation

The method of irrigation directly affects both the efficiency of water use and the way salts accumulate. Flood and sprinkler irrigation are designed to apply water evenly over the entire irrigated area. This results in most of the salts accumulating in the lower root zone. The degree of accumulation depends upon the leaching fraction. Figure 2 illustrates several typical salinity profiles resulting from surface flooding or sprinkler irrigation at leaching fractions varying from 0.1 to 0.4.

Table 9 RELATIVE EFFECT OF FERTILIZER MATERIALS ON THE SOIL SOLUTION [1]

Material	Salt Index[2]	Partial Salt Index per Unit of Plant Nutrient
Anhydrous ammonia	47.1	0.572
Ammonium nitrate	104.7	2.990
Ammonium nitrate-lime	61.1	2.982
Ammonium phosphate (11-48)	26.9	2.442
Ammonium sulphate	69.0	3.253
Calcium carbonate (limestone)	4.7	0.083
Calcium cyanamide	31.0	1.476
Calcium nitrate	52.5	4.409
Calcium sulphate (gypsum)	8.1	0.247
Diammonium phosphate	29.9	1.614
Dolomite (calcium and magnesium carbonates)	0.8	0.042
Kainit, 13.5%	105.9	8.475
Kainit, 17.5%	109.4	6.253
Manure salts, 20%	112.7	5.636
Manure salts, 30%	91.9	3.067
Monoammonium phosphate	34.2	2.453
Monocalcium phosphate	15.4	0.274
Nitrate of soda	100.0	6.060
Nitrogen solution 37%	77.8	2.104
Nitrogen solution 40%	70.4	1.724
Potassium chloride, 50%	109.4	2.189
Potassium chloride, 60%	116.3	1.936
Potassium chloride, 63%	114.3	1.812
Potassium nitrate	73.6	5.336
Potassium sulphate	46.1	0.853
Sodium chloride	153.8	2.899
Sulphate of potash-magnesia	43.2	1.971
Superphosphate, 16%	7.8	0.487
Superphosphate, 20%	7.8	0.390
Superphosphate, 45%	10.1	0.224
Superphosphate, 48%	10.1	0.210
Uramon	66.4	1.579
Urea	75.4	1.618

1 Data taken from Rader (1943).

2 The salt index is for various fertilizer materials when applied at equal weights. Sodium nitrate, with a salt index of 100, is used as a base for the index.

Figure 17 shows the salt accumulation patterns for surface flooding or sprinkler irrigation which apply a uniform depth of water across the entire field as contrasted to the salt accumulation patterns from furrow or localized (drip, trickle or spitter) irrigation which apply water to only part of the field surface. In the case of furrow irrigation, salt builds up with depth in the soil similar to flood irrigation, but salt also accumulates in the areas not covered by water. Salt moves with the water to the high points where the water evaporates most rapidly and is leached to greater depths as water drains by gravity. For localized irrigation, salts accumulate at the edges of the soil wetted from the emitter. This results in a wetted spherical shape with salinity highest at the outer edges of the sphere.

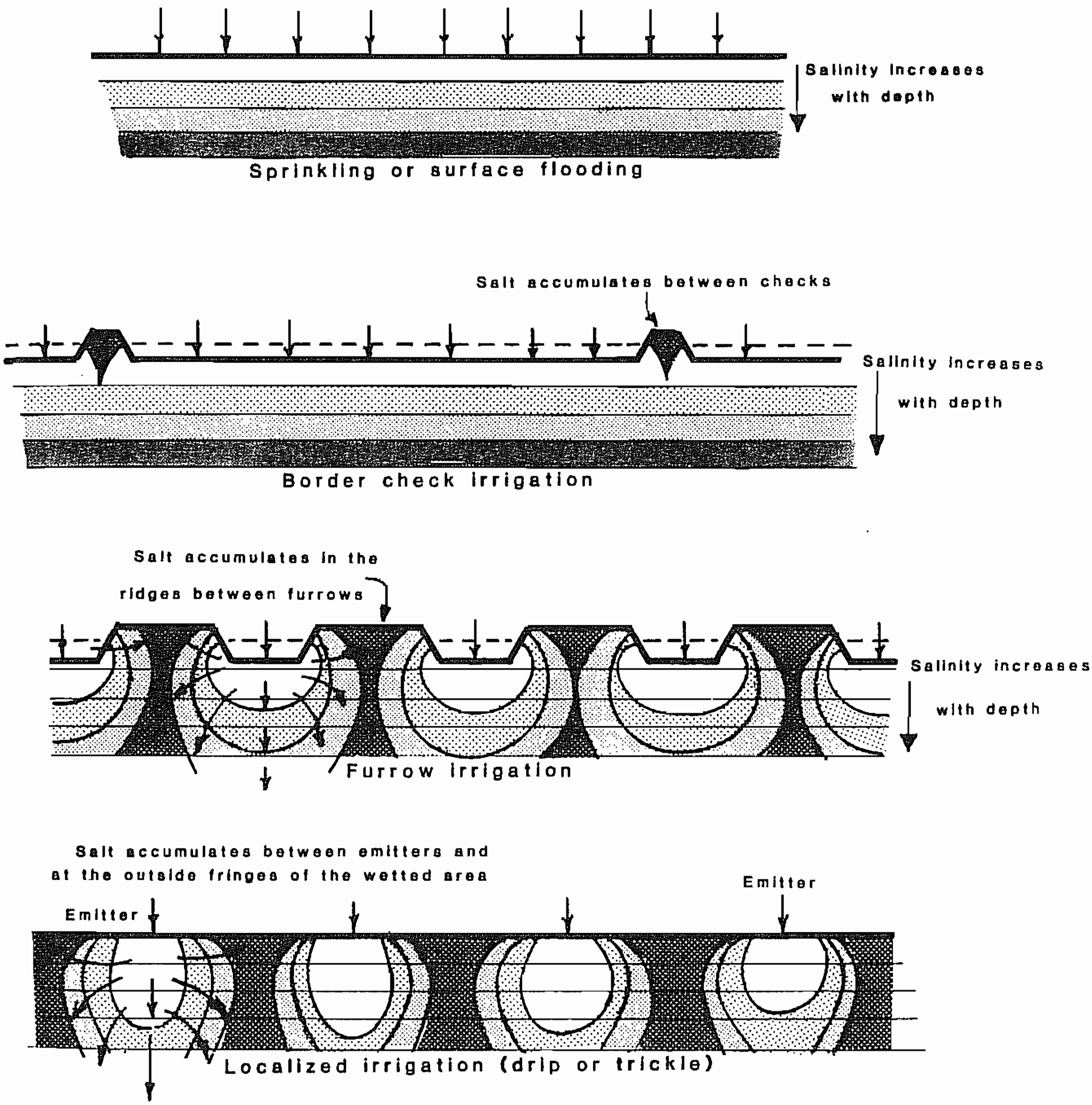


Fig. 17 Salt accumulation patterns for:

Sprinkling or surface flooding
Border check irrigation
Furrow irrigation
Localized irrigation (drip or trickle)

Isolated pockets of accumulated salt frequently result where water does not infiltrate sufficiently to accomplish leaching. These can be raised areas, areas of more dense soil, or areas not getting enough water during irrigation. Typically these show as bare spots or areas of reduced or stunted growth. A well designed sprinkler system generally provides the greatest uniformity of application, but this is often a problem no matter which system is used.

Each irrigation method has certain advantages and disadvantages and all known factors should be considered before attempting to improve salinity control by changing the method.

With surface flooding methods (flood, basin and furrow), depth of applied water entering the soil varies with location in the field and depends on the infiltration rate and time available for infiltration. Differences in the rate of infiltration are caused by land slope, degree of compaction, textural changes, and soil chemistry. The opportunity time during which infiltration can take place also varies; the upper end of the field nearest the water source usually has water on its surface for a much longer time than does the lower end. The driest area is typically about two-thirds of the distance down the field. High spots in the field also receive less water because, being high, they are covered by less water and for a shorter period.

These surface flooding methods are usually not sufficiently flexible to apply less than an 80 to 100 mm depth per irrigation. As a result, irrigating more frequently to reduce possible water stress may also waste water and cause waterlogging and drainage problems. In order to relieve water stress, it may be easier to increase the frequency of irrigation with sprinklers or drip irrigation rather than with surface flooding. However, sprinkler and localized irrigation have their problems too and are not adapted to all conditions of water, soil, climate, or type of crop.

A well-designed sprinkler system will apply water with good uniformity and at rates of application low enough to prevent runoff. If well managed, it will result in an excellent overall irrigation and adequate and uniform leaching. Depth of water applied is controlled by adjustments in the duration of application, sprinkler spacing and nozzle size. Wind can distort the water patterns and must be considered. Sprinklers are sometimes used to aid in temperature control, germination and early seedling growth at which time the crop may be particularly sensitive to salinity, high temperatures and soil crusting. On sensitive crops, however, sprinklers can cause leaf burn if the salts (sodium or chloride) concentrate excessively on the leaves as water evaporates between rotations of the sprinkler. These salts are absorbed and may cause a toxicity. These problems are discussed in detail in Section 4.3.

One of the concerns expressed about sprinkler use in hot arid areas is the evaporation loss during sprinkling and the possible increase in salinity of the water that infiltrates the soil, but there is no clear evidence that this evaporation is significant enough to warrant concern. One field study in the Imperial Valley of California, USA, using a solid set sprinkler system, showed that evaporation losses on a hot, dry day (temperature 47°C, relative humidity 27 percent and wind speed 3.7 km/h) caused a 20 percent increase in water salinity (ECw) near the field edge but less than 5 percent within the main portion of the field (Robinson 1973). Other trials have shown similar evaporation losses. A concentration factor of less than 5 percent is expected to have little effect, but the 20 percent factor could cause some difficulty for salt sensitive plants at the edge of the field.

Localized irrigation systems (drip, trickle or spitter) apply water on a daily or near daily basis at a very low application rate (2-8 litres per hour per emitter). The near daily replenishment of the water used by the crop keeps the soil moist and very near to or slightly above field water holding capacity. The irrigations should maintain a slight but nearly continuous downward movement of moisture and salts for excellent short-term salinity control. Irrigation efficiency can be close to 100 percent during the cropping period, meaning that the crop evapotranspiration demand can be met essentially without losses due to runoff or deep penetration.

Salts also accumulate with localized irrigation. However, they accumulate at the soil surface between emitters and at the outside edges of the area wetted by the water applicators (Figure 17). With time, this salt accumulation at the soil surface and in the wetted fringe between emitters can become appreciable, and is a hazard if the salt is then moved by rain into the root zone of the crop or, in the case of annual crops, if a new planting is made in these salty areas without prior leaching. On the other hand, if rainfall is sufficient each season to leach the accumulated salts, no problems should be anticipated. The most dangerous period is thought to be just after the first rainfall when the surface salt has been moved down into the root zone but sufficient rainfall has not yet fallen to move the salt below the root zone. It is recommended that regular irrigations continue during a rain or until 50-100 mm has fallen. If rainfall is insufficient, supplemental leaching with the localized system may be needed.

Leaching by sprinklers or surface flooding after a season of localized irrigation and before replanting has been effective in removing accumulated salts. However, this may require a second irrigation system and will require large quantities of additional water, but it may be necessary for continued good production when utilizing relatively salty water and localized irrigation.

With good quality water, yields with localized (drip) irrigation should be equal to, or slightly better than other methods under comparable conditions. With higher salinity water ($EC_w > 1.0$ dS/m), yields are often better, due to the continuous high moisture content maintained by daily replenishment of the water used by the crop. Frequent sprinkler irrigation might give similar results, but tests indicate the probability of excessive leaf burn and defoliation from leaf absorption of sodium and chloride, and reduction in yield. If accumulating salinity exceeds crop tolerance with the usual method of irrigation, a better yield may be possible with localized irrigation.

Sub-irrigation, adapted to only a few situations is accomplished by rapidly raising the water table into the root zone, and after a few hours to a day or two, draining it to prevent aeration problems. Lapsed time for the rise and fall of the water table is 2-5 days. The upward movement of the water tends to concentrate salts on or near the surface irrespective of whether the salinity originates from the water table or the soil. Salt accumulation must be controlled by adequate rainfall or pre-plant leaching. Sub-irrigation cannot be used with poor quality groundwater unless the soil is leached periodically by natural rainfall, or surface applied leaching water.

Figure 18 shows salt distribution patterns resulting from various methods of irrigation of bell peppers. It also shows that each method resulted in a significantly different yield although the same amount of water was applied. With localized (drip) irrigation, a crop irrigated with what is normally considered good quality water (EC_w = 06 dS/m) yielded about 50 percent more than the sprinkler and furrow irrigated plants. The advantage of the localized system was more pronounced with the higher salinity irrigation water (ECw = 3.8 dS/m). Part of the difference in yield can probably be explained by the close placement of the emitters to the plants and more frequent irrigations with the localized irrigation method. This provided good salinity control in contrast to crop damage by absorption of sodium or chloride through leaves wetted by the overhead sprinklers.

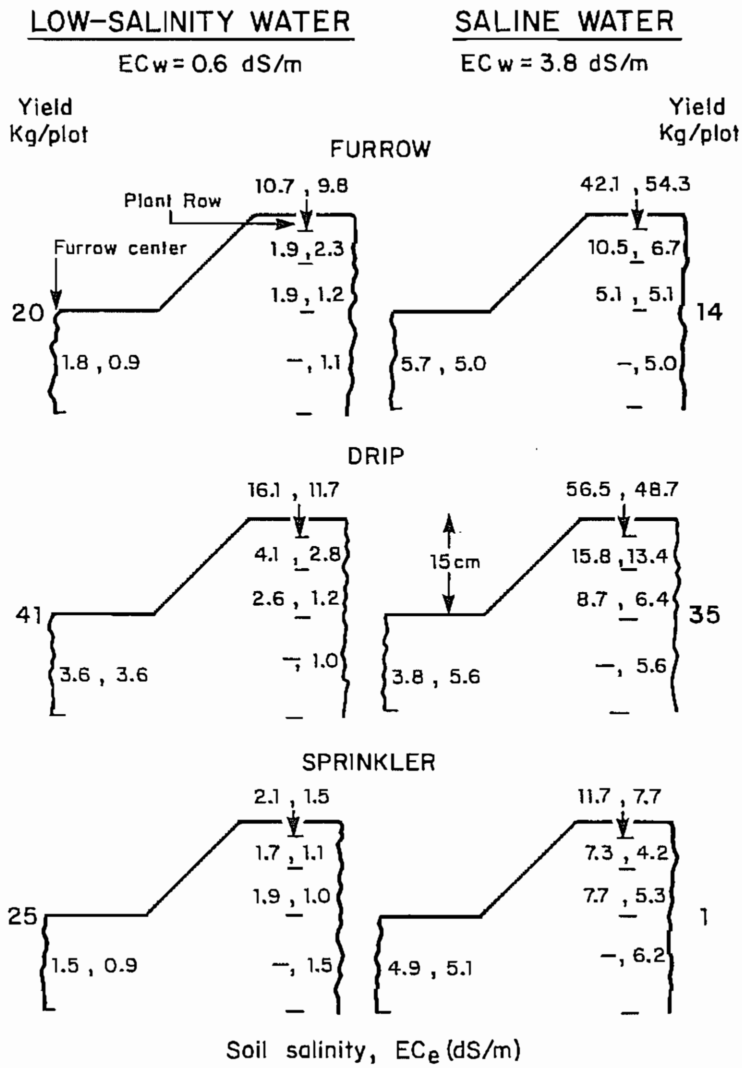


Fig. 18

Soil salinities in plant row and furrow, and yield of bell-pepper, using two qualities of irrigation water, by three methods of irrigation (the first figure in each pair indicates salinity before irrigation) (after Bernstein and Francois 1973a)

2.4.6 Land Development for Salinity Control

The foregoing discussion of salinity control alternatives emphasizes practices that are required each year or for each crop and are repeated frequently as opposed to those that may be performed once during early stages of land development, or as an aid to reclamation of deteriorated land. These latter techniques are seldom repeated and are often costly and require special engineering to complete. Their goal is to improve existing soil conditions permanently in order to make irrigation, salinity control and cropping easier. Typical practices performed during development stages are levelling land to a given slope, establishing adequate drainage (covered or open drains), deep ploughing or slip ploughing to alter the soil profile physically, and leaching to reduce excessive salinity.

i. Land grading

Salinity control is difficult if land is not sufficiently level to allow satisfactory water distribution and uniform infiltration. Land grading changes the natural slope of the field to a uniform grade. A certain amount of soil compaction is caused and it is advisable to follow the land grading procedure with subsoiling, chiselling or ploughing to break up the compaction caused by the heavy land grading equipment and improve uniformity of water penetration and leaching. Land planing simply smooths the surface and, although a good practice, cannot be considered equal to, or a substitute for land grading. Land grading and land smoothing are also discussed in Section 2.4.4.i.

ii. Improved subsurface drainage

Subsurface drainage problems and shallow water tables greatly complicate salinity control. Shallow water tables frequently occur due to the presence of a slowly permeable layer below the soil surface such as a clay barrier, hardpan or bedrock. Drainage problems are most frequently caused by over-irrigation but may also be caused by seepage from upslope areas or leakage from canals. The most effective control of salinity associated with a shallow water table is first to lower and stabilize the water table. A discussion of drainage needs is presented in Section 2.4.1 as one of the primary options considered for controlling salinity caused by poor quality water. An in-depth discussion of drainage needs, surveys and designs is given in Dieleman and Trafford (1976) and Dieleman **et al.** (1980). If new land is being brought into production, drainage must be considered, and it is essential for the long-term success of any irrigation project or irrigated area. If drainage problems are in any way to be anticipated, plans for their immediate or future control must be formulated. With adequate drainage established, surface soil salinity can be controlled by irrigation management.

iii. Deep cultivation

Stratified or layered soils are difficult to irrigate efficiently. Layers of clay, sand or hardpan frequently impede or prevent deep percolation of water which is essential for salinity control. Irrigations to supply crop water demand plus salinity control can be greatly simplified if these layers are broken, destroyed or at least made more permeable to water. Subsoiling and chiselling are considered to be temporary improvements only and are often short-lived (1-5 years), whereas deep and slip ploughing can permanently improve internal drainage. These are usually done after land grading and drainage but before any needed reclamation. Deep or slip ploughing is costly and usually necessitates growing an annual crop such as barley following the ploughing, to allow the disturbed soil to settle. Following one or two barley crops, a touch-up land grading to re-establish the proper grading is also usually necessary. In many cases, wind or water-deposited sands are sufficiently stratified and dense so that deep ploughing or deep chiselling will greatly improve crop response and yield.

iv. Reclamation leaching

If salinity is excessive and greatly exceeds the tolerance of the planned crops, a major leaching to lower salinity (reclamation) may be necessary before cropping is possible. The salts

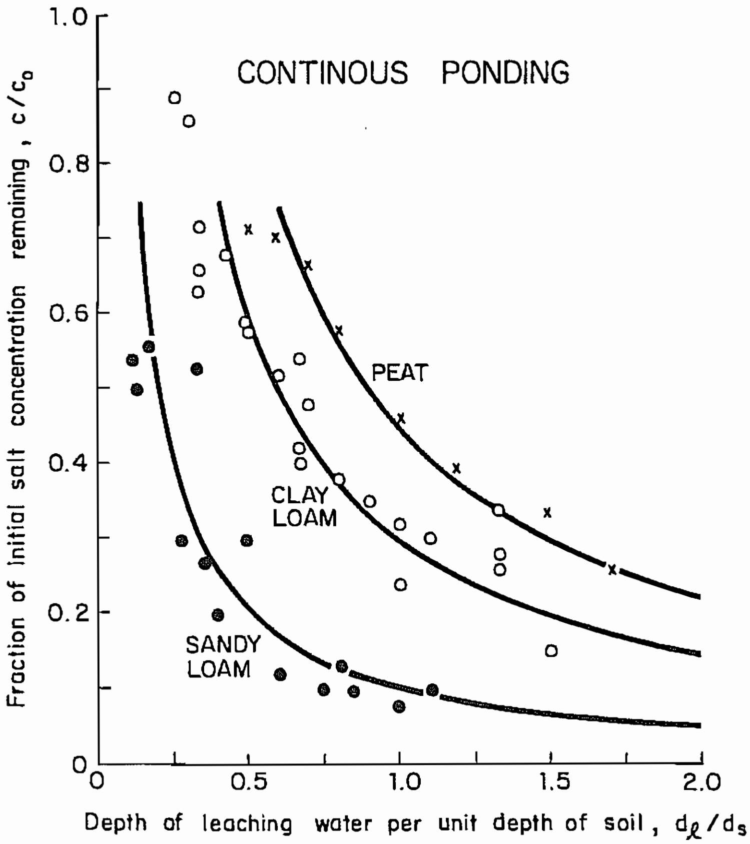


Fig. 19

Depth of leaching water per unit depth of soil required to reclaim a saline soil by continuous ponding (Hoffman 1980)

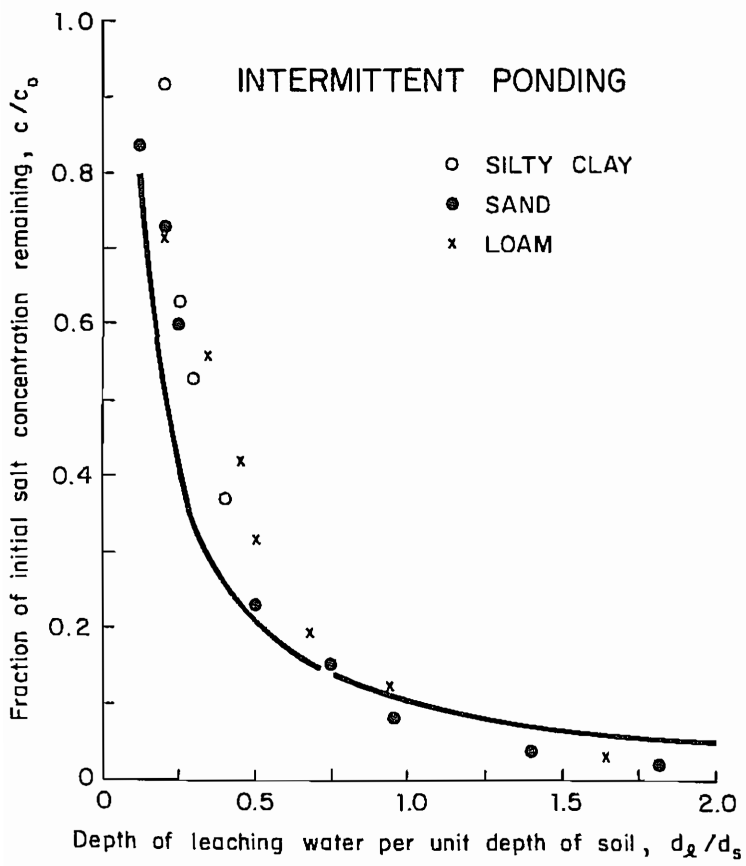


Fig. 20

Depth of leaching water per unit depth of soil required to reclaim a saline soil by ponding water intermittently (Hoffman 1980) may have accumulated due to events in the past history of the soil, to the presence of a shallow water table, or they may have accumulated from inadequate leaching of salts brought in with the irrigation water. In any case, their concentration in the upper root zone (0.3 m) must be reduced to near the tolerance of the crop before any cropping is attempted. In soils with upper root zone salinity less than about an ECe of 10-12 dS/m, an application of 10-20 cm of water as a pre-plant irrigation (sprinklers or flood) coupled with a light irrigation following planting is usually sufficient to start a tolerant crop such as barley or cotton. If the root zone salinity of the upper root zone is much greater than ECe of 10-12 dS/m, the pre-plant irrigation may not be sufficient and a reclamation leaching is advisable before planting even a tolerant crop such as barley.

The depth of water that must be applied to assure adequate reclamation depends on the initial soil salinity and the leaching method used. The higher the salinity, the greater the depth of water needed. Intermittent leaching will reduce the soil salinity more efficiently (use less water) than will continuous leaching (ponding), but the time required to accomplish the leaching will be greater. The influencing factor is the soil-water content during the reclamation leaching. Efficiency is increased if the percolating water moves more slowly (unsaturated flow) and is occasionally allowed to drain to field capacity as is done in intermittent leaching. Under continuous ponding a higher proportion of the leaching water moves through the larger soil pores and bypasses smaller pores. Salts trapped within these smaller pores, therefore, are removed at a slower rate per unit of water applied. Sprinklers apply water at a relatively slow rate and are very efficient in leaching.

It is not possible to predict with accuracy the depth of water that must be applied to accomplish the reclamation leaching, but as a guide for continuous ponding, 70-80 percent of the soluble salts initially present will be removed with a depth of applied water equal to the depth of soil to be reclaimed. For example, a 1 metre depth of percolated water can be expected to leach 70-80 percent of the salts from a 1 metre depth of soil. Figure 19 shows that the percentage removal is highly dependent on soil type but, as a general guide, the 70-80 percent removal should be reasonably representative for most irrigated soils. For sprinklers or intermittent ponding, about 80-90 percent of the salts initially present in the soil will be removed with a depth of applied water equal to the depth of soil to be reclaimed, but more time is required to accomplish the leaching. Figure 20 shows that with intermittent ponding, soil type does not play as important a role as with continuous ponding.

Localized irrigation has been used successfully for reclamation by placing one line of closely spaced emitters on the flattened top of a raised planting bed such as used in furrow irrigation. The irrigation is continued until the desired leaching has been accomplished. After planting, the crop is irrigated by localized irrigation. The resulting reclaimed zone in the soil may be spherical with the emitter at the top of the sphere (Figure 17). The salts are leached to the outermost fringe of the wetted area and into the unwetted areas between the emitters, and by evaporation an appreciable salinity develops at the soil surface. This surface salinity sometimes gives trouble if a light rain moves the accumulated salt back into the root zone (see Section 2.4.5, localized irrigation).

If salinity is not too severe, extra irrigation water applied during the growing of a salt-tolerant crop will accomplish reclamation. Barley and rice are common reclamation crops. The reclamation crop is planted as soon as possible after the topsoil salinity is reduced to within its tolerance. The crop is believed to aid reclamation due to a combination of effects including the physical action of roots to keep the soil more open to allow additional water to infiltrate, the addition of organic matter or the alternate drying and wetting of the soil which promotes better soil structure.

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

2.4.7 Changing or Blending Water Supplies

Changing water supplies is a simple but drastic solution to a water quality problem. This is only possible if a better quality supply is available. For example, a poor quality groundwater is usually abandoned if a better quality supply becomes available, but this is not necessary if there is still a water supply shortage. Under these conditions, consideration should be given to blending the poorer with the better quality supply, thus increasing the total quantity of usable water available. Blending will not reduce the total salt load but may allow more crop area to be planted because of the increase in volume caused by dilution. The guidelines of Table 1 can be used to evaluate the usability of the blended supply which should also be evaluated carefully to ensure that the total quantity of additional water needed for salinity control (the additional leaching requirement) does not exceed the net gain in amount of blended water available. The quality of the blended water can be found by using equation (13):

$$\text{Concentration of the blended water} = \left[\text{Concentration of water (a)} \cdot \text{proportion of water (a) used}\right] + \left[\text{Concentration of water (b)} \cdot \text{proportion of water (b) used}\right] \quad (13)$$

where the concentration can be expressed as either ECw or me/l but the same units of concentration must be used throughout the equation.

Blending water supplies for salinity control is not a common practice. Most users alternate between the two supplies. Alternating use can be beneficial, particularly in locations where winter rains or winter irrigations are used to meet most or all of the leaching requirement. Since the total salt load applied will remain the same, it may be advisable to use the better quality supply in the early part of the cropping season and the poorer quality blend later when the crop is less sensitive to salinity. An example of blending is given in Example 5 and Table 10.

EXAMPLE 5 - BLENDING IRRIGATION WATER FOR MAIZE

A farmer is irrigating a maize crop with canal water (ECw = 0.23 dS/m) and is able to achieve a leaching fraction (LF) of 0.15 by using efficient irrigation practices. The irrigated area could be expanded but no additional canal water is available. A well is available but the water quality is marginal for maize production (ECw = 3.6 dS/m). Could these two water sources be safely blended and thus expand the irrigated area?

Given:	Canal water	EC_w	=	0.23 dS/m
	Well water	EC_w	=	3.6 dS/m
	Water demand (ET) for maize	ET	=	800 mm/year
	Leaching fraction achieved	LF	=	0.15

Explanation:

The leaching needed for a 90% yield potential of maize is estimated using equation (9):

$$LR = \frac{EC_w}{5(EC_e) - EC_w} \quad (9)$$

$$LR_{(canal\ water)} = \frac{0.23}{5(2.5) - 0.23} = 0.02$$

$$LR_{(well\ water)} = \frac{3.6}{5(2.5) - 3.6} = 0.40$$

The calculated leaching requirement (LR) for the canal water is less than the actual leaching achieved by the farmer. Water is being lost by over leaching but a LF less than 0.15 is not often achievable. The calculated leaching requirement of well water alone when added to ET would greatly increase the amount of water needed for production. For example, with the canal water and a LF of 0.15, the applied water needed (Aw) is found from equation (7):

$$Aw = \frac{ET}{1 - LF} \quad (7)$$

$$Aw_{(canal\ water)} = \frac{800}{1 - 0.15} = 941 \text{ mm/year}$$

For the well water:

$$Aw_{(well\ water)} = \frac{800}{1 - 0.40} = 1333 \text{ mm/year}$$

The use of well water alone would result in a 40 percent increase in water use per hectare to achieve the same maize production as could be obtained using the canal water.

From Table 4, the maximum ECw of the blended water that will allow a 90% yield potential with a leaching fraction of 0.15 is 1.7 dS/m. The optimum blend of water can then be found by modifying equation (13):

$$EC_{w\ (canal\ water)} \cdot a) + (EC_{w\ (well\ water)} \cdot b) = \text{Maximum } EC_{w\ (blend\ water)} \quad (13)$$

where: $EC_{w\ (canal\ water)}$ = electrical conductivity of the canal water in dS/m
$EC_{w\ (well\ water)}$ = electrical conductivity of the well water in dS/m
a = proportion of canal water used
b = proportion of well water used
Maximum $EC_{w\ (blend\ water)}$ = Maximum electrical conductivity of the blended water in dS/m

if a = 1 - b, then the above equation is:

$$0.23\ (1 - b) + 3.6\ (b) = 1.7$$

$$3.37b = 1.47$$

$$b = 0.44 \text{ or 44 percent well water}$$

$$a = 1 - b = 0.56 \text{ or 56 percent canal water}$$

The above shows that the area presently irrigated with canal water at Aw = 941 mm/ha/year could be expanded with no increase in Aw/ha/year if the canal water were blended with up to 44% well water. Yield potential would be maintained at about 90% and the planted area could be expanded by 44%.

Table 10 WATER QUALITY FROM BLENDED CANAL AND WELL WATER [1]

Canal Water used (percent)	EC_w (dS/m)	SAR	Mixing Ratio (Well water/Canal water)
0	3.6	17.8	-
20	2.9	15.4	4 : 1
25	2.8	14.8	3 : 1
33	2.5	13.6	2 : 1
50	1.9	11.2	1 : 1
66	1.4	8.3	1 : 2
75	1.1	6.8	1 : 3
80	0.9	5.7	1 : 4
90	0.6	3.3	1 : 9
95	0.4	2.0	1 : 19
100	0.23	0.5	-

[1] The data from the water analysis is:

	ECw (dS/m)	Ca (me/l)	Mg (me/l)	Na (me/l)	HCO_3 (me/l)	Cl (me/l)	SO_4 (me/l)	SAR
Canal water	0.23	1.41	0.54	0.48	1.8	0.29	0.17	0.5
Well water	3.60	2.52	4.0	32.0	4.5	25.1	8.9	18.0

3. INFILTRATION PROBLEMS

3.1 THE INFILTRATION PROBLEM

An infiltration problem occurs if the irrigation water does not enter the soil rapidly enough during a normal irrigation cycle to replenish the soil with water needed by the crop before the next irrigation. The reduced infiltration rate, if due to quality of applied water, is generally a problem within the upper few centimetres of soil but occasionally may occur at greater depths. The end result is a decrease in water supply to the crop, similar to the reduction due to salinity, but for a different reason. A water infiltration problem reduces the quantity of water put into the soil for later use by the crop while salinity reduces the availability of the water in storage.

Infiltration refers to the entry of water into the soil. The rate at which water enters is referred to as the rate of infiltration. Permeability, the term used in the previous edition of Irrigation and Drainage Paper 29 (1976), more correctly refers to the percolation of infiltrated water through the soil. Since the water quality problem is primarily one related to the ease with which water enters and moves through the upper few centimetres of soil, we have chosen the term 'infiltration problem' rather than the previously used term 'permeability problem'. An infiltration rate as low as 3 mm/hour is considered low while a rate above 12 mm/hour is relatively high. This can be affected, however, by many factors other than water quality, including physical characteristics of the soil, such as soil texture and type of clay minerals, and chemical characteristics including exchangeable cations. The guidelines of Table 1 refer to infiltration problems as they relate directly to the unfavourable changes in soil chemistry caused by the quality of irrigation water applied. These problems concern both salinity and relative sodium content in the applied water. Figure 21 shows in graphic form that both salinity (ECw) and the sodium adsorption ratio (SAR) of the applied water affect the rate of infiltration of water into surface soil. Figure 21 can be used in place of the numerical evaluations in Table 1 given for infiltration problems.

The infiltration rate generally increases with increasing salinity and decreases with either decreasing salinity or increasing sodium content relative to calcium and magnesium - the sodium adsorption ratio. Therefore, the two factors, salinity and SAR, must be considered together for a proper evaluation of the ultimate effect on water infiltration rate.

3.1.1 Infiltration Problem Evaluation

Low salinity water (less than 0.5 dS/m and especially below 0.2 dS/m) is corrosive and tends to leach surface soils free of soluble minerals and salts, especially calcium, reducing their strong stabilizing influence on soil aggregates and soil structure. Without salts and without calcium, the soil disperses and the dispersed finer soil particles fill many of the smaller pore spaces, sealing the surface and greatly reducing the rate at which water infiltrates the soil surface. Soil crusting and crop emergence problems often result, in addition to a reduction in the amount of water that will enter the soil in a given amount of time and which may ultimately cause water stress between irrigations.

Very low salinity water (less than ECw = 0.2 dS/m) almost invariably results in water infiltration problems, regardless of the relative sodium ratio (or SAR). Rainfall is a very low salinity water

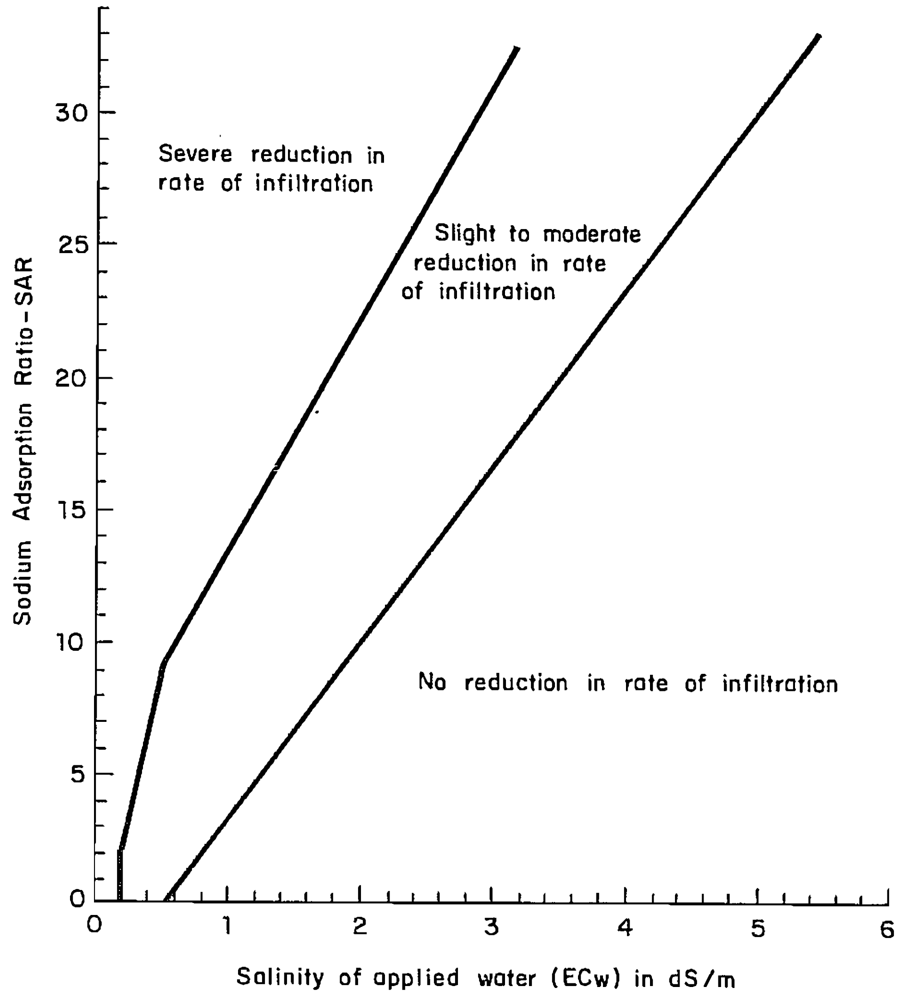


Fig. 21 Relative rate of water infiltration as affected by salinity and sodium adsorption ratio (Adapted from Rhoades 1977; and Oster and Schroer 1979)

and irrigated areas frequently experience exceptionally low rates of infiltration of rainfall resulting in excessive runoff.

Excessive sodium in irrigation water also promotes soil dispersion and structural breakdown but only if sodium exceeds calcium by more than a ratio of about 3:1. Such a relatively high sodium content (>3:1) often results in a severe water infiltration problem due to soil dispersion and plugging and sealing of the surface pores, in much the same way as does the very low salinity water. This is due to lack of sufficient calcium to counter the dispersing effects of the sodium. Excessive sodium may also make it extremely difficult to supply enough water to meet the crop water demand. Other related problems such as soil crusting, poor seedling emergence, lack of aeration, plant and root diseases, weed and mosquito control problems caused by the low rate of infiltration may further complicate crop management.

In the past, several procedures have been used to predict a potential infiltration problem. The Residual Sodium Carbonate (RSC) method (Eaton 1950; Richards 1954) was widely used at one time. The most commonly used recent method to evaluate the infiltration problem potential has been and probably still is the Sodium Adsorption Ratio (SAR) (Richards 1954). The SAR equation (1) as given in Figure 1 is:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \quad (1)$$

where: Na = sodium in me/l
Ca = calcium in me/l
Mg = magnesium in me/l

In recent reports and journal articles, SAR is more and more frequently being reported as RNa and not SAR. The terms are synonymous. The SAR procedure encompasses the infiltration problems due to an excess of sodium in relation to calcium and magnesium. It does not take into account changes in calcium in the soil water that take place because of changes in solubility of calcium resulting from precipitation or dissolution during or following an irrigation. Sodium, an important part of salinity, remains soluble and in equilibrium with exchangeable soil sodium at all times. Whether concentrated from withdrawal of water by the crop between long irrigation intervals, diluted with applied water, or leached away in drainage, outside influences have little effect on sodium solubility or precipitation. Calcium, however, does not remain completely soluble or in constant supply but is constantly changing until an equilibrium is established. Calcium changes occur due to dissolution of soil minerals into the soil-water thus raising its calcium content, or to precipitation from soil-water, usually as calcium carbonate, thus reducing the calcium. Dissolution is encouraged by dilution and by carbon dioxide dissolved in the soil-water; precipitation may take place because of the presence of sufficient calcium along with enough carbonate, bicarbonate or sulphates to exceed the solubility of calcium carbonate (limestone) or calcium sulphate (gypsum). Soon after an irrigation, dissolution or precipitation may occur, changing the supply of calcium and establishing an equilibrium at a new calcium concentration, different to that in the applied water. The SAR equation, since it does not account for these changes, is therefore somewhat in error. However, the SAR equation and procedure is still considered an acceptable evaluation procedure for most of the irrigation water encountered in irrigated agriculture.

NOTE

The adjusted SAR procedure presented in the previous edition of this paper (Ayers and Westcot 1976) is no longer recommended. Oster and Rhoades (1977), Oster and Schroer (1979) and Suarez (1981) carefully evaluated that procedure and concluded that it overpredicts the sodium hazard. They suggest that, if used, the value obtained by that method should be further adjusted by an 0.5 factor to evaluate more correctly the effects of HCO_3 on calcium precipitation (adj SAR x 0.5).

In this present edition the newer adj RNa procedure of Suarez (1981) is recommended but both the older SAR procedure and the new adj RNa are acceptable, with a preference expressed towards the adj RNa because it and the Cax of Table 11 offer a better insight into the change in calcium in the soil-water due to addition by dissolution of calcium from soil carbonates and silicates, or loss of calcium from soil-water by precipitation as carbonates.

Table 11 CALCIUM CONCENTRATION (Ca_x) EXPECTED TO REMAIN IN NEAR-SURFACE SOIL-WATER FOLLOWING IRRIGATION WITH WATER OF GIVEN HCO_3/Ca RATIO AND EC_w [1,2,3]

Ratio of HCO_3/Ca	Salinity of applied water (EC_w) (dS/m) 0.1	0.2	0.3	0.5	0.7	1.0	1.5	2.0	3.0	4.0	6.0	8.0
.05	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
.10	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
.15	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
.20	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
.25	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
.30	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
.35	3.61	3.72	3.80	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
.40	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
.45	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
.50	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
.75	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
1.00	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
1.25	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
1.50	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
1.75	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
2.00	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
2.25	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.51	1.58
2.50	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
3.00	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
3.50	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
4.00	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
4.50	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
5.00	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
7.00	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
10.00	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
20.00	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37
30.00	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.24	0.25	0.27	0.28

1 Adapted from Suarez (1981).

2 Assumes a soil source of calcium from lime ($CaCO_3$) or silicates; no precipitation of magnesium, and partial pressure of CO_2 near the soil surface (P_{CO_2}) is .0007 atmospheres.

3 Ca_x, HCO_3, Ca are reported in me/l; EC_w is in dS/m.

An alternative procedure, discussed in the following paragraphs, takes a new look at the older SAR equation and adjusts the calcium concentration of the irrigation water to the expected equilibrium value following an irrigation, and includes the effects of carbon dioxide (CO_2), of bicarbonate (HCO_3) and of salinity (ECw) upon the calcium originally present in the applied water but now a part of the soil-water. The procedure assumes a soil source of calcium - from soil lime ($CaCO_3$) or other soil minerals such as silicates - and no precipitation of magnesium.

The new term for this is adj RNa (adjusted Sodium Adsorption Ratio) and the calculation procedure is presented in the following example as an improvement on the older Sodium Adsorption Ratio (SAR). It can be used to predict more correctly potential infiltration problems due to relatively high sodium (or low calcium) in irrigation water supplies (Suarez 1981; Rhoades 1982) and can be substituted for SAR in Table 1. The equation for calculation of adj RNa of the surface soil is very similar to the older SAR equation and is:

$$\text{adj } R_{Na} = \frac{Na}{\sqrt{\frac{Ca_x + Mg}{2}}} \qquad (14)$$

where: Na = sodium in the irrigation water reported in me/l

Ca_x = a modified calcium value taken from Table 11, reported in me/l. Cax represents Ca in the applied irrigation water but modified due to salinity of the applied water (ECw), its HCO_3/Ca ratio (HCO_3 and Ca in me/l) and the estimated partial pressure of CO_2 in the surface few millimetres of soil (P_{CO_2} = 0.0007 atmospheres)

Mg = magnesium in the irrigation water reported in me/l

To use the Cax table (Table 11), first determine the HCO_3 to Ca ratio (HCO_3/Ca) and ECw from the water analysis, using HCO_3 and Ca in me/l and the water salinity (ECw) in deciSiemens per metre. An appropriate range of calculated HCO_3/Ca ratios appears on the left side of the table and the range of ECw across the top. Find the HCO_3/Ca ratio that falls nearest to the calculated HCO_3/Ca value for the subject water and read across to the ECw column that most closely approximates the ECw for the water being evaluated. The Cax value shown represents the me/l of Ca that is expected to remain in solution in the soil water at equilibrium and is to be used in equation (1). In Example 6, the three calculation procedures are compared 1) SAR, 2) adj SAR from FAO-29 1976, and 3) adj RNa.

The adj RNa obtained is used in place of the SAR in Table 1 to evaluate better the potential of the water to cause an infiltration problem if used for irrigation. Comparison of SAR and adj RNa for various types of water from around the world are presented in Table 31. The data in Table 31 show that for most water, the SAR calculation is within ±10 percent of the value obtained after adjustment of the calcium concentration using equation (14) and Table 11.

If computer facilities are available, a simulation model can be relied upon to give valid evaluations of these adjusted sodium adsorption ratios (adj RNa). The adj RNa outlined in the foregoing is adapted from the procedure of Suarez (1981). A computer simulation model is also available (Rhoades 1982). Both give closely comparable results.

EXAMPLE 6 - COMPARISON OF METHODS TO CALCULATE THE SODIUM HAZARD OF A WATER

Given: The water analysis is:

Ca	=	2.32 me/l
Mg	=	1.44 me/l
Na	=	7.73 me/l
Sum	=	11.49 me/l
CO_3	=	0.42 me/l
HCO_3	=	3.66 me/l
Sum	=	4.08 me/l
EC_w	=	1.15 dS/m

Explanation: 1. The Sodium Adsorption Ratio (SAR) can be calculated from equation (1):

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad (1)$$

$$SAR = \frac{7.73}{\sqrt{\frac{2.32 + 1.44}{2}}} = 5.64$$

2. The adjusted Sodium Adsorption Ratio (adj SAR) can be calculated from the procedure given in Ayers and Westcot (1976):

$$adj\ SAR = SAR\ [1 + (8.4 - pHc)] \qquad (15)$$

where $pHc = (pk_2 - pk_c) + p\ (Ca + Mg) + p\ (Alk)$

$(pk_2 - pk_c) = 2.3$

$p\ (Ca + Mg) = 2.7$

$p\ (Alk) = 2.4$

$pHc = 7.4$

$$adj\ SAR = 5.64\ [1 + (8.4 - 7.40] = 11.3$$

3. The adjusted Sodium Adsorption Ratio (adj RNa) can be calculated from equation (14) and Table 11):

$$adj\ R_{Na} = \frac{Na}{\sqrt{\frac{Ca_x + Mg}{2}}} \qquad (14)$$

$EC_w = 1.15$ dS/m

$HCO_3/Ca = 1.76$

From Table 11, $Ca_x = 1.43$ me/l

$$adj\ R_{Na} = \frac{7.73}{\sqrt{\frac{1.43 + 1.44}{2}}} = 6.45$$

3.2 MANAGEMENT OF INFILTRATION PROBLEMS

Irrigating to fill the soil-water reservoir for later withdrawal by the crop is difficult when infiltration rates are low, but there is little need to take action to increase infiltration unless the crop water demand or the leaching requirement cannot be met. Water ponding for too long a time frequently gives rise to secondary problems which are as important in causing yield loss as is an actual water shortage and often determine remedial measures to correct the infiltration problem. Some of the more troublesome secondary problems are crusting of seed beds, excessive weed growth and surface saturation which can cause root rot, diseases, nutritional disorders, poor aeration and poor germination. In some cases, water ponding for an excessive period of time has caused mosquito problems.

The management steps available to help maintain yields can be either chemical or physical. Chemical practices involve changing the soil or water chemistry that influences soil infiltration rates. This is normally accomplished by adding a chemical amendment, such as gypsum, to either the soil or the water or, in a few cases, by blending two or more sources of water to reduce the potential hazard. Physical methods include cultural practices that can be expected to improve or maintain infiltration rates during periods of irrigation or rainfall. Whether the physical or chemical approach is used, local conditions play an important role. A reduced infiltration caused by water quality is a different problem to a low infiltration rate caused by a clayey or compacted surface soil. Infiltration problems due to water quality are related to the impurities (Ca, Mg, Na, HCO_3 and ECw) present in the water supply. Several possible options to solve a water quality-related infiltration problem are discussed in the following paragraphs. Each must be adapted to the local conditions and thoroughly field tested before any large-scale implementation.

The following management steps are directed at evaluating and overcoming infiltration problems caused by the chemical quality of the irrigation supply. Of equal importance, and also a water quality problem, is the reduction in infiltration that can take place due to a high sediment content in the supply water. It is beyond the scope of this publication to include this factor but it should be considered. See Section 8.17 for an example of the impacts from sediment.

3.2.1 Soil and Water Amendments

Certain chemical amendments added to soil or water should improve a low infiltration rate caused by low salinity or by excessive sodium (high SAR) in the irrigation water. Improvement can be expected if the amendment increases the soluble calcium content or causes a significant increase in the salinity (ECw) of the applied water. Amendments are used to help increase the infiltration or counter the effects of sodium, since, at present, there is no economical process available for removing salts or sodium from irrigation water which is low enough in cost for general agricultural use. An amendment, such as gypsum, when added to soil or water, will increase the calcium concentration in the water, thus reducing the sodium to calcium ratio and the SAR. Adding gypsum is also beneficial because it increases the salinity of low salt waters, thus improving infiltration (Figure 21). Gypsum or other similar additives will not cause any important improvement if poor infiltration is due to adverse soil texture, soil compaction, restrictive claypan or hardpan layers, or a high water table.

Most soil and water amendments in common use supply calcium directly (gypsum) or indirectly through an acid or acid-forming substance (sulphuric acid or sulphur) which reacts with soil lime ($CaCO_3$) to release calcium to the soil solution. Acid or acid-forming amendments are not effective if lime is absent from the soil. Chemical amendments are expensive and add to the cost of crop production. They are justified only if their use results in a substantial improvement that can be evaluated in relation to cost. Field trials should be conducted to determine whether water or soil amendments improve water penetration or yield to an extent that justifies the cost. A crop receiving adequate water and producing near maximum yield would not be expected to show a further yield increase from the use of amendments, but, in some instances, such amendments may make irrigation management easier, though at an increased cost for the amendments, their handling and application.

Water amendments are most effective if the water infiltration problem is caused by a low salinity water (ECw < 0.2 dS/m) or by high SAR in a water of low to moderate salinity (ECw < 1.0 dS/m). If water salinity is moderate to high (ECw >1.0 dS/m) in addition to a high SAR, soil applied amendments such as low-grade gypsum or sulphur may be preferred and often are more effective.

i. Gypsum

Gypsum can be either a soil or water amendment and is the most commonly used and widely available amendment for both. For reclamation of sodic soils, gypsum, in granular form, is applied broadcast at rates ranging from 5 to 40 t/ha and is worked into the soil. The 40 t/ha rate is used as a one-time application for extremely sodic soils and if rapid reclamation is needed. Annual rates of application in excess of 10 t/ha are usually uneconomical. High rates over 10 t/ha have normally been for immediate soil reclamation to allow roots to establish a proper rooting depth.

A water infiltration problem caused by low ECw or high SAR occurs primarily in the upper few centimetres of soil; therefore, the low application rates of gypsum to correct the surface problem are more effective if left on the soil surface or mixed with soil to a shallow depth rather than incorporated deeper into the soil as for reclamation. However, surface applied gypsum may be rapidly leached and the soil will again show the infiltration problem even though the gypsum may still be present a few centimetres below the soil surface. Small but repeated soil applications may be more effective for water-related surface infiltration problems, whereas single, large applications are more effective for sodic soil reclamation.

The application of gypsum to irrigation water to solve a water-related infiltration problem usually requires less gypsum per hectare than does a soil application. Gypsum is particularly effective when added to water if the water salinity is low (EC less than 0.5 dS/m). It is much less effective for higher salinity water because of the difficulty in applying and getting sufficient calcium into solution to counter the sodium present effectively. In practice it is unusual to get more than 1 to 4 me/l dissolved Ca in the usual fast-moving irrigation stream. These relatively small amounts of calcium in a low salinity water may increase infiltration by as much as 100-300 percent - a significant increase. However, if water salinity is relatively high, these small amounts of calcium are much less effective and change the infiltration rate to a much lesser degree.

The rate at which gypsum goes into solution will depend to a great extent upon the surface area or fineness of the grind. Finely-ground gypsum (less than 0.25 mm in diameter) dissolves much more rapidly. Therefore, the finely-ground, usually purer grades of gypsum are generally more satisfactory for water applications; the biggest drawback is the higher cost which often prevents small farmers from maintaining a continuous supply. The coarse grinds and lower grades are more satisfactory for soil application, but with care and ingenuity farmers have successfully used low grades for water amendments. Even though the finely-ground gypsum is much more costly per unit than is the coarse and lower grade, for water application the ease of handling and speed of dissolution often make it worth the added cost. Example 7 illustrates how gypsum can be used as a water amendment to improve infiltration.

EXAMPLE 7 - USE OF GYPSUM AS AN AMENDMENT

A low salinity water (ECw = 0.15 dS/m) is being used for irrigation of citrus. Infiltration problems have been experienced in the past causing oxygen stress in the citrus trees. The cause has been attributed to water ponding on the soil surface for extended periods of time. Since the critical time of fruit set is taking place, it was decided to add gypsum to the irrigation water to increase infiltration and reduce waterlogging and oxygen stress. A 5 hectare area needs an irrigation depth of 100 mm. The gypsum available is 70 percent pure and an increase of 2 me/l of calcium is desired in the water. How much gypsum should be used?

Given:

ECw = 0.15 dS/m
Area = 5 ha
Gypsum = 70 percent pure
Total water requirement = 500 hectare mm = 5000 m^3
1 milliequivalent per litre of calcium = 86 kg of 100% gypsum per 1000 m^3 of water

Explanation: The amount of 100 percent gypsum needed to supply 2 me/l of Ca in 5000 m^3 of water can be found by:

1. 1 me/l (Ca) = 86 kg (100% gypsum)/1000 m^3

2. For 1 me/l (Ca) in 5000 m^3
   1 me/l (Ca) = 5 x 86 = 430 kg of 100% gypsum

3. For 2 me/l (Ca) in 5000 m^3
   2 me/l (Ca) = 430 kg x 2 = 860 kg of 100% gypsum

4. Since the gypsum is only 70% pure, the amount of gypsum needed is found by (860 x 100) ÷ 70 = 1230 kg of 70% pure gypsum

A finely ground gypsum is best for water applications. Therefore the total quality of gyspum needed to supply 2 me/l of calcium in the 5000 m^3 of water is 1230 kg of 70% pure gypsum.

In a few instances, large pieces of rock gypsum have been placed in the irrigation ditch to supply calcium to the irrigation stream. The amount of calcium dissolving from the rock is low, so effectiveness depends upon the stream velocity and volume. The amount being dissolved can be determined by comparing the calcium concentration of upstream water with the concentration downstream. Its probable effectiveness can then be estimated by the changes in ECw and SAR brought about by the additional calcium and the potential change in infiltration as predicted by the guidelines of Table 1. Rock gypsum placed in the irrigation channel may increase maintenance costs as weed control and watercourse maintenance become more difficult because the gypsum will have to be removed during mechanical cleaning or dredging.

The ultimate goal of either water or soil amendment with gypsum is an increase in yield or a substantial increase in ease of irrigation management. An effective treatment should improve the water infiltration rate but the improvement must be weighed against the costs to determine whether the treatment is worthwhile.

Gypsum occurs naturally in many soils in arid climates and some soils will contain gypsum in sufficient quantity to affect interpretations of both soil salinity (ECe) and sodicity (exchangeable sodium), and require a correction both to the measured soil salinity (ECe) and to the reported SAR which is frequently used to estimate the soil exchangeable sodium percent (ESP) (see Figure 1). The ECe procedure involves a saturated soil paste and, if gypsum is present, the ECe will include salinity attributable to the dissolution of gypsum - about 2 dS/m. Since gypsum is generally beneficial to most soils and detrimental to very few crops (citrus), the additional soil salinity due to gypsum may be subtracted from the measured ECe to give a more correct assessment of the soil salinity hazard. For example, a gypsiferous soil has a measured ECe of 6 dS/m, a soil salinity which is expected to reduce yields of many salt sensitive crops. Since 2 dS/m of the reported ECe can be attributed to the gypsum, the ECe safely can be discounted by 2 dS/m and the corrected ECe now becomes ECe = 4 dS/m, an amount much less hazardous to sensitive crops.

Naturally occurring soil gypsum also has a bearing on interpretation of many laboratory analyses of soils. In soil analysis, the laboratory sometimes reports the SAR of the saturation extract (ESP), as shown in Figure 1. This is not a correct evaluation if gypsum is present because all the sodium salts are completely soluble whereas the gypsum is only slightly soluble and can contribute a maximum of about 20 to 30 me/l calcium to the saturation extract. As an example of the problem in interpretation, a strongly gypsiferous soil, but with high salinity, may have an ECe of 12 dS/m, of which 2 dS/m can be attributed to the gypsum. If all the other salts are sodium, there should be, in the saturation extract, Na = 100 me/l and Ca not more than 30 me/l, yielding a calculated SAR of 26. Such a soil, having ECe = 12 dS/m and SAR of the saturation extract equal to 26, is normally classified as a saline-alkali soil which requires extensive reclamation by a massive gypsum application plus extensive leaching before cropping. This is an incorrect interpretation. The soil is moderately saline (ECe = 12 dS/m) but it is not sodic because the gypsum provides a steady supply of calcium. Even without leaching, it should be capable of growing excellent barley (tolerance of barley = 10 dS/m at 90 percent yield potential) and with 50 percent reduction in salinity (to ECe = 7 dS/m including 2 dS/m per cm attributed to the naturally occurring gypsum in the soil), it could be planted to field crops such as barley, cotton, sugarbeets, grain sorghum, wheat and soybeans without a loss in yield caused by salinity. The soil is not sodic and does not require soil amendments, but it does need leaching to widen the range of crop adaptability. Such soils are sometimes called "self reclaiming", meaning that leaching alone will reclaim them and soil amendments are not needed.

A good rule of thumb to prevent such all-too-frequent interpretive errors has been adopted by the University of California Cooperative Extension Laboratories and is as follows: if the SAR of the saturation extract exceeds SAR = 10, confirmation of the indicated sodium problem is required by the laboratory. Confirmation is by the Schoonover Gypsum Requirement test given as method 22d in the USDA Handbook 60 (Richards 1954) or by the Exchangeable Cation Method given as methods 18 and 20a in the same handbook. These methods correct for the soluble cations attributable to salinity and estimate SAR and ESP more correctly. Where appropriate, the Schoonover method is simple and reliable, but it is not appropriate if appreciable exchangeable potassium is present.

Gypsum is sometimes present in irrigation water. If the soluble salts in the irrigation water include appreciable calcium, many sodic soils can be reclaimed over a period of one to five or more years simply by planting tolerant crops and adopting cultural practices to promote deep percolation of applied irrigation water. To reclaim a severely sodic soil in one year may require up to 40 t/ha of gypsum and extensive leaching to remove sodium (salts) released during reclamation. To reclaim the same soil relying upon calcium present in the irrigation water (Ca = 2-3 me/l or more) plus cultural practices (disking, ploughing, deep cultivation) and planting sodium-tolerant crops (pasture grasses and forage or similar), may take several years. Success or failure will depend to a great extent upon an adequate rate of infiltration and the depth of water that enters the soil, the calcium content of the irrigation water and the severity of the sodic problem. Deep cultivation will greatly enhance infiltration and speed reclamation whether amendments are used or not.

ii. Acid-forming amendments

Acids or acid-forming amendments also supply calcium to soils, but lime ($CaCO_3$) must be present in the soil for them to be effective. Sulphur and sulphuric acid are both used extensively, but relatively few others have been used to any great extent. Table 12 gives comparative data for several common calcium supplying materials used for reclamation of sodic soil, but gypsum remains the most widely used because it is usually readily available and costs less for the me/l of calcium supplied. Several fertilizers are acid residual and contribute calcium through their acidic reaction.

Sulphur furnishes calcium if lime is present in the soil and is an excellent amendment for reclamation of sodic soils. It is not a satisfactory amendment for water application and is not very effective to improve a water infiltration problem. It is slow to react. The sulphur must first be acted upon by soil bacteria and be oxidized to form sulphurous and sulphuric acid which then reacts with lime to release calcium. The oxidation process is rather slow and requires a warm, well-aerated moist soil for about 30 days or longer. If sufficient time is available, it has proved to be a good amendment for reclamation of sodic-calcareous soils, but is not expected to provide a satisfactory solution for a water infiltration problem because the oxidation process is too slow and calcium released near the surface is soon leached during irrigations.

Sulphuric acid is a strong, corrosive acid, used for direct application to the soil surface at full strength or added to irrigation water where it reduces the water concentration of bicarbonate and contributes acidity to the soil surface to release calcium. It is very effective for reclaiming sodic soils and to improve water infiltration of limey soils because the sulphuric acid does not have to go through an oxidation process. It reacts rapidly with soil lime. Soil applications are made before cropping and are usually followed by extensive leaching to remove any excessive soluble salts present or formed because of the sulphuric acid reaction with lime and the soil. Applications in water must be carefully controlled and monitored to ensure that they are safe for the conditions of use - safe for pipelines, sprinklers, irrigation water distribution systems, and personnel. The ultimate effect on infiltration is about the same as that for a chemically equivalent amount of gypsum (Table 12). Sulphuric acid is highly corrosive and dangerous to handle. It may damage concrete pipelines, steel culverts, checkgates and aluminium pipes. It should only be applied by experienced operators.

Table 12 WATER AND SOIL AMENDMENTS AND THEIR RELATIVE EFFECTIVENESS IN SUPPLYING CALCIUM[1]

Amendment	Tons equivalent to 1 ton of 100 percent gypsum[2]
Gypsum ($CaSO_4 \cdot 2H_2O$) *	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 percent Ca + 24 percent S) *	0.78
Calcium chloride ($CaCl_2 \cdot 2H_2O$) *	0.86
Calcium nitrate ($Ca(NO_3)_2 \cdot 2H_2O$) *	1.06
Calcium carbonate[3] ($CaCO_3$) **	0.58

* Suitable for use as a water or soil amendment
** Suitable only for soil application

[1] Adapted from Fireman and Branson (1965).

[2] The above are based on 100 percent pure materials. If not 100 percent, make the following calculation to find tons (X) that are equivalent to a 100 percent material:

$$X = \frac{100 \ . \ tons}{percent\ purity} \qquad (16)$$

Example: If gypsum is 50 percent pure, X = 2.00 tons. This says that 2.00 tons of 50 percent pure gypsum is equivalent to 1 ton of 100 percent pure gypsum.

[3] For acid soils only.

Other amendments are sometimes used in local areas but their use depends greatly on the cost of supply and application. As shown in Table 13, several common fertilizers can also act as direct or indirect

Table 13 AVERAGE COMPOSITION AND EQUIVALENT ACIDITY OR BASICITY OF FERTILIZER MATERIALS[1]

Fertilizer materials	Chemical Formula	Total Nitrogen (N)	Available Phosphoric Acid (P_2O_5)	Water Soluble Potash (K_2O)	Combined Calcium (Ca)	Combined Sulphur (S)	Equivalent[2] Acid or Base in kg Acid	$CaCO_3$ Base
		Percent						
Nitrogen materials								
Ammonium nitrate	NH_4NO_3	33.5-34					62	
Ammonium nitrate-sulphate	$NH_4NO_3.(NH_4)_2SO_4$	30				6.5	68	
Monoammonium phosphate	$NH_4H_2PO_4$	11	48				58	
Ammonium phosphate-sulphate	$NH_4H_2PO_4.(NH_4)_2SO_4$	13	39			7	69	
Ammonium phosphate-sulphate	$NH_4H_2PO_4.(NH_4)_2SO_4$	16	20			15	88	
Ammonium phosphate-nitrate	$NH_4H_2PO_4.NH_4NO_3$	27	12			4.5	75	
Diammonium phosphate	$(NH_4)_2HPO_4$	16-18	46-48				70	
Ammonium sulphate	$(NH_4)_2SO_4$	21				24	110	
Anhydrous ammonia	NH_3	82					147	
Aqua ammonia	NH_4OH	20					36	
Calcium ammonium nitrate solution	$Ca(NO_3)_2.NH_4NO_3$	17			8.8		9	
Calcium nitrate	$Ca(NO_3)_2$	15.5			21			20
Calcium cyanamide	$CaCN_2$	20-22			37			63
Sodium nitrate	$NaNO_3$	16						29
Urea	$CO(NH_2)_2$	45-46					71	
Urea formaldehyde[3]		38					60	
Urea ammonium nitrate solution	$NH_4NO_3.CO(NH_2)_2$	32					57	
Phosphate materials								
Single superphosphate	$Ca(H_2PO_4)_2$		18-20		18-21	12		neutral
Triple superphosphate	$Ca(H_2PO_4)_2$		45-46		12-14	1		neutral
Phosphoric acid	H_3PO_4		52-54				110	
Superphosphoric acid[4]			76-83				160	
Potash materials								
Potassium chloride	KCl			60-62				neutral
Potassium nitrate	KNO_3	13		44			23	
Potassium sulphate	K_2SO_4			50-53		18		neutral
Sulphate of potash-magnesia	$K_2SO_4.2MgSO_4$			26	1	15		neutral

[1] From Soil Improvement Committee (1975).

[2] Equivalent per 100 kg of each material.

[3] Also known as ureaform, reaction product of urea and formaldehyde.

[4] H_3PO_4, $H_4P_2O_7$, $H_5P_3O_{10}$, $H_6P_4O_{13}$ and other higher forms.

sources of calcium. Most acid fertilizers must go through an oxidation process similar to that for sulphur, and a source of calcium must be present in the soil (CaCO). Therefore, they are of limited value for a water infiltration problem, but may be useful to prevent or delay formation of a sodic soil that may gradually develop as a result of using a slightly marginal sodic water.

3.2.2 Blending Water Supplies

As shown in Table 1, an SAR of 12 or greater may appreciably reduce the rate of infiltration of water with a salinity less than ECw of 3 dS/m, and an SAR as low as 6 may appreciably reduce the infiltration rate of water with a salinity less than ECw of 1.2 dS/m. The infiltration rate can be increased either by increasing the water salinity or reducing the SAR.

Dilution reduces the SAR. This is due to the nature of the SAR equation (1). The numerator (Na) is reduced in proportion to the dilution and at a greater rate than is the denominator (Ca + Mg) because the denominator is reduced by the square root of the dilution. Example 8 shows how the SAR of a blended water is reduced when a tubewell water in Pakistan is blended into the normal canal supplies. Without blending the tubewell water would have very limited use, but as a result of blending the total amount of usable water has increased by the amount supplied by the tubewell.

EXAMPLE 8 – BLENDING IRRIGATION WATER TO REDUCE THE SAR OF A POOR QUALITY SUPPLY

A canal water supply is available but will not meet the total crop water demand. The canal supply could be blended with a poorer quality well water to the extent of 75% canal water and 25% well water. What is the SAR of the blended water?

Given: The water analysis is:

	ECw (dS/m)	Ca (me/l)	Mg (me/l)	Na (me/l)	HCO_3 (me/l)	SAR
Canal water	0.23	1.41	0.54	0.48	1.8	0.5
Well water	3.60	2.52	4.00	32.0	4.5	18.0

Explanation: The resulting blend quality can be found by using equation (13):

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

Ca = (1.41x0.75) + (2.52x0.25) = 1.69 me/l (blend)
Mg = (0.54x0.75) + (4.00x0.25) = 1.41 me/l (blend)
Na = (0.48x0.75) + (32.0x0.25) = 8.36 me/l (blend)
HCO_3 = (1.8 x0.75) + (4.5 x0.25) = 2.48 me/l (blend)
EC_w = (0.23x0.75) + (3.6 x0.25) = 1.07 dS/m (blend)

$$SAR = \frac{8.36}{\sqrt{\frac{1.69 + 1.41}{2}}} = 6.7$$

Many high SAR waters are usually abandoned if an alternate better quality source is made available. If the better supply is adequate for the area to be irrigated, there is nothing to be gained from blending the two supplies. However, if the better quality supply is not adequate for the land available for planting, blending a less desirable water with a better supply may allow more land to be planted, resulting in greater overall crop production and more income for the farmer.

Blending water supplies is not a common practice even when two supplies are available, one of which is much poorer in quality. Normally a better quality surface supply is used whenever available and the poorer quality groundwater is used whenever the surface supply is insufficient. Alternating supplies does not, however, offset an infiltration problem caused by the high SAR of a poorer quality supply. In fact, the problem can be greatly aggravated if low salinity-low SAR supplies are used after a highly saline-high SAR water. The high SAR water causes a correspondingly high ESP in the surface soil and, if low salinity water is then used, it can soon cause an appreciably reduced infiltration rate. An even more severe problem occurs when rain falls after using a saline or high SAR irrigation water. A light application of surface applied gypsum (1 to 2 t/ha) prior to irrigation with the better quality supply or before the rainy season is sometimes used in an attempt to overcome this problem. Blending would also prevent many of the secondary problems caused by short-term usage of high SAR water, such as surface crusting and sealing. Wherever possible high SAR water should be diluted to reduce infiltration problems, but in those instances where its use is alternated, the use of supplemental amendments should be considered.

3.2.3 Cultivation and Deep Tillage

Soil and water amendments and blending change the chemical nature of the water while physical methods keep the soil open by mechanical means. The most common physical method is either cultivation or deep tillage. Both are effective but normally short-lived and are thus only temporary solutions to a water infiltration problem.

Cultivation is usually done for weed control or soil aeration rather than to improve water penetration. Where infiltration problems are severe, cultivation or tillage are helpful as they roughen the surface and slow the flow of water, increasing the time during which infiltration can take place. A rough, cloddy furrow or field improves infiltration during the first one or two irrigations, after which another cultivation may be needed. Cultivation equipment can often be modified to leave a rougher surface. Cultivation breaks up the crust in the upper few centimetres of soil to improve infiltration. A common practice in areas where a water infiltration problem has been caused by low salinity water is to cultivate before each irrigation or before every second irrigation. This roughens the soil and opens cracks and air spaces that greatly increase the surface area exposed for infiltration.

Deeper tillage (chiselling, subsoiling) can be expected to improve deep water penetration for only one or two irrigations since the soil surface soon reverts to its original condition but, although improvement is not permanent, this practice may temporarily allow sufficient water to enter to make an appreciable difference in stored water and in the crop yield. Deep tillage physically tears, shatters and rips the soil, and is done prior to planting or during periods of dormancy when root pruning or root disturbances of permanent crops are less disruptive. Deep tillage should only be performed when soils are dry enough to shatter and crack. If done wet, increased compaction, aeration and permeability problems can be expected.

3.2.4 Organic Residues

Crop residues or other organic matter left in the field will improve water penetration and is becoming a more widely accepted practice. It is one of the easiest methods to improve water infiltration, especially for small farmers who do not have the resources to implement more costly corrective measures. Unfortunately, in many instances, the small farmers use crop residues for other purposes and little, if any, is returned to the soil.

Crop residues left on the soil or worked into a rough cloddy soil surface will improve water penetration on sodic soils and will also improve water penetration into soils being irrigated by high SAR or low salinity water. Both crop residue left on the soil surface as well as the root system of the crop help in keeping the soil open. The benefits decline with time until replenished at the next cropping season.

The more fibrous and less easily decomposed crop residues, as from barley, rice, wheat, maize and sorghum, have improved water penetration, whereas residues from legumes and vegetable crops generally have not. The best residues are those which do not decompose or break down rapidly. These keep the soil porous by maintaining open channels and voids which improve water penetration. To be effective, relatively large quantities of residues are needed; for instance, manure has been used at rates of 40 to 400 metric tons per hectare to improve water infiltration. An organic application in the range of 10-30 percent by soil volume in the upper 15 cm of soil may be needed to be effective.

Where water quality is affecting water infiltration, and organics are being tried to improve infiltration, it is important to incorporate the residues into the surface few centimetres of soil. Deeper incorporation is beneficial for soil structure and deeper percolation of applied water, but for infiltration problems caused by water quality, it is the surface soil that usually controls the depth of water entering the soil in a given period of time.

Rice hulls, sawdust, shredded bark, and many other waste products have been used in large volumes but with varying degrees of success. Tests with rice hulls in India increased the yield of rice in the first cropping season but yields reverted to their original level when the treatment was discontinued. From a long-term standpoint, the return of organic matter to the soil helps maintain soil structure and returns needed nutrients, but using a high rate of organic matter also causes problems. These include nutritional upsets, salinity effects caused by salty manure, nitrogen shortages or excesses owing to the use of certain types of materials (manures vs sawdust) and toxicities (chloride and potassium toxicities from rice hulls).

3.2.5 Irrigation Management

Physical and chemical methods in combination have proved to be the most effective approaches to solving water infiltration problems. However, these require extensive and continuing annual investment in both time and money to be effective. Many users try to complement these methods with irrigation practices to make the water infiltration problem easier to solve or manage. Several practices are discussed here.

i. Irrigating more frequently is a simple and effective approach especially for soils having an initially high infiltration rate but for which the rate drops rather quickly due to low salinity or high SAR. The objective is to supply the crop with adequate water at all times without secondary problems developing (waterlogging, poor aeration).

Irrigating more frequently maintains a higher average soil water content and reduces the possibility of a water stress that might result if irrigations were spaced further apart. If the crop is not stressed for water between irrigations, increasing the irrigation frequency does little good.

ii. Pre-plant irrigation can be relied upon to fill the rooting depth to field capacity at a time when there is little chance of causing crop damage. In some difficult soils a pre-plant irrigation is the only opportunity to wet the deeper part of the crop root zone. It is also an effective method for wetting soils with a very slow infiltration rate.

iii. Extending the duration of an irrigation applies more water and is beneficial provided that soil aeration, waterlogging, runoff and surface drainage problems do not result. Many irrigators try to extend the irrigation by reducing the volume of flow to a field and holding the water on the field for a greater period of time. Careful management and monitoring is needed to maintain water use efficiency and to keep runoff to a minimum. Excessive runoff is frequently collected in a pond at the low side of the irrigated field and is pumped back up slope through a pipeline to be re-circulated into the irrigation stream. These re-circulation (return-flow) systems are becoming common in surface irrigated areas and can aid greatly in efficiently irrigating a soil with a low infiltration rate. In a few instances this system is installed following a comprehensive land levelling or grading programme to improve water use efficiency. By collecting and re-circulating water, both the total water use efficiency and depth of penetration can be more easily controlled.

iv. Changing irrigation systems may be necessary on more difficult soils. For instance, changing from a surface irrigation system to one which applies water more precisely (sprinklers for sandy soils and localized (drip) irrigation for heavier clayey soils) may allow the user to approach the soil intake rate more closely. These changes require large capital expenditures and additional power to operate, but the system can be designed to apply water at the rate desired. If runoff occurs with sprinklers or localized (drip) irrigation, the application rate is too high. Changing the rate of application after installation may be difficult and complete redesigning of the system may be needed. In some cases an existing sprinkler or localized irrigation system can be intermittently operated to match the infiltration rate more closely, stopping irrigation at the time runoff begins and re-irrigating every few hours until the desired depth of applied water is reached. This technique does allow the use of an existing sprinkler or localized irrigation system, but will probably use a little more water, thus increasing production cost, and it may also need more investment in equipment to offset idle time.

Sprinklers apply water in droplets, some quite large. On impact, these large droplets can disperse the soil surface particles and aggravate or cause an infiltration problem accompanied by excessive runoff. Application rates normally vary from 3 mm to 6 mm per hour over the irrigated area. Sprinklers are well adapted to sandy and loamy soils but less so to heavy or clayey type soils. Localized drip or trickle irrigation systems are better adapted to loamy or clayey soils and apply water through many small outlets (emitters) at a rate of 2 to 4 litres per hour. At these low rates they do not disperse the soil particles as do sprinklers. They are less well adapted to sandy soils.

4. TOXICITY PROBLEMS

4.1 SPECIFIC IONS AND THEIR EFFECTS

A toxicity problem is different from a salinity problem in that it occurs within the plant itself and is not caused by a water shortage. Toxicity normally results when certain ions are taken up with the soil-water and accumulate in the leaves during water transpiration to an extent that results in damage to the plant. The degree of damage depends upon time, concentration, crop sensitivity and crop water use, and if damage is severe enough, crop yield is reduced. The usual toxic ions in irrigation water are chloride, sodium and boron. Damage can be caused by each, individually or in combination.

Not all crops are equally sensitive to these toxic ions. Most annual crops are not sensitive at the concentrations shown in Table 1 but the majority of tree crops and woody perennial-type plants are. Toxicity symptoms, however, can appear on almost any crop if concentrations are high enough. Toxicity often accompanies or complicates a salinity or infiltration problem although it may appear even when salinity is low.

The toxic ions sodium and chloride can also be absorbed directly into the plant through the leaves moistened during sprinkler irrigation. This occurs typically during periods of high temperature and low humidity. The leaf absorption speeds the rate of accumulation of a toxic ion and may be a primary source of the toxicity.

Many trace elements, in addition to sodium, chloride and boron, are toxic to plants at very low concentrations. Fortunately most irrigation supplies contain very low concentrations of these trace elements and are generally not a problem. Suggested maximum concentrations for these unusual trace elements are given in Section 5.5. These concentrations are based upon limits established to protect the soil resource from contamination if continuously irrigated with water which contains them.

4.1.1 Chloride

The most common toxicity is from chloride in the irrigation water. Chloride is not adsorbed or held back by soils, therefore it moves readily with the soil-water, is taken up by the crop, moves in the transpiration stream, and accumulates in the leaves. If the chloride concentration in the leaves exceeds the tolerance of the crop, injury symptoms develop such as leaf burn or drying of leaf tissue. Normally, plant injury occurs first at the leaf tips (which is common for chloride toxicity), and progresses from the tip back along the edges as severity increases. Excessive necrosis (dead tissue) is often accompanied by early leaf drop or defoliation. With sensitive crops, these symptoms occur when leaves accumulate from 0.3 to 1.0 percent chloride on a dry weight basis, but sensitivity varies among these crops. Many tree crops, for example, begin to show injury above 0.3 percent chloride (dry weight).

Chemical analysis of plant tissue is commonly used to confirm a chloride toxicity. The part of the plant generally used for analysis varies with the crop, depending upon which of the available interpretative values is being followed. Leaf blades are most often used, but the petioles of some crops (grapes) are sometimes used rather than leaves. For irrigated areas, the chloride uptake depends not only on the water quality but also on the soil chloride, controlled by the

Table 14 CHLORIDE TOLERANCE OF SOME FRUIT CROP CULTIVARS AND ROOTSTOCKS [1]

Crop	Rootstock or Cultivar	Maximum Permissible Cl^- without Leaf Injury [2] Root Zone (Cl_e) (me/l)	Irrigation Water (Cl_w) [3] [4] (me/l)
	Rootstocks		
Avocado	West Indian	7.5	5.0
(Persea americana)	Guatemalan	6.0	4.0
	Mexican	5.0	3.3
Citrus	Sunki Mandarin	25.0	16.6
(Citrus spp.)	Grapefruit		
	Cleopatra mandarin		
	Rangpur lime		
	Sampson tangelo	15.0	10.0
	Rough lemon		
	Sour orange		
	Ponkan mandarin		
	Citrumelo 4475	10.0	6.7
	Trifoliate orange		
	Cuban shaddock		
	Calamondin		
	Sweet orange		
	Savage citrange		
	Rusk citrange		
	Troyer citrange		
Grape	Salt Creek, 1613-3	40.0	27.0
(Vitis spp.)	Dog Ridge	30.0	20.0
Stone Fruits	Marianna	25.0	17.0
(Prunus spp.)	Lovell, Shalil	10.0	6.7
	Yunnan	7.5	5.0
	Cultivars		
Berries	Boysenberry	10.0	6.7
(Rubus spp.)	Olallie blackberry	10.0	6.7
	Indian Summer Raspberry	5.0	3.3
Grape	Thompson seedless	20.0	13.3
(Vitis spp.)	Perlette	20.0	13.3
	Cardinal	10.0	6.7
	Black Rose	10.0	6.7
Strawberry	Lassen	7.5	5.0
(Fragaria spp.)	Shasta	5.0	3.3

[1] Adapted from Maas (1984).

[2] For some crops, the concentration given may exceed the overall salinity tolerance of that crop and cause some reduction in yield in addition to that caused by chloride ion toxicities.

[3] Values given are for the maximum concentration in the irrigation water. The values were derived from saturation extract data (EC_e) assuming a 15-20 percent leaching fraction and $EC_e = 1.5\ EC_w$.

[4] The maximum permissible values apply only to surface irrigated crops. Sprinkler irrigation may cause excessive leaf burn at values far below these (see Section 4.3).

amount of leaching that has taken place and the ability of the crop to exclude chloride. Crop tolerances to chloride are not nearly so well documented as crop tolerances to salinity. Table 14 gives the known tolerances of several crops to chloride in the saturation extract or in the applied water. These values may need to be changed where local experience indicates that different levels cause damage. For example, tobacco, although tolerant to chloride, acquires progressively more undesirable burning characteristics of the leaf as well as reduced storage life if chloride levels in irrigation water increase above a few milliequivalents per litre. This greatly affects its market value.

A chloride toxicity can occur by direct leaf absorption through leaves wet during overhead sprinkler irrigation. This occurs most frequently with the rotating type sprinkler heads and is discussed in Section 4.3.

4.1.2 Sodium

Sodium toxicity is not as easily diagnosed as chloride toxicity, but clear cases of the former have been recorded as a result of relatively high sodium concentrations in the water (high Na or SAR). Typical toxicity symptoms are leaf burn, scorch and dead tissue along the outside edges of leaves in contrast to symptoms of chloride toxicity which normally occur initially at the extreme leaf tip. An extended period of time (many days or weeks) is normally required before accumulation reaches toxic concentrations. Symptoms appear first on the older leaves, starting at the outer edges and, as the severity increases, move progressively inward between the veins toward the leaf centre. Sensitive crops include deciduous fruits, nuts, citrus, avocados and beans, but there are many others. For tree crops, sodium in the leaf tissue in excess of 0.25 to 0.50 percent (dry weight basis) is often associated with sodium toxicity.

Leaf tissue analysis is commonly used to confirm or monitor sodium toxicity but a combination of soil, water and plant tissue analyses greatly increases the probability of a correct diagnosis. When using only leaf blade analysis to diagnose sodium toxicity, it is advisable to include analyses of leaf blades from damaged trees as well as nearby undamaged ones for comparative purposes.

Sodium toxicity is often modified or reduced if sufficient calcium is available in the soil. Whether an indicated sodium toxicity is a simple one or is more complicated involving a possible calcium deficiency or other interaction is presently being researched. Preliminary results indicate that for at least a few annual crops, calcium deficiency rather than sodium toxicity may be occurring. If confirmed, these crops should respond to calcium fertilization using material such as gypsum or calcium nitrate. For a discussion of possible calcium deficiency, see Section 5.6 on Nutrition and Water Quality.

Many crops do show sodium toxicity. The toxicity guidelines of Table 1 use SAR as the indicator of the potential for a sodium toxicity problem which is expected to develop following surface irrigation with a particular quality of water. Table 15 gives the relative sodium tolerance of several representative crops. The data in the table are given not in terms of SAR but of soil exchangeable sodium (ESP). Estimates of soil ESP that are expected to result from long-term (several years) use of water of given SAR can be made using the nomogram in Figure 1. (Refer to Section 3.2.1 for a discussion of the impact of erroneous interpretations of SAR-ESP relationships in presence of gypsum.)

Table 15 RELATIVE TOLERANCE OF SELECTED CROPS TO EXCHANGEABLE SODIUM[1]

Sensitive[2]	Semi-tolerant[2]	Tolerant[2]
Avocado (*Persea americana*)	Carrot (*Daucus carota*)	Alfalfa (*Medicago sativa*)
Deciduous Fruits	Clover, Ladino (*Trifolium repens*)	Barley (*Hordeum vulgare*)
Nuts	Dallisgrass (*Paspalum dilatatum*)	Beet, garden (*Beta vulgaris*)
Bean, green (*Phaseolus vulgaris*)	Fescue, tall (*Festuca arundinacea*)	Beet, sugar (*Beta vulgaris*)
Cotton (at germination) (*Gossypium hirsutum*)	Lettuce (*Lactuca sativa*)	Bermuda grass (*Cynodon dactylon*)
Maize (*Zea mays*)	Bajara (*Pennisetum typhoides*)	Cotton (*Gossypium hirsutum*)
Peas (*Pisum sativum*)	Sugarcane (*Saccharum officinarum*)	Paragrass (*Brachiaria mutica*)
Grapefruit (*Citrus paradisi*)	Berseem (*Trifolium alexandrinum*)	Rhodes grass (*Chloris gayana*)
Orange (*Citrus sinensis*)	Benji (*Melilotus parviflora*)	Wheatgrass, crested (*Agropyron cristatum*)
Peach (*Prunus persica*)	Raya (*Brassica juncea*)	Wheatgrass, fairway (*Agropyron cristatum*)
Tangerine (*Citrus reticulata*)	Oat (*Avena sativa*)	Wheatgrass, tall (*Agropyron elongatum*)
Mung (*Phaseolus aurus*)	Onion (*Allium cepa*)	Karnal grass (*Diplachna fusca*)
Mash (*Phaseolus mungo*)	Radish (*Raphanus sativus*)	
Lentil (*Lens culinaris*)	Rice (*Oryza sativus*)	
Groundnut (peanut) (*Arachis hypogaea*)	Rye (*Secale cereale*)	
Gram (*Cicer arietinum*)	Ryegrass, Italian (*Lolium multiflorum*)	
Cowpeas (*Vigna sinensis*)	Sorghum (*Sorghum vulgare*)	
	Spinach (*Spinacia oleracea*)	
	Tomato (*Lycopersicon esculentum*)	
	Vetch (*Vicia sativa*)	
	Wheat (*Triticum vulgare*)	

Adapted from data of FAO-Unesco (1973); Pearson (1960); and Abrol (1982).

The approximate levels of exchangeable sodium percentage (ESP) corresponding to the three categories of tolerance are: sensitive less than 15 ESP; semi-tolerant 15-40 ESP; tolerant more than 40 ESP. Tolerance decreases in each column from top to bottom. The tolerances listed are relative because, usually, nutritional factors and adverse soil conditions stunt growth before reaching these levels. Soil with an ESP above 30 will usually have too poor physical structure for good crop production. Tolerances in most instances were established by first stabilizing soil structure.

Particular care in assessment of a potential toxicity due to SAR or sodium is needed with high SAR water because apparent toxic effects of sodium may be due to or complicated by poor water infiltration. As shown in Table 15, only the more sensitive perennial crops have yield losses due to sodium if the physical condition of the soil remains good enough to allow adequate infiltration. Several of the crops listed as more tolerant do show fair growth when soil structure is maintained and, in general, these crops can withstand higher ESP levels if the soil structure and aeration can be maintained, as in coarse textured soils.

4.1.3 Boron

Boron, unlike sodium, is an essential element for plant growth. (Chloride is also essential but in such small quantities that it is frequently classed non-essential.) Boron is needed in relatively small amounts, however, and if present in amounts appreciably greater than needed, it becomes toxic. For some crops, if 0.2 mg/l boron in water is essential, 1 to 2 mg/l may be toxic. Surface water rarely contains enough boron to be toxic but well water or springs occasionally contain toxic amounts, especially near geothermal areas and earthquake faults. Boron problems originating from the water are probably more frequent than those originating in the soil. Boron toxicity can affect nearly all crops but, like salinity, there is a wide range of tolerance among crops.

Boron toxicity symptoms normally show first on older leaves as a yellowing, spotting, or drying of leaf tissue at the tips and edges. Drying and chlorosis often progress toward the centre between the veins (interveinal) as more and more boron accumulates with time. On seriously affected trees, such as almonds and other tree crops which do not show typical leaf symptoms, a gum or exudate on limbs or trunk is often noticeable.

Most crop toxicity symptoms occur after boron concentrations in leaf blades exceed 250-300 mg/kg (dry weight) but not all sensitive crops accumulate boron in leaf blades. For example, stone fruits (peaches, plums, almonds, etc.), and pome fruits (apples, pears and others) are easily damaged by boron but they do not accumulate sufficient boron in the leaf tissue for leaf analysis to be a reliable diagnostic test. With these crops, boron excess must be confirmed from soil and water analyses, tree symptoms and growth characteristics.

A wide range of crops was tested for boron tolerance by using sand-culture techniques (Eaton 1944). Previous boron tolerance tables in general use have been based for the most part on these data. These tables reflected boron tolerance at which toxicity symptoms were first observed and, depending on crop, covered one to three seasons of irrigation. The original data from these early experiments, plus data from many other sources, have recently been reviewed (Maas 1984). Table 16 presents this recent revision of the data. It is not based on plant symptoms, but upon a significant loss in yield to be expected if the indicated boron value is exceeded. Table 17 presents recent data on citrus and stone fruit rootstocks and are listed in order of increasing boron accumulation.

4.2 MANAGEMENT OF TOXICITY PROBLEMS

Obviously, the most effective method to prevent occurrence of a toxicity problem is to choose an irrigation water that has no potential to develop a toxicity. But if such water is not available, there are

Table 16 RELATIVE BORON TOLERANCE OF AGRICULTURAL CROPS[1,2]

Very Sensitive (<0.5 mg/l)	
Lemon	*Citrus limon*
Blackberry	*Rubus spp.*
Sensitive (0.5 - 0.75 mg/l)	
Avocado	*Persea americana*
Grapefruit	*Citrus X paradisi*
Orange	*Citrus sinensis*
Apricot	*Prunus armeniaca*
Peach	*Prunus persica*
Cherry	*Prunus avium*
Plum	*Prunus domestica*
Persimmon	*Diospyros kaki*
Fig, kadota	*Ficus carica*
Grape	*Vitis vinifera*
Walnut	*Juglans regia*
Pecan	*Carya illinoiensis*
Cowpea	*Vigna unguiculata*
Onion	*Allium cepa*
Sensitive (0.75 - 1.0 mg/l)	
Garlic	*Allium sativum*
Sweet potato	*Ipomoea batatas*
Wheat	*Triticum eastivum*
Barley	*Hordeum vulgare*
Sunflower	*Helianthus annuus*
Bean, mung	*Vigna radiata*
Sesame	*Sesamum indicum*
Lupine	*Lupinus hartwegii*
Strawberry	*Fragaria spp.*
Artichoke, Jerusalem	*Helianthus tuberosus*
Bean, kidney	*Phaseolus vulgaris*
Bean, lima	*Phaseolus lunatus*
Groundnut/Peanut	*Arachis hypogaea*
Moderately Sensitive (1.0 - 2.0 mg/l)	
Pepper, red	*Capsicum annuum*
Pea	*Pisum sativa*
Carrot	*Daucus carota*
Radish	*Raphanus sativus*
Potato	*Solanum tuberosum*
Cucumber	*Cucumis sativus*
Moderately Tolerant (2.0 - 4.0 mg/l)	
Lettuce	*Lactuca sativa*
Cabbage	*Brassica oleracea capitata*
Celery	*Apium graveolens*
Turnip	*Brassica rapa*
Bluegrass, Kentucky	*Poa pratensis*
Oats	*Avena sativa*
Maize	*Zea mays*
Artichoke	*Cynara scolymus*
Tobacco	*Nicotiana tabacum*
Mustard	*Brassica juncea*
Clover, sweet	*Melilotus indica*
Squash	*Cucurbita pepo*
Muskmelon	*Cucumis melo*
Tolerant (4.0 - 6.0 mg/l)	
Sorghum	*Sorghum bicolor*
Tomato	*Lycopersicon lycopersicum*
Alfalfa	*Medicago sativa*
Vetch, purple	*Vicia benghalensis*
Parsley	*Petroselinum crispum*
Beet, red	*Beta vulgaris*
Sugarbeet	*Beta vulgaris*
Very Tolerant (6.0 - 15.0 mg/l)	
Cotton	*Gossypium hirsutum*
Asparagus	*Asparagus officinalis*

[1] Data taken from Maas (1984).

[2] Maximum concentrations tolerated in soil-water without yield or vegetative growth reductions. Boron tolerances vary depending upon climate, soil conditions and crop varieties. Maximum concentrations in the irrigation water are approximately equal to these values or slightly less.

Table 17 CITRUS AND STONE FRUIT ROOTSTOCKS LISTED IN ORDER OF INCREASING BORON ACCUMULATION AND TRANSPORT TO LEAVES[1]

Common Name	Botanical Name	Level of Boron accumulation
	Citrus	
Alemow	*Citrus macrophylla*	Low
Gajanimma	*Citrus pennivesiculata or Citrus moi*	↓
Chinese box orange	*Severinia buxifolia*	
Sour orange	*Citrus aurantium*	
Calamondin	*X Citrofortunella mitis*	
Sweet orange	*Citrus sinensis*	
Yuzu	*Citrus junos*	
Rough lemon	*Citrus limon*	
Grapefruit	*Citrus X paradisi*	
Rangpur lime	*Citrus X limonia*	
Troyer citrange	*X Citroncirus webberi*	
Savage citrange	*X Citroncirus webberi*	
Cleopatra mandarin	*Citrus reticulata*	
Rusk citrange	*X Citroncirus webberi*	
Sunki mandarin	*Citrus reticulata*	
Sweet lemon	*Citrus limon*	
Trifoliate orange	*Poncirus trifoliata*	
Citrumelo 4475	*Poncirus trifoliata X Citrus paradisi*	
Ponkan mandarin	*Citrus reticulata*	
Sampson tangelo	*Citrus X tangelo*	
Cuban shaddock	*Citrus maxima*	
Sweet lime	*Citrus aurantiifolia*	High
	Stone Fruit	
Almond	*Prunus dulcis*	Low
Myrobalan plum	*Prunus cerasifera*	↓
Apricot	*Prunus armeniaca*	
Marianna plum	*Prunus domestica*	
Shalil peach	*Prunus persica*	High

[1] Data taken from Maas (1984).

often management options than can be adopted to reduce toxicity and improve yields.

The potentially toxic ions sodium, chloride and boron can each be reduced by leaching in a manner similar to that for salinity, but the depth of water required varies with the toxic ion and may in some cases become excessive. If leaching becomes excessive, many growers change to a more tolerant crop. Increasing the leaching or changing crops in an attempt to live with the higher levels of toxic ions may require extensive changes in the farming system. In cases where the toxicity problem is not too severe, relatively minor changes in farm cultural practices can minimize the impact. In a few cases, an alternative water supply may be available to blend with a poorer supply to lower the hazard from the poorer one.

Alternatives for management of toxicity and to maintain production are discussed in the following sections.

4.2.1 Leaching

A parallel can be drawn between salinity and toxicity. The toxic ions (chloride, sodium and to a lesser extent boron) are an appreciable part of the normal salinity accumulation in the root zone and, as with salinity, leaching is the only practical way to reduce and control these toxic ions in the crop root zone. A toxicity can develop within a few irrigations or within one or more growing seasons, depending upon the toxic ion concentrations in the irrigation water and the leaching fraction accomplished.

Leaching can be used either to prevent a problem or to correct the problem after it has been recognized from plant symptoms or damage to the crop. Plant symptoms along with soil, plant and water analyses are very useful for monitoring for both potential toxicity and the adequacy of present leaching practices and crop management. If the toxic ion is coming from the irrigation water, emphasis should be placed on prevention through adequate leaching. In continuously irrigated areas, reclamation should not be necessary unless leaching has been inadequate and excess toxic ions have built up to concentrations that affect crop production.

Chloride ions move readily in the applied irrigation water and make up an important part of water and soil salinity. The concentration factors for salinity given in Table 4 also apply for the chloride ion. The concentration factor for a certain leaching fraction (Table 3) multiplied by the concentration of the chloride ion in the water will closely approximate the expected average concentration in the crop root zone. Chloride can be leached and the leaching requirement equation (9) for salinity (Rhoades 1974), as described in Section 2.4.2, is equally appropriate for calculating the leaching requirement for chloride if the chloride tolerance (Cle in saturation extract) and the chloride in the irrigation water (Clw) are known. The LR equation then becomes:

$$LR_{(Cl)} = \frac{Cl_w}{5\ Cl_e - Cl_w} \qquad (17)$$

where: $LR_{(Cl)}$ = the minimum leaching requirement needed to control chloride with ordinary surface methods of irrigation

Cl_w = chloride concentration in the applied irrigation water in milliequivalents per litre (me/l)

Cl_e = chloride concentration tolerated by crop as determined in the soil saturation extract, in milliequivalents per litre (me/l)

Sodium ions cause toxicities to sodium sensitive crops (mostly tree crops and woody ornamentals) at a lower SAR value than would be expected to cause a permeability problem. The sodium ions move less readily with the soil-water than do chlorides. However, research indicates that high leaching fractions (LF) can be effective to maintain a low soil SAR but for SAR values in the water in excess of 9, without added amendments, a leaching fraction of 0.30 or greater may be required. Deliberately adding such large quantities of water in an attempt to control sodium toxicity may not be practical because this may cause problems with soil aeration and drainage. A preferred solution is to add moderate amounts of gypsum or calcium supplying fertilizer materials (acidifying if lime is present; basic or calcium supplying if no soil lime is present). If leaching plus amendments cannot control the sodium toxicity problem, a change to a more tolerant crop may be advisable.

Boron is much more difficult to leach than are chloride and sodium. Boron moves slowly with the soil-water and requires about three times as much leaching water as would be needed to reduce an equivalent amount of chloride or salinity. In many field observations, the boron concentration in the soil saturation extract of the upper root zone usually approaches that in the irrigation water applied. With good irrigation management, it should be possible to reduce and maintain the upper root zone soil at nearly the same boron concentration as in the applied water.

As discussed above, the key to controlling a toxicity problem is to select a good source of irrigation water and then leach as needed to control any toxic build-up which may impair crop production. If the irrigation management is poor and harmful concentrations develop, amendments and reclamation leaching may be needed to restore soil productivity. For reclamation leaching, the same general guides apply for both salinity and chloride (see Section 2.4.6). For boron, the same principles apply but about three times as much water will be needed. Figure 22 shows the depth of water required to leach a high boron soil compared with that required to leach a saline soil. Recent research indicates that soil application of sulphuric acid may speed reclamation of a boron affected soil but no extensive field tests or observations are available to confirm this.

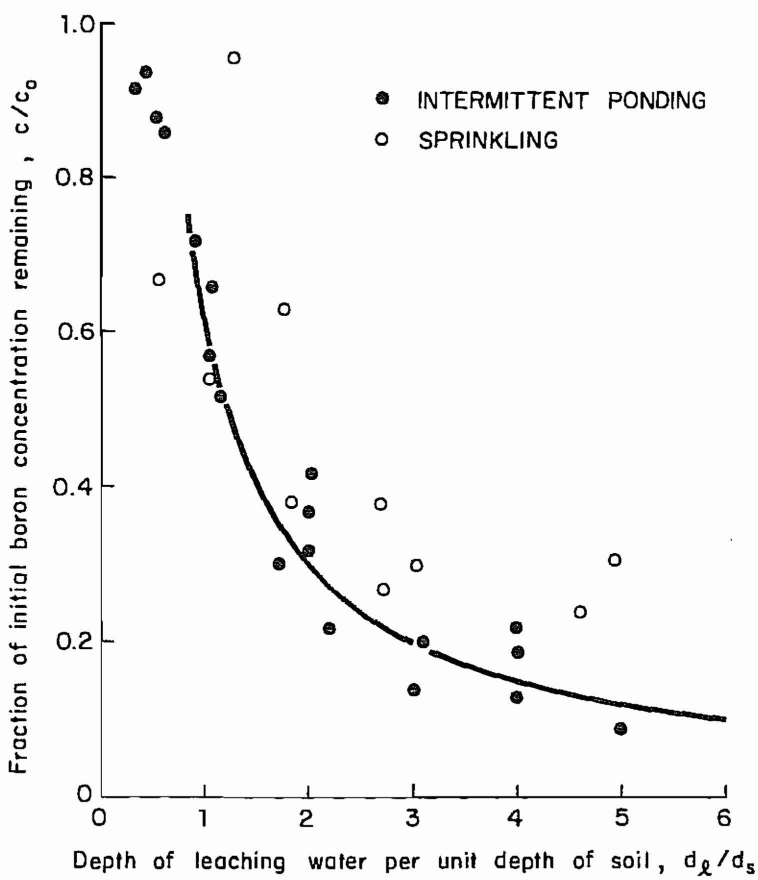


Fig. 22 Depth of leaching water per unit depth of soil required to reclaim a soil inherently high in boron (Hoffman 1980)

4.2.2 Crop Selection

Selecting a more tolerant crop 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. Limited information is available on the relative tolerance of crops to toxic ions. Table 14 presents data for chloride, Table 15 for sodium, and Tables 16 and 17 for boron. It must be kept in mind that these are approximations and local farming conditions may modify them. Factors affecting tolerance include climate, irrigation management, leaching fraction, drainage, growth stage of the crop and crop maturity date.

The selection of tolerant rootstocks or cultivars is another method of changing the crop to cope with the existing conditions. Certain rootstocks or varieties differ in their ability to exclude ions such as chloride (see Table 14) or boron (see Table 17) and produce good crops under less than ideal conditions.

4.2.3 Cultural Practices

Since leaching is the principal method of toxic ion control, cultural practices to aid in management of irrigation water at the farm level are the keys to success. Cultural practices which offer better control and distribution of water include land grading, profile modification and artificial drainage if natural drainage is inadequate. These steps are complementary to those previously discussed for improved salinity and toxicity control.

The severity of a toxicity problem will increase as the crop withdraws soil-water and the soil dries between irrigations (Figure 4). The ions become concentrated in the smaller volume of soil-water. As the upper soil dries, the crop must withdraw more and more of its water needs from the deeper soil where salinity and toxic ions are usually in greater concentration. Increasing the frequency of irrigation supplies a greater proportion of the water needs from the upper soil as well as diluting the deeper soil-water and should reduce the impact of both salinity and toxic ions. This has been previously discussed in Section 2.4.4.

Fertilization practices are normally thought to offer little benefit to counter salinity, but for a toxicity such as that from boron in a citrus crop, many growers are applying extra nitrogen to stimulate vegetative growth. Boron first accumulates to toxic amounts in the older leaves which then become necrotic and drop, thereby reducing the photosynthetic capability of the tree. In this case, nitrogen is used to stimulate new growth to restore the leaf area and photosynthetic capability. Leaf analysis for nitrogen is the guide to the nitrogen requirement. For example, the recommended nitrogen guideline for the Washington Navel Orange is 2.4-2.6 percent nitrogen (dry weight) in 5 to 7-month old terminal spring cycle leaves from non-fruiting, non-flushing shoots. But, if boron becomes a problem, this guideline is raised to nearer to 2.7-2.8 percent N and fertilization practices are modified to reach it.

It takes time to accumulate boron in the leaves. A crop like walnuts may not accumulate sufficient quantities from moderate amounts of boron (1 to 2 mg/l) in the water to damage the crop before it is harvested. In such a case, toxicity is a potential threat and by the end of the season most leaves will show severe boron toxicity (B = 1500 mg/kg). Even though the quality of crop is not greatly affected, the tree vigour and size may be. Alfalfa grown in the Clear Lake area of

California using relatively high boron water (>10 mg/l) is apparently cut frequently enough to avoid recognizeable problems; similarly, golf course greens at Calistoga, California, irrigated with high boron wastewater (2 to 3 mg/l) have not shown toxicity symptoms, presumably for the same reason (see Section 8.25).

Sodium toxicity (high SAR) from applied water is generally countered by use of a soil or water amendment such as gypsum. In general, where salinity of water is relatively low ($EC_w < 0.5$ dS/m), the beneficial response to a water-applied amendment is much greater than if salinity is high because it is far easier to change the sodium to calcium ratio of a relatively low salinity water than one of higher salinity. Soil amendments rather than water amendments are relied upon to correct a sodium problem related to a highly saline water or to a high ESP soil. It also becomes more difficult to correct the sodium toxicity as the soil clay content increases. Using amendments should not be expected to mitigate chloride or boron problems, unless the amendment improves water infiltration and soil permeability which would permit increased leaching to take place. Amendments are discussed in more detail in Section 3.2.1.

4.2.4 Blending Water Supplies

If an alternative water supply is available, but not fully adequate in quantity or quality, a blend of waters may offer an overall improvement in quality and reduce the potential toxicity problem. Blending is especially effective for a sodium toxicity problem since proportions of monovalent (Na^+) and divalent (Ca^{++}) cations absorbed on the soil depend on concentration, with dilution favouring adsorption of the divalent calcium and magnesium ions rather than the monovalent sodium. A discussion of a quality change resulting from blending is given in Section 2.4.7 and Section 3.2.2.

4.3 TOXICITY EFFECTS DUE TO SPRINKLER IRRIGATION

Overhead sprinkling of sensitive crops can cause toxicities not encountered when irrigating by surface methods. The toxicity occurs due to excess quantities of sodium and chloride from the irrigation water being absorbed through leaves wet by the sprinklers. Extreme cases have resulted in severe leaf burn and defoliation. Absorption and toxicity occur mostly during periods of high temperature and low humidity (<30 percent), frequently aggravated by windy conditions. Rotating sprinkler heads present the greatest risk. Between rotations water evaporates and the salts become more concentrated in the shrinking volume of water. Slowly rotating sprinklers (less than 1 revolution per minute) cause alternate wetting and drying cycles; the slower the speed of rotation, the greater the absorption. High frequency (near daily) spray irrigation has also created problems in some cases.

The leaf burn and resulting crop damage seems to be due to uptake from the applied water of either sodium or chloride. In some instances both sodium and chloride have been absorbed and both accumulate. Toxicity to sensitive crops occurs at relatively low sodium or chloride concentrations (>3 me/l) and, in general, crops sensitive to sodium or chloride are thought to be most sensitive to foliar absorption. Most annual crops are not sensitive but they will be damaged if concentrations are high enough. Crop tolerances to sodium and chloride in sprinkler-applied irrigation water are not well established due to limited data and the pronounced influence of climatic conditions, but Table 18 gives estimates based upon recent field investigations. They should be used as a first approximation of the potential hazard and any situation which approaches the sodium or chloride values given should be further evaluated by field testing before full implementation of the application system.

Table 18 RELATIVE TOLERANCE OF SELECTED CROPS TO FOLIAR INJURY FROM SALINE WATER APPLIED BY SPRINKLERS [1,2]

Na+ or Cl^- concentrations causing foliar injury[3] me/l			
< 5	5 - 10	10 - 20	> 20
Almond *(Prunus dulcis)*	Grape *(Vitis spp.)*	Alfalfa *(Medicago sativa)*	Cauliflower *(Brassica oleracea botrytis)*
Apricot *(Prunus armeniaca)*	Pepper *(Capsicum annuum)*	Barley *(Hordeum vulgare)*	Cotton *(Gossypium hirsutum)*
Citrus *(Citrus sp.)*	Potato *(Solanum tuberosum)*	Corn (maize) *(Zea mays)*	Sugarbeet *(Beta vulgaris)*
Plum *(Prunus domestica)*	Tomato *(Lycopersicon lycopersicum)*	Cucumber *(Cucumis sativus)*	Sunflower *(Helianthus annuus)*
		Safflower *(Carthamus tinctorius)*	
		Sesame *(Sesamum indicum)*	
		Sorghum *(Sorghum bicolor)*	

1 Data taken from Maas (1984).

2 Susceptibility based on direct accumulation of salts through the leaves.

3 Leaf absorption and foliar injury are influenced by cultural and environmental conditions such as drying winds, low humidity, speed of rotation of sprinklers, and the timing and frequency of irrigations. Data presented are only general guidelines for late spring and summer daytime sprinkling.

Toxicity has occurred in California citrus areas on leaves wet by sprinklers with water at concentrations as low as 3 me/l of either sodium or chloride. With furrow and flood irrigation this same water causes no toxicity or leaf burn. Slight damage has been reported on alfalfa using water with ECw = 1.35 dS/m and 6 me/l sodium and 7 me/l chloride, but this was under high evaporative, possibly windy conditions, using rotating sprinklers (Table 19). In contrast, water as high as ECw = 4.4 dS/m with 24 me/l sodium and 37 me/l chloride showed little or no damage when evaporative conditions were low (Table 20). The sensitivity also depends upon the crop. Several vegetable crops tested were fairly insensitive to foliar effects even at very high concentrations and in semi-arid areas.

Foliage can be damaged by salt from ocean spray or from drift from sprinklers accumulating on the leaf surface. This has occurred along the Pacific Coast of California as well as in downwind drift areas from sprinklers. Other less frequent problems also occurring with sprinklers include reddish deposits on leaves due to iron content of the sprinkler-applied water and white deposits from bicarbonate or other deposits from water solubles such as gypsum. While these are not toxicities, they can reduce the marketability of a foliage crop or the acceptability of a crop such as table grapes (see Section 5.3).

Where foliar absorption or deposition is a problem, certain management practices have been successful to counter it. Each particular problem will need to be evaluated separately. Some practices may

Table 19 LEAF BURN ON ALFALFA WITH THREE RATES OF WATER APPLICATION BY SPRINKLER IRRIGATION IN IMPERIAL VALLEY, CALIFORNIA [1,2]

	Rate of Application (mm/hr)		
	1.8	2.7	4.0
Alfalfa plants with leaf burn (percent)	92.5	5.0	2.5

[1] Data taken from Robinson (1980).

[2] Irrigation water quality ECw = 1.35 dS/m
TDS = 875 mg/l
Na = 6 me/l
Cl = 7 me/l

Table 20 SODIUM CONTENT IN COTTON LEAVES IN PERCENT OVEN DRY WEIGHT [1,2]

Variety	Day Sprinkled	Night Sprinkled	Surface Irrigated
Short staple	0.73	0.46	0.44
Long staple	0.29	0.12	0.10

[1] Data taken from Busch and Turner (1967).

[2] Irrigation water quality ECw = 4.4 dS/m
Na = 24 me/l

require minor changes in management while others will require more elaborate alterations including holding reservoirs or replacing the irrigation system.

Irrigate at night: Night sprinkling is quite effective in reducing or eliminating both sodium and chloride toxicity due to foliar absorption and has also reduced the problem of foliar deposits. As humidity generally rises at night and winds decrease, the rate of evaporation and concentration is reduced. Night irrigation has also been of benefit by lowering night-time temperatures during very hot periods. Table 20 shows differences in sodium content in cotton leaves when night and daytime sprinkler irrigation was compared.

Avoid periods of high wind: Hot, dry winds are a major factor in the concentration, absorption and deposition. Avoiding these periods for overhead sprinkling minimizes the problem and avoids possible leaf burn caused by drift to downwind crop areas. In some areas, this may require night irrigation.

Control sprinkler drift: In hot, windy areas, the downwind drift from sprinkler irrigation presents a risk. This drift, if it lands on adjacent plant leaves, is more concentrated than the applied sprinkler water. To minimize the potential leaf burn, movable sprinklers should be moved progressively downwind rather than upwind in order to wash away drifted salts as soon as possible. To avoid drift during high risk periods requires sprinkling during early morning, late evening and night hours when the winds are likely to be less than in the middle of the day. Mist nozzles or high pressure impact sprinklers should be avoided in windy areas where drift is likely to be a problem. Grouping sprinklers in blocks is preferable to long widely spaced single rows if drift is likely to be a problem.

Increase sprinkler rotation speeds: Slowly rotating sprinklers allow appreciable drying on the leaves between sprinkler rotations. More frequent or continuous wetting of foliage allows less drying of leaves and less absorption than intermittent wetting and drying. A sprinkler head rotation of one revolution per minute or less is often recommended, but to achieve this may involve changing the type of sprinkler head and, in some cases, the pressure and design of the system. This alternative may prove costly to implement if the same water use efficiency is to be maintained.

Increase rate of application: If soil water storage capacity and water infiltration rate permit, a higher rate of application may reduce damage by reducing the total period of crop wetting. This would reduce the severity of toxicity due to leaf absorption. Increasing the application rate can be accomplished by enlarging the sprinkler orifices, increasing the pressure, or reducing the spacing on the sprinkler system, but this might require a costly change in sprinkler system design. Table 19 shows the leaf burn associated with different rates of application for the Imperial Valley of California. The data indicate that application rates less than 2.7 mm/hr cause excessive amounts of leaf burn on alfalfa during the high evaporative demand (summer) period in this California desert climate (Robinson 1980).

Change irrigation method: Sprinkler systems which moisten only a little of the foliage can greatly reduce the absorption problem. Low angle or undertree sprinklers wet less of the leaves, but in many cases any lower leaves that are moistened still show symptoms from foliar absorption and in some cases the lower branches may be defoliated. A survey of citrus orchards in California showed that leaf burn and defoliation were associated with the lower leaves that had been wetted by sprinkler spray. Non-sprayed leaves from the upper portions of the trees and leaves from furrow-irrigated trees showed no leaf damage and markedly lower sodium content. In Bahrain (see Section 8.6), similar results have been shown with lemon trees. Furrow, flood, basin or drip irrigation are viable alternatives since they do not wet the leaves.

As demonstrated on some commercial farms in western USA, pivot irrigation sprinkler systems can be modified with drop lines to apply the water to the soil and not to the leaves for many crops.

Increase droplet size: Where a change in sprinkler system design is needed, sprinkler heads that apply a larger droplet size will result in less absorption as small droplets are more subject to evaporation and wind drift. While increasing droplet size may reduce the effect from foliar absorption, a further assessment needs to be made of the effect of droplet size on soil dispersion, sealing and compaction which could cause greater runoff.

Select different crops: In extreme cases it may be necessary to change from the more sensitive crops, such as beans and grapes, if they can no longer be economically produced. Local experience should provide a guide to crops more tolerant to the given conditions.

Plant during cooler seasons: Planting crops during the cooler part of the growing season reduces total water use and the hazards from sprinkler applied water. These cooler season crops can sometimes be harvested before periods of extremely low humidity. Crops planted in the cooler season have a better chance to mature before the sodium or chloride can accumulate to high enough concentrations to cause toxicity damage. Changing the growing season is an extreme alternative which should only be taken after assessment of the market possibilities for the new planting date.

5. MISCELLANEOUS PROBLEMS

5.1 EXCESS NITROGEN

Nitrogen is a plant nutrient and stimulates crop growth. Natural soil nitrogen or added fertilizers are the usual sources, but nitrogen in the irrigation water has much the same effect as soil-applied fertilizer nitrogen and an excess will cause problems, just as too much fertilizer would. If excessive quantities are present or applied, production of several commonly grown crops may be upset because of over-stimulation of growth, delayed maturity or poor quality.

The most readily available forms of nitrogen are nitrate and ammonium but nitrate (NO_3-N) occurs most frequently in irrigation water. Ammonium-nitrogen is seldom present in excess of 1 mg/l unless ammonia fertilizer or wastewater is being added to the water supply. The concentration in most surface and groundwater is usually less than 5 mg/l NO_3-N but some unusual groundwater may contain quantities in excess of 50 mg/l. Drainage water from below the root zone frequently has higher levels of nitrogen due to deep leaching of fertilizers. Since nitrogen is present in so many water supplies, it is recommended that the nitrogen content of all irrigation water be monitored and the nitrogen present included as an integral part of the planned fertilization programme. Wastewater, especially from food processing and domestic sources, is known to be high in nitrogen with values ranging from 10 to 50 mg/l (1 mg/l NO_3-N = 1 kg N/1000 m^3 of water).

There are many ways of reporting nitrogen since it is combined in various organic and inorganic complexes. The most important factor for plants is the total amount of nitrogen (N) regardless of whether it is in the form of nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N) or organic-nitrogen (Org-N). By reporting in the form of nitrogen, comparisons can be made. For example, NO_3-N means nitrogen in the form of NO_3 while NH_4-N means nitrogen in the form of NH_4 reported as N in mg/l (10 mg/l N = 45 mg/l NO_3 = 13 mg/l NH_4, but each should be reported as 10 mg/l NO_3-N or 10 mg/l NH_4-N). In the guidelines of Table 1, it is reported as nitrogen in the form of nitrate (NO_3-N) because this is the usual form found in natural water.

Sensitive crops may be affected by nitrogen concentrations above 5 mg/l. Most other crops are relatively unaffected until nitrogen exceeds 30 mg/l. For example, sugarbeets, a sensitive crop, increase in size with excessive nitrogen fertilization but the sugar content and sugar purity are lower, thus the total quantity of recoverable sugar produced per hectare may actually be reduced. Grapes are also sensitive and may continue to grow late into the season at the expense of fruit production. Yields are often reduced and grapes may be late in maturing and have a lower sugar content. Experience in Libya indicated that almost no fruiting occurred in grapes when a water containing >50 mg/l of N was used continuously. Maturity of fruit such as apricot, citrus and avocade may also be delayed and the fruit may be poorer in quality, thus affecting the marketability and storage life. In many grain crops, excessive vegetative growth produces weak stalks that cannot support the grain weight, resulting in severe lodging and difficulties for machine harvesting. Lodging is especially serious in areas with high winds or periodic heavy rains. The new short-stature wheats are better adapted and are heavily fertilized without severe lodging. Ruminant animals are sensitive to nitrogen and heavy applications to pastures used for direct or indirect livestock feed may cause excessive quantities to accumulate in the forage. This may be hazardous to the animals' health.

The sensitivity of crops varies with the growth stage. High nitrogen levels may be beneficial during early growth stages but may cause yield losses during the later flowering and fruiting stages. High nitrogen water can be used as a fertilizer early in the season. However, as the nitrogen needs of the crop diminish later in the growing season, the nitrogen applied to the crop must be substantially reduced. Blending or changing supplies during the later more critical growth stages should be helpful. Another option is to plant a less sensitive crop, such as maize, which can utilize the nitrogen from the irrigation water more effectively. For crops irrigated with water containing nitrogen, the rates of nitrogen fertilizer supplied to the crop can be reduced by an amount very nearly equal to that available from the water supply. Crop rotations can be planned to utilize residual nitrogen in the soil during the non-irrigation season. This may also be helpful in reducing the impact in succeeding years.

Less than 5 mg/l N has little effect, even on nitrogen sensitive crops, but may stimulate nuisance growth of algae and aquatic plants in streams, lakes, canals and drainage ditches. Very rapid growth of algae can occur when temperature, sunlight and other nutrients are optimum, and may result in plugged valves, pipelines and sprinklers requiring either mechanical controls such as screens and filters, or chemical control, with materials such as copper sulphate. Nitrogen in water also increases maintenance costs for clearing vegetation from canals and drainage channels.

Denitrification to remove NO_3-N from the water supply before use may be the only other alternative but is not used because of the high cost of equipment and energy. Since nitrogen is a valuable resource it should be utilized if possible.

5.2 ABNORMAL pH

pH is an indicator of the acidity or basicity of a water, but is seldom a problem by itself. The main use of pH in a water analysis is for detecting an abnormal water. The normal pH range for irrigation water is from 6.5 to 8.4. An abnormal value is a warning that the water needs further evaluation. Irrigation water with a pH outside the normal range may cause a nutritional imbalance or may contain a toxic ion.

Low salinity water (ECw $<$ 0.2 dS/m) sometimes has a pH outside the normal range since it has a very low buffering capacity. This should not cause undue alarm other than to alert the user to a possible imbalance of ions and the need to establish the reason for the adverse pH through full laboratory analysis. Such water normally causes few problems for soils or crops but is very corrosive and may rapidly corrode pipelines, sprinklers and control equipment.

Any change in the soil pH caused by the water will take place slowly since the soil is strongly buffered and resists change. An adverse pH may need to be corrected, if possible, by the introduction of an amendment into the water, but this will only be practical in a few instances. It may be easier to correct the soil pH problem that may develop rather than try to treat the water. Lime is commonly applied to the soil to correct a low pH and sulphur or other acid material may be used to correct a high pH. Gypsum has little or no effect in controlling an acid soil problem apart from supplying a nutritional source of calcium, but it is effective in reducing a high soil pH (pH greater than 8.5) caused by high exchangeable sodium.

The greatest direct hazard of an abnormal pH in water is the impact on irrigation equipment. Equipment will need to be chosen carefully for unusual water (see Section 5.8).

5.3 SCALE DEPOSITS

Irrigation water containing a high proportion of slightly soluble salts such as calcium, bicarbonate and sulphate presents a continual problem of white scale formation on leaves or fruit when sprinklers are used. Although there is no toxicity involved, the deposits often build up on the leaves and fruit and are of special concern when flowers, vegetables or fruits are grown for the fresh market. The deposit reduces the marketability of fruit and foliage and, in the case of fruit like apples and pears, requires an expensive treatment (acid wash) before marketing. (Small drip emitters are also subject to deposits accumulating near small openings, resulting in clogging. This clogging problem is covered in Section 5.7.)

The principal problem is caused by calcium in combination with bicarbonate and occasionally with sulphate (gypsum). Deposits form even at very low concentrations if sprinklers are used during periods of very low humidity (less than 30 percent), resulting in a high rate of evaporation. Between rotations or cycles of certain sprinkler types, the droplets left on the leaves partially evaporate to concentrate the salts. If the concentration is great enough, the less soluble salts such as lime ($CaCO_3$) and gypsum ($CaSO_4$) will precipitate and once precipitated will not readily re-dissolve during subsequent wettings as the sprinkler rotates. Deposits then begin to build up. These may become a serious problem with certain water when newer types of sprinkler systems are used that apply light, frequent applications or have high pressure which presents a hazard from drift to adjacent areas.

Management options to prevent or correct a deposit problem will depend upon the concentration and the irrigation method. One technique is to add an acid material to the water supply to reduce the bicarbonate, which should in turn reduce the lime precipitate. This has been used for special ornamental and foliage crops grown in the greenhouse. One recommendation has been to add sulphuric acid to 90 percent of the HCO_3 equivalent (personal communication, Rhoades 1976). The acidifying effects of sulphuric acid are immediate, but the acid is difficult and hazardous to handle and application is normally made on a contract basis by experienced people. With the high level of skill needed for application, such an operation will most likely be costly and restricted to high income crops. As with any acid material, the low pH may cause damage to pipelines, sprinklers and other equipment, and careful choice of resistant materials will be necessary or pH must be carefully controlled. A pH not less than pH 6.5 seems to be safe for sprinklers.

An alternative approach might be to change the design and operation of the sprinkler system. This will probably not solve the problem but may minimize it so as to make the product more marketable. The same steps taken to reduce toxicity effects (leaf absorption) due to sprinkler irrigation will also reduce deposits on leaves and fruit (see Section 4.3). The most useful measures are:

- irrigate at night

- increase the speed of sprinkler rotation or use spray heads

- decrease the frequency of irrigation.

These management steps may reduce the problem but they must be cost efficient. Under some circumstances, it may be more economical to change to an alternative form of irrigation which keeps the water off fruit and foliage.

5.4 MAGNESIUM PROBLEMS

Soils containing high levels of exchangeable magnesium are often thought to be troubled with soil infiltration problems. The role of magnesium in causing or partly causing these problems is not well documented but researchers from several irrigated areas have studied the problem. At present there is reasonably good agreement that magnesium acts on soils in a way which is more like calcium than sodium, and that it is preferentially adsorbed by the soil to a much greater degree than sodium but to a slightly less degree than calcium.

In a magnesium dominated water (ratio of Ca/Mg < 1) or a magnesium soil (soil-water ratio of Ca/Mg < 1), the potential effect of sodium may be slightly increased. In other words, a given SAR value will show slightly more damage if the Ca/Mg ratio is less than 1. The lower the ratio, the more damaging is the SAR. Research findings show that at a given SAR of the applied water, a higher soil ESP than normal will result when using a water with a Ca/Mg ratio less than 1 (Rahman and Rowell 1979).

One concern, however, is that productivity is sometimes reported to be low on high magnesium soils or on soils being irrigated with high magnesium water even though infiltration problems may not be evident. The effect may be due to a magnesium-induced calcium deficiency caused by high levels of exchangeable magnesium in the soil. Some research evidence shows that yields of crops such as barley, wheat, maize and sugarbeets are reduced when the Ca/Mg ratio in soil-water is less than one. The function of calcium in plants is not totally understood, but calcium appears to reduce possible toxicities due to other ions (Na, Mg) in the root environment. If the Ca/Mg ratio is near or less than 1, the uptake and translocation of Ca from soil-water to the above-ground parts of the growing crop is diminished due to antagonistic effects of high magnesium or competition for absorption sites to such an extent that less calcium is absorbed. A calcium deficiency may then be experienced at a higher calcium concentration in the applied water or in soil-water than would occur if the Ca/Mg ratio were higher. Although not definitely confirmed, it can be anticipated that irrigation water with a similar ratio (Ca/Mg < 1) will produce a similar effect if a readily available source of calcium is not present in the soil.

Other limited research indicates that the ratio of calcium to total cations in the soil-water may also be critical. A calcium to total cation ratio of 0.10 - 0.15 or greater has been mentioned as needed for optimum root growth of barley and cotton.

There are insufficient data to make either the Ca/Mg ratio or the calcium to total cation ratio an evaluation factor when judging the suitability of a water for irrigation, but if an irrigation water is being used that has a Ca/Mg ratio less than one, or a calcium to total cation ratio less than 0.15, a further evaluation is needed. Although no conclusive recommendations can be made, such water may pose a potential problem related to plant nutrition and an evaluation may be needed to determine if a readily available source of soluble calcium exists in the soil or whether further studies are needed to determine if calcium should be added as a fertilizer or soil amendment.

Additional references include: Paliwal and Gandhi (1976); Koenigs and Brinkman (1964); Howard and Adams (1965); Simpson **et al.** (1979); Carter and Webster (1979); Ulrich and Mostafa (1976); Fong and Ulrich (1970).

5.5 TRACE ELEMENTS AND THEIR TOXICITY

5.5.1 Natural Occurrence in Water

Trace elements occur in almost all water supplies but at very low concentrations, usually less than a few mg/l with most less than 100 micrograms per litre (µg/l). They are not often included in a routine analysis. Surface water normally contains lower concentrations than groundwater, but this is variable and no general guidelines can be given. As a rule of thumb, irrigation water supplies do not need to be checked for trace elements unless there is some reason to suspect toxicity. In almost all cases where trace elements are at high levels, they are the result of man's activities, particularly wastewater disposal. Any project using wastewater should check for trace elements.

5.5.2 Toxicities

Not all trace elements are toxic and in small quantities many are essential for plant growth (Fe, Mn, Mo, Zn). However, excessive quantities will cause undesirable accumulations in plant tissue and growth reductions. There have been few field experiments from which toxic limits could be established, especially for irrigation water. However, research dealing with disposal of wastewater has gained sufficient experience to prove useful in defining limitations. It is now recognized that most trace elements are readily fixed and accumulate in soils, and because this process is largely irreversible, repeated applications of amounts in excess of plant needs eventually contaminate a soil and may either render it non-productive or the product unusable. Recent surveys of wastewater use have shown that more than 85 percent of the applied trace element accumulates in the soil and most accumulates in the surface few centimetres (Figure 23). Although plants do take up the trace elements, the uptake is normally so small that this alone cannot be expected to reduce appreciably the trace element in the soil in any reasonable period of time.

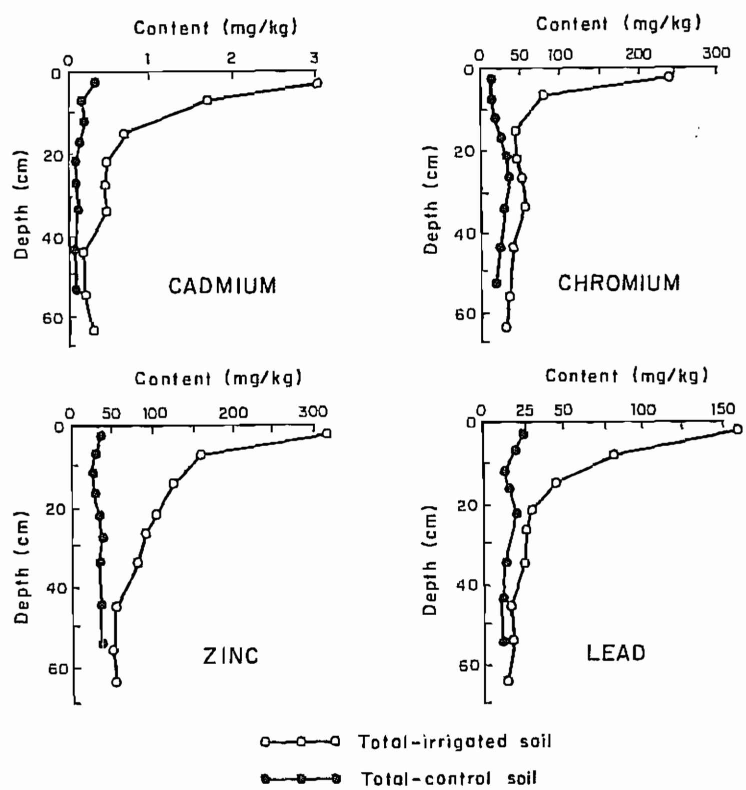


Fig. 23

Heavy metal content of the soil profile after 80 years of irrigation with wastewater (Evans, Mitchell and Salau 1979)

Table 21 RECOMMENDED MAXIMUM CONCENTRATIONS OF TRACE ELEMENTS IN IRRIGATION WATER [1]

Element		Recommended Maximum Concentration [2] (mg/l)	Remarks
Al	(aluminium)	5.0	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
As	(arsenic)	0.10	Toxicity to plants varies widely, ranging from 12 mg/l for Sudan grass to less than 0.05 mg/l for rice.
Be	(beryllium)	0.10	Toxicity to plants varies widely, ranging from 5 mg/l for kale to 0.5 mg/l for bush beans.
Cd	(cadmium)	0.01	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/l in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co	(cobalt)	0.05	Toxic to tomato plants at 0.1 mg/l in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr	(chromium)	0.10	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on its toxicity to plants.
Cu	(copper)	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/l in nutrient solutions.
F	(fluoride)	1.0	Inactivated by neutral and alkaline soils.
Fe	(iron)	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Li	(lithium)	2.5	Tolerated by most crops up to 5 mg/l; mobile in soil. Toxic to citrus at low concentrations (<0.075 mg/l). Acts similarly to boron.
Mn	(manganese)	0.20	Toxic to a number of crops at a few-tenths to a few mg/l, but usually only in acid soils.
Mo	(molybdenum)	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Ni	(nickel)	0.20	Toxic to a number of plants at 0.5 mg/l to 1.0 mg/l; reduced toxicity at neutral or alkaline pH.
Pd b	(lead)	5.0	Can inhibit plant cell growth at very high concentrations.
Se	(selenium)	0.02	Toxic to plants at concentrations as low as 0.025 mg/l and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element to animals but in very low concentrations.
Sn Ti W	(tin) (titanium) (tungsten)	——	Effectively excluded by plants; specific tolerance unknown.
V	(vanadium)	0.10	Toxic to many plants at relatively low concentrations.
Zn	(zinc)	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine textured or organic soils.

[1] Adapted from National Academy of Sciences (1972) and Pratt (1972).

[2] The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10 000 m^3 per hectare per year). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates less than 10 000 m^3 per hectare per year. The values given are for water used on a continuous basis at one site.

5.5.3 Evaluation Criteria

With the high retention rate in the soil and the low use by plants, ideally the maximum application rate should not exceed that which will allow normal crop growth and still not exceed any allowable concentration in the produce coming from the field. Suggested maximum concentrations of trace elements in irrigation water are shown in Table 21. These concentrations are set because of concern for long-term build-up of trace elements in the soil and for protection of the agricultural soil resource from irreversible damage. Under normal irrigation practices, these suggested levels should prevent a build-up that might limit future crop production or utilization of the product. Whether wastewater is used as all or only a part of the supply will not modify these guidelines as they are based on protection of the soil resource to assure its present and future production capability.

The guidelines reflect the current information available but as they are supported by only limited, long-term field experience, they are necessarily conservative, which means that, if the suggested limit is exceeded, a phytotoxicity still may not occur. The suggested limits in Table 21 are to ensure that the site can be used for all potential crops in the future. It is recommended that the values be considered as the maximum long-term average concentration based upon normal irrigation application rates. When more reliable data become available, the levels may be adjusted. If water above or close to the levels given in Table 21 is considered for use, an up-to-date review of more recent information is suggested to prevent possible future problems.

5.6 NUTRITION AND WATER QUALITY

Water quality has been discussed in this paper based upon four different effects on crops or soils: salinity, reduced water infiltration, toxicity, or effects related to a group of miscellaneous water constituents. These effects sometimes cause nutritional imbalances or interactions which result in nutritional imbalances.

5.6.1 Nutrition and Salinity

Excessive salinity stunts the crop by reducing the availability of soil-water, slowing crop growth and restricting root development. With higher salinity water, sodium and chloride toxicity are also likely to be evident. As long as the crop is well supplied with fertilizer elements, application of extra nutrients to combat the salinity effects will not improve yield. However, if nutrients such as nitrogen are in short supply, raising the nutrient level will usually improve yield. Saline areas in the field are normally dark green to blue-green, indicating that they are well supplied with nitrogen. If yellow, additional nitrogen should improve yield.

Most fertilizers, however, are water soluble salts and placement and rates of use must take into consideration their potential salinity impact. (See Table 9 for relative salinity of representative fertilizers.)

Plant tissue analysis for an annual crop is useful to confirm the presence or absence of a calcium deficiency. For example, with potato, petioles or leaf material from the most recent fully-formed leaves are normally used. Calcium (dry weight basis) below 0.15 percent is probably indicative of a calcium deficiency, while values in the range of 0.15 to 0.20 percent may be suspect. Table 11 may also be used to predict a probable calcium deficiency through the Cax value. Cax values less than about 1 me/l are often associated with deficiency.

The ratio of Ca/Mg or calcium to total cations (Ca/TC) in the soil-water may also be used to predict a potential calcium deficiency. There are reports that Ca/Mg ratios less than 1 or Ca/TC less than 0.15 are sometimes associated with calcium deficiencies (Ca, Mg and TC in me/l) (see Section 5.4).

5.6.2 Water Infiltration Problems and Nutrition

A severe reduction in water infiltration rate due to water quality is usually related to either very low water salinity or to a high sodium adsorption ratio (SAR). In either case, the calcium content of the water may be at a relatively low concentration. If the calcium in the soil-water taken up by the crop is less than 2 me/l, there is a strong probability that the crop yield will be reduced due to a calcium deficiency (Rhoades 1982). A potential evaluation technique is to use the Cax values in Table 11 to prevent a possible calcium deficiency. Irrigation water for which a predicted equilibrium soil-water calcium (Cax) is less than 0.7 me/l at LF = 0.15 or is less than 1.0 me/l at LF = 0.30 may result in a calcium deficiency. In such cases, calcium fertilization using granular gypsum or a calcium source included in the fertilizer mix to supply calcium may restore production potential.

Iron chlorosis in susceptible crops (maize, sorghum, Sudan grass, and a few others) is sometimes caused by water with a relatively high sodium adsorption ratio (SAR >6) and can often be corrected by repeated sprays of ferrous iron or iron chelate, or by using soil sulphur or gypsum to maintain soil pH less than 8.5 or, as with Sudan grass, withholding of water (delayed irrigation) for several days may improve aeration and correct the chlorosis.

Zinc deficiency of paddy rice, too, has been associated with sodic soils and a high soil pH (pH > 8.5). In other cases, zinc deficiency has been attributed to a high bicarbonate level in the applied water ($HCO_3 > 2.0$ me/l) (see Section 5.6.3).

If soils become waterlogged and temporarily flooded due to a reduced water infiltration rate for even short periods of a few days, and if they lack good aeration, much of the nitrate-nitrogen present may be quickly denitrified and lost from the soil to the atmosphere as N_2 gas. In such cases, the crop may soon show yellowed areas indicating depleted nitrogen and will benefit from added fertilizer nitrogen.

5.6.3 Nutrition and Toxicity

Sodium, chloride or boron from the irrigation water, taken up by the crop with the soil-water, gradually accumulate in the leaves. If these toxic ions accumulate to excessive concentrations, they cause chlorosis, bronzing and leaf burn (necrosis) primarily at the leaf top, leaf edges and, in more severe cases, symptoms may extend between the veins from the leaf edges toward the mid-leaf area.

Leaf necrosis caused by boron can sometimes be severe enough to reduce markedly the total leaf surface available for photosynthesis. For tree crops such as citrus, if boron accumulation threatens to reduce total leaf area appreciably, extra nitrogen fertilization has been applied to stimulate additional vegetative growth to counteract this effect.

In the case of sodium and chloride toxicities, reliance is placed upon selection of cultivars and rootstocks more tolerant to sodium or chloride. Additional fertilization does not appear to be effective.

Bicarbonate, although not ordinarily thought to be a toxic ion, is reported to cause zinc deficiency in rice. Bicarbonate in excess of 2 me/l in the water used for flooding and growing paddy rice is reported to cause severe zinc deficiency (Mikkelson 1983). This can be remedied by adding zinc to soil before flooding or at the time of earliest appearance of the chlorosis. Actual zinc of 8 to 10 kg/ha from zinc oxide or zinc sulphate is surface applied to remain in the upper 5 to 10 cm of soil.

5.6.4 Miscellaneous

Nitrogen in the applied irrigation water is generally beneficial to most crops but may cause problems for some. Nitrogen in the irrigation water is readily available and if present should be considered as an important part of the fertilizer programme. For most crops, this nitrogen is equivalent to fertilizer nitrogen and should be included in the total nitrogen planned for application. For a few crops, however, the added nitrogen from the water may be too much and result in excessive and vigorous growth, delayed or uneven maturity, and reduced quality. These sensitive crops include apricots, grapes, sugarbeets and cotton, but there are probably others.

In such cases, the stimulating nitrogen can be reduced by applying less water: apply the minimum depth required to supply the crop water demand. If water applied nitrogen is still excessive, irrigate to cause a moderate but increasing water stress as the crop approaches maturity.

Soils high in magnesium or high magnesium water may cause a calcium-induced nutritional deficiency. This is discussed in Section 5.4.

5.7 CLOGGING PROBLEMS IN LOCALIZED (DRIP) IRRIGATION SYSTEMS

A localized (drip) irrigation system is designed to deliver a very low rate of water application to the plant. Understandably, the water must pass through very small openings or emitters which invite clogging problems. A completely blocked opening is easily noticed, but a partially clogged one is very difficult to detect. Detection of partial clogging might involve measuring the delivery of each opening which would be an endless task. Plugging results in decreased uniformity of application and higher operational costs due to increased labour requirements to detect and correct it. Plugging can be prevented if the system is properly planned and designed. Installation of proper equipment to prevent clogging at the beginning is usually less expensive than to try to correct the problem afterwards. Recognizing potential problems beforehand should, therefore, carry a high priority. References include: Nakayama (1982); Vermeiren and Jobling (1980); Bucks **et al.** (1979); Ford and Tucker (1974).

The potential for clogging problems is often related to water quality. The principal physical, chemical and biological contributors to clogging problems are summarized in Table 22. Often these factors are interrelated and the severity can be worsened by a combination; for example, bacterial slime growths inside distribution and emitter lines may cause further plugging when flow is reduced and suspended particles stick to the slime growths.

Table 22 PHYSICAL, CHEMICAL AND BIOLOGICAL CONTRIBUTORS TO CLOGGING OF LOCALIZED (DRIP) IRRIGATION SYSTEMS AS RELATED TO IRRIGATION WATER QUALITY[1]

PHYSICAL (Suspended Solids)	CHEMICAL (Precipitation)	BIOLOGICAL (Bacteria and algae)
1. Sand	1. Calcium or magnesium carbonate	1. Filaments
2. Silt	2. Calcium sulphate	2. Slimes
3. Clay	3. Heavy metal hydroxides, oxides, carbonates, silicates and sulphides	3. Microbial depositions: (a) Iron (b) Sulphur (c) Manganese
4. Organic matter	4. Fertilizers (a) Phosphate (b) Aqueous ammonia (c) Iron, zinc, copper, manganese	4. Bacteria
		5. Small aquatic organisms: (a) Snail eggs (b) Larva

[1] Adapted from Bucks **et al.** (1979).

It is recommended that a complete water analysis be conducted before a system is designed in order to allow for treatment to improve water quality before it reaches the small openings. It should be kept in mind that there can be large fluctuations in water quality during a single irrigation cycle, especially if surface water is used. Therefore, a series of analyses should be taken. This series will disclose water quality variations and also indicate how particular pieces of equipment will perform during certain times of the year.

The analysis needed will vary with each situation but localized irrigation systems are expensive and the cost of analysis is so small compared to the total investment that all the standard tests in Table 23 should be completed.

Table 23 STANDARD WATER QUALITY TESTS NEEDED FOR DESIGN AND OPERATION OF LOCALIZED (DRIP) IRRIGATION SYSTEMS

1. Major Inorganic Salts (see Table 2)	8. Micro-organisms
2. Hardness[1]	9. Iron
3. Suspended Solids	10. Dissolved Oxygen
4. Total Dissolved Solids (TDS)[1]	11. Hydrogen Sulphide
5. BOD (Biological Oxygen Demand)	12. Iron Bacteria
6. COD (Chemical Oxygen Demand)	13. Sulphate Reducing Bacteria
7. Organics and Organic Matter	

[1] A calculated value from analyses included in Table 2.

For surface water, particular attention should be given to tests 1-4 as the major problems usually occur from suspended material or chemical deposits. It is recommended, however, that tests 5-8 be included as a check, especially if wastewater is suspected in the water supply. When groundwater is used, tests 1-4 and 9-13 are considered to be a minimum, especially if ECw >1.0 dS/m.

There is not enough experience with localized (drip) irrigation systems to predict with precision if or when clogging problems will occur with a given water. Experience gained so far, however, does allow us to prepare a relative scale for situations when clogging problems may occur due to water quality. Table 24 presents a first approximation of potential problems but should not be used to provide firm criteria; rather, situations which indicate slight to severe potential for restrictions may need a testing programme to determine the economics of solutions that must be considered. A rating of no restriction may also develop a problem but the costs of solving the problem are usually within the capability of irrigated agriculture.

Table 24 INFLUENCE OF WATER QUALITY ON THE POTENTIAL FOR CLOGGING PROBLEMS IN LOCALIZED (DRIP) IRRIGATION SYSTEMS[1]

Potential Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Physical				
Suspended Solids	mg/l	< 50	50 - 100	> 100
Chemical				
pH		< 7.0	7.0 - 8.0	> 8.0
Dissolved Solids	mg/l	< 500	500 - 2000	> 2000
Manganese[2]	mg/l	< 0.1	0.1 - 1.5	> 1.5
Iron[3]	mg/l	< 0.1	0.1 - 1.5	> 1.5
Hydrogen Sulphide	mg/l	< 0.5	0.5 - 2.0	> 2.0
Biological				
Bacterial populations	maximum number/ml	<10 000	10 000 - 50 000	>50 000

[1] Adapted from Nakayama (1982).

[2] While restrictions in use of localized (drip) irrigation systems may not occur at these manganese concentrations, plant toxicities may occur at lower concentrations (see Table 21).

[3] Iron concentrations >5.0 mg/l may cause nutritional imbalances in certain crops (see Table 21).

The chief cause of clogging is solid particles in suspension, but this is also the easiest problem to solve. Suspended particles are most frequent in surface water but can also occur in groundwater from sand and silt pumped from wells. Suspended particles consist of soil particles of different sizes, lime carbonates, solid material washed into canals, algae, and eroded material from reservoirs. Particles heavier than water can be filtered or settled out. The oldest and cheapest method is sedimentation but this may not provide the consistent quality needed. Filtration is more reliable and consists of screening or passage through a suitable medium, normally graded sand. Screening alone is not adequate to prevent clogging in all cases, as small particles may still get through the screens. Various screening materials and filters are available as well as new emitter designs, some of which are self-cleaning and these greatly reduce the plugging hazard.

Another cause of clogging is chemical precipitation of materials such as lime ($CaCO_3$) and phosphates ($Ca_3(PO_4)_2$). Normally this is gradual and difficult to locate. High temperatures or high pH are usually part of the precipitation problem. Precipitation can result from an excess of calcium or magnesium carbonates and sulphates, or from iron which is in the ferrous form but when in contact with oxygen is oxidized to the insoluble ferric form (reddish-brown precipitate).

The tendency of a water to cause calcium precipitation can be predicted although there is no proven practical method to evaluate how serious the problem will be since it depends upon many factors. A first approximation of the calcium precipitation can be made using the saturation index of Langelier which simply says that upon reaching the calcium saturation point in the presence of bicarbonate, lime ($CaCO_3$) will precipitate from the solution. The saturation index is defined as the actual pH of the water (pHa) minus the theoretical pH (pHc) that the water could have if in equilibrium with $CaCO_3$.

$$\text{Saturation Index} = \text{pHa} - \text{pHc} \qquad (18)$$

Positive values of the index (pHa > pHc) indicate a tendency for $CaCO_3$ to precipitate from the water whereas negative values indicate that the water will dissolve $CaCO_3$. The value of pHa is obtained from laboratory data, while pHc is estimated using the procedures described in Table 25. All water having positive values should be considered as potential problem water for use through drip systems and the need for preventative measures should be considered in design. For example, an irrigation water with a measured pH of 7.7, Ca = 3.65 me/l, HCO_3 = 3.80 me/l and total salts of 8.23 me/l (Ca + Mg + Na) will have a theoretical pH of 7.4, giving a saturation index of +0.3, which indicates a possibility of carbonate (lime) precipitation. This may or may not result in a plugging problem but if the pH is adjusted to 7.0 by acid addition, the saturation index becomes -0.4 and carbonate precipitation should not occur. From Table 24, a problem is much more likely at a measured pH greater than pH = 8.0; this is the pH of water close to equilibrium with finely ground limestone ($CaCO_3$).

Iron is more difficult to evaluate for its clogging potential as it is frequently a contributor to other problems, especially those of iron bacterial slime. The limitation given in Table 21 of 5 mg/l should be considered a maximum for drip irrigation systems but, in practical terms, a value above 2.0 may be near maximum since filtration costs become excessive above this limit. A concentration of 0.5 mg/l should be considered a potential problem if tannin-like compounds (often in acid waters) or total sulphides exceed 2 mg/l. The combination of the two normally produces undesirable slime growths.

To prevent iron precipitation in lines or at the emitters iron should be precipitated and filtered out before it enters the irrigation system. In order to filter out the iron, it must first be oxidized to the insoluble form, usually by chlorination, to a residual of 1 mg/l chlorine. An alternative method is aeration in an open pond or by injection of air into the water supply by mechanical means. This causes oxidized iron to precipitate. Then it can be filtered and removed before the water enters the irrigation line. Both are expensive and difficult processes and the practicality of treatment plus filtering should be evaluated.

The most effective method of preventing problems caused by precipitation of calcium carbonate is to control the pH or to clean the system periodically with an acid in order to prevent deposits building

Table 25 PROCEDURE FOR CALCULATION OF pHc[1,2]

$$pHc = (pK_2 - pKc) + pCa + p(Alk)$$

$pK_2 - pKc$ is obtained from the concentration of Ca + Mg + Na in me/l
pCa is obtained from the Ca in me/l
p(Alk) is obtained from the concentration of $CO_3 + HCO_3$ in me/l
} Obtained from the water analysis

Concentration (me/l)	$pK_2 - pKc$	pCa	p(Alk)
0.05	2.0	4.6	4.3
0.10	2.0	4.3	4.0
0.15	2.0	4.1	3.8
0.20	2.0	4.0	3.7
0.25	2.0	3.9	3.6
0.30	2.0	3.8	3.5
0.40	2.0	3.7	3.4
0.50	2.1	3.6	3.3
0.75	2.1	3.4	3.1
1.00	2.1	3.3	3.0
1.25	2.1	3.2	2.9
1.50	2.1	3.1	2.8
2.00	2.2	3.0	2.7
2.50	2.2	2.9	2.6
3.00	2.2	2.8	2.5
4.00	2.2	2.7	2.4
5.00	2.2	2.6	2.3
6.00	2.2	2.5	2.2
8.00	2.3	2.4	2.1
10.00	2.3	2.3	2.0
12.50	2.3	2.2	1.9
15.00	2.3	2.1	1.8
20.00	2.4	2.0	1.7
30.00	2.4	1.8	1.5
50.00	2.5	1.6	1.3
80.00	2.5	1.4	1.1

[1] Procedure from Nakayama (1982).

[2] pHc is a theoretical, calculated pH of the irrigation water.

up to levels where clogging might occur. A common practice among those with problems is to inject hydrochloric (muriatic) or sulphuric acid into the system periodically. The system may need to be flushed as often as once a week.

The acid can be added to the system on a continuous basis if the problem is severe enough but this is expensive and difficult and the acid is dangerous to handle. It is recommended that acid be added at a rate to maintain pH close to but not lower than pH 6.5. Sulphur burners have also been used to acidify the supply water for drip irrigation. The SO_2 formed is put into the irrigation water by means of water spray scrubbers that form H_2SO_3 and H_2SO_4 acidified solutions.

If fertilizers are injected into the irrigation water, possible precipitation due to water chemistry must be considered. For example, if calcium (Ca) concentration is greater than 6 me/l, most phosphorus fertilizers will cause clogging of emitters. Clogging is more severe if bicarbonates are high (>5 me/l). Anhydrous or liquid ammonia should not be applied through these systems as the ammonia can increase pH of the water to values above 11 and cause rapid precipitation of $CaCO_3$ which clogs the entire system.

Many cases of clogging have occurred from biological growths inside the irrigation lines and openings. These are caused by small quantities of micro-organisms such as algae, slimes, fungi, bacteria, snails, and miscellaneous larvae. These problems are difficult to evaluate and prevent since they are affected by a number of factors. Such problems occur when the water contains organics and iron or hydrogen sulphide. One of the most severe forms of clogging is caused by a white, gelatinous sulphur slime associated with sulphur bacteria. Another common one is the brown slime mass caused by filamentous iron bacteria. These grow rapidly in water containing as low as 0.4 me/l iron and are especially troublesome in water containing soluble dark, tannin-like organics which act as a readily available food source for the bacteria. Algae and other growths can cause problems especially if their growth rates are enhanced by excess nutrient levels (nitrogen or phosphorous). The use of wastewater in localized (drip) irrigation systems would be especially troublesome since effluents normally contain nutrients, dissolved organics, and micro-organisms, all of which may increase the potential for clogging problems.

Chemical treatment (chlorine) is one of the most effective methods for controlling biological growths but is costly and requires close and careful management to use safely. Chlorine kills the organism, oxidizes the organic matter and may require filtering or flushing of the system to clear the organic matter. Continuous chlorine injection is an excellent method but may be too expensive for most agricultural use. Its efficiency is related to the pH of the water, with more chlorine required at higher pH. Table 26 gives examples of typical chlorine dosages used in localized (drip) irrigation systems to inhibit microbial growth, slime and bacterial development.

Table 26 CHLORINE DOSAGES FOR CONTROL OF BIOLOGICAL GROWTHS [1]

Problem	Dosage
Algae	0.5-1.0 mg/l continuous or 20 mg/l for 20 minutes
Hydrogen Sulphide	3.5-9.0 times the hydrogen sulphide content (mg/l)
Iron Bacteria	1.0 mg/l but varies with bacterial count
Slimes	0.5 mg/l continuous

[1] Data from Vermeiren and Jobling (1980).

5.8 CORROSION AND ENCRUSTATION

5.8.1 Metal Corrosion

Most corrosion and encrustation problems are associated with groundwater. Groundwater varies significantly in composition from one area to another but most types are at least mildly corrosive to iron and some will severely attack it and even affect more resistant metals. Corrosion is basically an electrolytic process which attacks and dissolves away a metal surface. The rate at which corrosion proceeds depends upon a variety of chemical equilibrium reactions as well as upon certain physical factors such as velocity, temperature and pressure. Most corrosion problems are associated with low salinity water; most encrustation problems are associated with higher salinity groundwater.

Other types of groundwater may cause unusual amounts of organic and inorganic materials to be deposited on equipment and in wells. These deposits may restrict water passage in well screens, pipelines, and outlets. Although an endless variety of dissolved and suspended solids can cause such effects, the more common ones are sand, silt, carbonate deposition, iron, and biological growths.

Corrosion and encrustation processes are complex and interactive. For this reason, no single test or index is an infallible indicator of the potential life of equipment. Nevertheless, certain accelerated performance tests and chemical indicators have proved to be of considerable value in planning equipment needs and evaluating performance. Considering the high cost of well construction and irrigation equipment, it is desirable to apply all known indicator tests and to use the most conservative (safest) in planning for full-scale development. Because of the varying nature of the tests, it is suggested that reputable reference guides be used to make the appraisal. One of the latest guides is Corrosion and Encrustation in Water Wells: A Field Guide for Assessment, Prediction and Control (Clarke 1980). Although this deals with water wells, the predictive tools could also be applicable to irrigation equipment.

5.8.2 Concrete Corrosion

Groundwater and certain surface water supplies can be corrosive to concrete. This corrosion may affect the life of an irrigation canal lining but the most frequent corrosion occurs when groundwater is pumped through a closed concrete pipeline.

There are three general types of corrosion that might result in deterioration in concrete canals and pipelines when they are exposed to a corrosive water:

TYPE I: Leaching corrosion is when lime in concrete is dissolved by low salinity soft water (low carbonate hardness) or by water that contains free carbon dioxide (carbonic acid). This type of corrosion does not do excessive damage to good concrete but can be pronounced in poor quality, porous concrete. The rate of this type of corrosion in dense concrete is very slow to non-existent but can be relatively rapid in jointing materials.

For water containing carbonic acid (H_2CO_3), the pH may vary from 4.5 to 7.9, therefore, pH should not be a sole indicator. A characteristic of low salinity water is that even though the pH may vary between 7.0 and 7.9, the water may still attack concrete. This is because it may be 'lime dissolving' instead of lime depositing. Therefore, it is advisable to check the Langelier Saturation Index of the water (see Section 5.7 and Equation 18). If the saturation index is negative, then some attack on concrete is likely but the rate of attack will be very slow. The Cax values in Table 11 may also indicate a corrosion potential since concrete would be a good source of lime ($CaCO_3$).

TYPE II: Ion exchange corrosion occurs as a result of base exchange reactions between the readily soluble compounds in the hardened cement and the alkaline cations (Ca, Mg, K, NH_4) in the water. The exchange products are then leached or remain in place in the concrete as non-binding components. Magnesium and salts are commonly involved.

TYPE III: Corrosion by expansion occurs from a chemical reaction that results in the formation of compounds which occupy a greater volume than the original cement compounds, thus causing internal stress which ultimately destroys the concrete by swelling. Sulphates are a known cause of this type of corrosion. The sulphates tend to combine with some of the calcium and aluminium compounds in the hardened cement and form calcium aluminate-sulphate or gypsum, which causes the concrete to swell. It should be noted that some sulphates are potentially more aggressive than others; these are magnesium and ammonium sulphates. The increased aggression by $MgSO_4$ and NH_4SO_4 is due to the fact that they decompose the hydrated calcium silicates (Type II corrosion) in addition to reacting with the aluminium and calcium hydroxide in the concrete. The action of ammonium sulphate may be enhanced in the presence of nitrate. Both may be present in water supplies especially if they are receiving industrial wastes or runoff from agricultural land.

As with metals, corrosion processes of concrete are complex, therefore, no single test or index is an infallible indicator. Guidelines have been suggested to estimate the potential of a water to be aggressive against concrete (Table 27). These are relative degrees of aggressivity of water of predominantly natural origin and do not take into account resistance of the concrete to corrosion. The developer of Table 27 suggests that even if only one of the values points to a potential, a further evaluation should be made.

Table 27 LIMIT VALUES FOR EVALUATING THE AGGRESSIVITY OF WATER AND SOIL TO CONCRETE [1]

Test	Intensity of attack			
	None to slight	Mild	Strong	Very Strong
Water				
pH	>6.5	6.5-5.5	5.5-4.5	<4.5
Lime-dissolving carbonic acid (CO_2), mg/l	<15	15-30	30-60	>60
Ammonium (NH_4), mg/l	<15	15-30	30-60	>60
Magnesium (Mg), mg/l	<100	100-300	300-1500	>1500
Sulphate in water (SO_4), mg/l	<200	200-600	600-3000	>3000
Soil				
Sulphate in soil (air-dry) (SO_4), mg/kg	<2000	2000-5000	>5000	

[1] Data taken from Biczok (1972).

Further references include: Biczok (1972); United States Bureau of Reclamation (1975); Taylor (1977); and Perkins (1981).

5.9 VECTOR PROBLEMS ASSOCIATED WITH WATER QUALITY

In most countries where there is a risk to health from vector-borne diseases such as malaria, lymphatic filariasis, encephalitis, onchocerciasis, schistosomiasis, there is an awareness of the possibility that water development projects may have an impact on vector populations and human health. This is particularly true of irrigation schemes, which tend to increase opportunities for human/water/vector contact in addition to their creation of habitats well suited to vector production. Even in the absence of an associated disease, a similar problem may arise in relation to nuisance species of insects which cause personal discomfort and can be extremely disruptive of community life, work and leisure activities.

The existence of an aquatic environment is usually the primary cause of these problems, and there is ample literature on vector control through chemical, biological and environmental management methods. However, there is less information on the relationships between water quality and vector production although quality aspects may often intensify a vector problem and may even create the physical conditions leading to the problem.

Put simply, the ideal conditions for good irrigation management are similar to those which will discourage vector production in irrigated agriculture or will at least assist in vector control. This implies a minimum of unnecessary water surface, well constructed and maintained supply channels, effective, unimpeded drainage of excess water and efficient, economical water application. When the quality of irrigation water causes a departure from these conditions, there is increased risk of vector production.

There are four ways in which water quality may affect the size and species composition of the populations of disease vectors and nuisance insects:

- by creating soil conditions which extend water surfaces in area, or in duration;
- by requiring irrigation practices which also result in the extension of water surfaces in area, or duration;
- by modification of the aquatic flora or fauna; and
- by direct influence on the vector.

Adverse soil conditions, with low rates of infiltration, may arise when the irrigation water has very low salinity or a high sodium content relative to the calcium and magnesium content. This has the obvious effect of extending the time when irrigation water is standing in the field and also results in longer periods of stagnant water, following rainfall, outside the irrigation season. Where the intensity of land use under irrigation is relatively low, this may mean that the exposed water surface is even greater than the irrigated area and that the period of standing water is sufficient for a number of breeding cycles of vector and pest insects or for the proliferation of populations of snail intermediate hosts necessary for the development and multiplication of schistosome larvae.

When salinity is high, it may be necessary to supply irrigation at very short intervals so that the soil surface is often wet, and depressions will always contain water. When salt accumulation must be corrected by leaching, this may call for the ponding of water in the field for periods of many days. In either case, with an inevitable carry-over period to complete drainage or drying out of low spots, there may be sufficient time for completion of the aquatic part of the mosquito life cycle (usually within two weeks under tropical conditions) and the production of a new generation of adults.

A problem which most commonly affects agricultural drains is that of growth stimulation of aquatic weeds due to excess nitrogen from fertilizers. This can also occur in irrigation canals where there is a mixing of the supply with agricultural runoff or with wastewater from domestic or food-processing sources. The associated issues of weed clearance and channel maintenance have been referred to earlier, but the presence of dense aquatic weeds and algal growth also introduces conditions which are suited to the development of some insect vectors, pest insects and snails. In addition, it makes control by chemicals such as larvicides and molluscicides more difficult, more expensive and less effective.

The use of chemicals in vector control and for the control of agricultural pests may be, in itself, a cause of degraded water quality where it creates problems for other water uses. Examples of this can be found in the damage to beneficial aquatic fauna such as fish cultivated for their protein value, deterioration of livestock water supplies and, most dangerous of all, the contamination of domestic water which, in many developing countries, is derived from the irrigation supply with minimum, or no treatment.

The use of domestic wastewater in irrigation can be an attractive way to raise crop yields, but it has been known to result in a dramatic increase in the breeding of mosquitoes. This led to a recent ban on wastewater re-use for rice irrigation in California (see Section 8.22).

Sometimes a change in water quality will have a marked impact on aquatic fauna other than the vector or pest species of primary concern. This can happen when water from different sources is used conjunctively, either by mixing or in sequence. If the affected organisms represent a food supply for the vector, it is likely to discourage the growth of vector populations. On the other hand, if the result is a suppression of species which are natural predators or competitors of the vector, an upsurge of vector populations is likely. In the case of a periodic quality change, as for seasonal groundwater used to supplement low-flow surface supply, the impact may be detrimental to either vector or predator or both. Experience from such examples suggests that vector species tend to be more resilient and to recover more quickly, with consequent progressive increase in their populations.

Direct influence of water quality on vector populations and species distribution is usually related to species preference. For mosquitoes, this ranges from fresh running water to brackish water, salt pools, mineral groundwater, water contaminated with domestic effluent and even to septic tanks and cesspools. Vector mosquitoes can be found within the whole range of these preferences, therefore the assessment of possible water quality impact on mosquito-transmitted diseases calls for a careful study of the actual and potential status of the diseases in the human population, the locally occurring mosquito species and the quality characteristics of the water. These characteristics may in fact vary with season and from place to place, even within a scheme, producing an extremely complex set of circumstances.

Snail intermediate hosts are fairly tolerant to water quality conditions which fall within the range of suitability for irrigation. The presence of calcium is advantageous to the snail whereas a low pH is not. There is often a snail preference for a sediment content and for some organic pollution and, where this latter is due to domestic effluent in the water, the risk of schistosomiasis transmission is evident within endemic areas.

It can be seen that the association between water quality and vector-borne diseases is both complex and specific to the site and the human population. Even the more limited relationship between water quality and the presence and production of vector and pest species is subject to many physical and biological influences. This section has therefore been restricted to a brief outline of some of the general issues to be taken into consideration where there is a possibility of a health problem arising or being modified as a result of water quality characteristics in agricultural development. The subject of disease transmission through the re-use of wastewater is a separate and distinct issue on which there is already extensive literature and for which there are many guidelines and examples of national control and legislation. This has not therefore been included in the present text, but the following list of references contains information and references related to this problem in addition to that of vector-borne diseases. References include: Agency for International Development (1975); Mather (1984); Feachem **et al.** (1977); McJunkin (1982); Tillman (1981); WHO (1973); and WHO (1982).

As a further source of information, the reader may always direct enquiries to the World Health Organization, 1211 Geneva 27, Switzerland.

6. WATER QUALITY FOR LIVESTOCK AND POULTRY

6.1 INTRODUCTION

Irrigation canals frequently serve as sources for livestock drinking water but other sources, including poor quality supplies, are often used. Salinity requirements for irrigation are more restrictive than those for animals but highly saline water or water containing toxic elements may be hazardous to animal health and may even render the milk or meat unfit for consumption. In such cases, providing an alternate good quality supply should minimize the problem.

6.2 USE OF SALINE WATER FOR LIVESTOCK

In the arid and semi-arid regions of the world, livestock commonly use poor or marginal quality drinking water for several months of the year. These supplies originate from small wells, canals, streams or 'water holes', only the better of which are also used for irrigation. Occasionally such water is high in salt which may cause physiological upset or even death in livestock. The main reported effect is depression of appetite, which is usually caused by a water imbalance rather than related to any specific ion. The most common exception is water containing a high level of magnesium which is known to cause scouring and diarrhoea.

In evaluating the usability of any particular water, local conditions and availability of alternate supplies will play an important role, and a number of factors should be considered:

- Water source: Small shallow wells and streams are more likely to become contaminated or produce poor quality water than are the larger wells and flowing streams. Also groundwater is likely to be more chemically imbalanced than surface water.

- Seasonal changes: Marginal quality water may become unsuitable in hot dry periods because of: (a) increases in natural salinity due to evaporation during these periods; (b) increased water consumption by the animal due to the heat and increased intake of dry feed; (c) very high evaporation from stock watering ponds or tanks during these periods with the resulting higher salt concentration; and (d) increased water temperature.

- Age and condition of the animal: Lactating, young and weak animals are normally more susceptible.

- Feed composition: Dry pastures and high protein supplementary feed in place of previously green pastures may reduce the salinity tolerance of the animal due to the lower moisture content of the feed and higher salt content (intake of some feed supplements are purposely controlled by additions of salt to slow consumption).

- Species: Variation in tolerance to water salinity is considerable between animal species.

Considering the above factors and the need to avoid any risk of economic loss, the National Academy of Sciences (1972) established that, from a salinity standpoint, livestock drinking water with an electrical conductivity (ECw) less than 5 dS/m should be satisfactory under almost any circumstances. This recognized that minor physiological upset might occur with water near this limit, but there was

Table 28 WATER QUALITY GUIDE FOR LIVESTOCK AND POULTRY USES [1]

Water Salinity (EC_w) (dS/m)	Rating	Remarks
< 1.5	Excellent	Usable for all classes of livestock and poultry.
1.5 - 5.0	Very Satisfactory	Usable for all classes of livestock and poultry. May cause temporary diarrhoea in livestock not accustomed to such water; watery droppings in poultry.
5.0 - 8.0	Satisfactory for Livestock	May cause temporary diarrhoea or be refused at first by animals not accustomed to such water.
	Unfit for Poultry	Often causes watery faeces, increased mortality and decreased growth, especially in turkeys.
8.0 - 11.0	Limited Use for Livestock	Usable with reasonable safety for dairy and beef cattle, sheep, swine and horses. Avoid use for pregnant or lactating animals.
	Unfit for Poultry	Not acceptable for poultry.
11.0 - 16.0	Very Limited Use	Unfit for poultry and probably unfit for swine. Considerable risk in using for pregnant or lactating cows, horses or sheep, or for the young of these species. In general, use should be avoided although older ruminants, horses, poultry and swine may subsist on waters such as these under certain conditions.
> 16.0	Not Recommended	Risks with such highly saline water are so great that it cannot be recommended for use under any conditions.

[1] Adapted from National Academy of Sciences (1972; 1974).

Table 29 SUGGESTED LIMITS FOR MAGNESIUM IN DRINKING WATER FOR LIVESTOCK [1]

Livestock	Magnesium Concentration (mg/l)	(me/l)
Poultry [2]	< 250	< 21
Swine [2]	< 250	< 21
Horses	250	< 21
Cows (lactating)	250	< 21
Ewes with lambs	250	< 21
Beef cattle	400	33
Adult sheep on dry feed	500	41

[1] Adapted from Australian Water Resources Council (1969).

[2] The tolerance of swine and poultry for magnesium is unknown but could well be less than 250 mg/l.

little chance that economic losses or serious physiological disturbances would occur.

It is often necessary in arid and semi-arid regions to use water which exceeds this recommended limit. While all attempts should be made to stay within the criteria suggested above, there are situations where it will be necessary to use poorer quality water for short or long periods of time. Table 28 gives guidelines for those situations where poorer quality supplies must be used. These guidelines have a small margin of safety but their use probably does not eliminate all risk of economic loss. However, with sound judgement, they should provide a framework within which decisions can be made.

The National Academy of Sciences pointed out that among other things, several key items should be considered when using Table 28. They are:

- animals drink little, if any, highly saline water if low salt content water is available to them;
- unless they have been previously deprived of water, animals can consume moderate amounts of highly saline water for a few days without being harmed;
- abrupt changes from water of low salinity to highly saline water cause more problems than a gradual change;
- depressed water intake is very likely to be accompanied by depressed feed intake.

The guides in Table 28 assume that the effect is from the total salt content (osmotic effect) rather than from any specific toxic ion. The ions largely responsible for water salinity are in themselves not very toxic. However, magnesium is of major concern. Australian standards recommend that it be taken into account, particularly if the ECw exceeds 6.6 dS/m (4000 mg/l) for cattle and 10.0 dS/m (6000 mg/l) for sheep. No actual limits have been established due to varying conditions of use but Table 29 can be used as a guide. Animals using water near or above these values should be watched closely for ill effects.

Tables 28 and 29 are the basic guides for determining the suitability of a particular water supply for drinking water for animals, but local factors, especially effects of evaporation and concentration, must be considered. There may be no alternative to using poor or marginal water for extended periods; therefore, efforts should be directed toward minimizing their effects on animal health.

Animals can subsist for short periods with very poor water. Longer periods will require more careful monitoring but in either case one of the following steps may prove helpful to minimize the problems:

- provide drains or overflows on troughs and tanks to flush them occasionally. This will prevent poor water concentrating further by evaporation;
- provide dilution water if available;
- increase rainfall collection for dilution purposes;
- reduce evaporation losses (various methods available);
- control high water-using vegetation along streams and around holding ponds, or spring sources of water;
- provide settling basins to remove sediment.

6.3 TOXIC SUBSTANCES IN LIVESTOCK WATER

There are a number of substances or toxic ions which cause toxicity in animals. These sometimes occur naturally in water, but more frequently they are a result of man's activities, including waste disposal. Toxic substances in natural water are usually at concentrations well below the toxic levels. If unusually high and toxic levels are found, this often implies the existence of some outside contaminating source such as a wastewater and the use of the water should be restricted until the source of the toxic element is located and reduced or eliminated. The common toxicants include many inorganic elements, organic wastes, pathogenic organisms, and herbicides and pesticides and their residues. These may be directly toxic to the animal, cause the water to be unpalatable, or accumulate in the animal making its edible product unsafe or unfit for human consumption.

The National Academy of Sciences (1972 and 1974) has prepared guidelines on the safe level of many toxic inorganic elements in livestock drinking water. These are presented in Table 30. These guidelines have a wide safety margin. They are based on amounts normally found in usable surface and groundwater and are not necessarily the limits of animal tolerance. This approach is taken since the safe concentration of these substances is dependent upon many factors, including the quantity of water an animal consumes each day and the weight of the animal. The original discussions presented by the National Academy of Sciences publication and other sources should be consulted before using a water of questionable quality.

Table 30 GUIDELINES FOR LEVELS OF TOXIC SUBSTANCES IN LIVESTOCK DRINKING WATER[1]

Constituent (Symbol)	Upper Limit (mg/l)
Aluminium (Al)	5.0
Arsenic (As)	0.2
Beryllium (Be)[2]	0.1
Boron (B)	5.0
Cadmium (Cd)	0.05
Chromium (Cr)	1.0
Cobalt (Co)	1.0
Copper (Cu)	0.5
Fluoride (F)	2.0
Iron (Fe)	not needed
Lead (Pb)[3]	0.1
Manganese (Mn)[4]	0.05
Mercury (Hg)	0.01
Nitrate + Nitrite (NO_3-N + NO_2-N)	100.0
Nitrite (NO_2-N)	10.0
Selenium (Se)	0.05
Vanadium (V)	0.10
Zinc (Zn)	24.0

1 Adapted from National Academy of Sciences (1972).

2 Insufficient data for livestock. Value for marine aquatic life is used here.

3 Lead is accumulative and problems may begin at a threshold value of 0.05 mg/l.

4 Insufficient data for livestock. Value for human drinking water used.

The most common management problems are related to fluoride, iron, nitrate, or hydrogen sulphide. Most of the fluoride problems noted are not actually toxicity; rather, fluoride causes tooth mottling and bone problems. In areas where fluoride water constitutes the sole source of livestock drinking water, attempts should be made to minimize evaporative concentration. If high fluoride water must be used in certain seasons, alternating the exposure of the animal to it will be helpful. An alternative approach would be retention of low fluoride water for the use of young stock since this is the most susceptible age, especially before eruption of the permanent teeth.

Toxicity problems are amplified when the forage used is also irrigated with the same potentially toxic water. The plants take up the salts, thus raising the toxicity risk to the animal when both the sources of feed and water combine to exceed the critical levels. This may also happen with an element such as selenium.

Livestock poisoning by nitrates or nitrites should not occur with levels less than the guideline values. This does not exclude all problems, however, as a high nitrate level may cause heavy growth of algae in watering points. No direct link has been established between heavy algae growths and livestock deaths. Researchers point to the possibility that the sudden decomposition of algae may produce circumstances conducive to the development of botulism. Blue-green algae have also been suggested as containing possible toxins although no concrete evidence is available at present. Care should be taken when animals are using watering points with heavy growths. Copper sulphate is effective in controlling algae growths even at concentrations of 1 mg/l but care and professional advice should be sought before using it, as the solution to one problem could be the start of another.

Not all unusual constituents in animal drinking water are toxic. Some only cause management problems or nuisances. For example, a common problem in using shallow groundwater is the high level of hydrogen sulphide. Although by itself it does not harm the animal, the odour influences the animals to reject the water. A common practice of first running such water down a splash board for aeration has proved very effective, because the greater part of the hydrogen sulphide is dissipated before entering the water trough or tank. Water containing hydrogen sulphide also presents a corrosion problem to watering tanks or equipment due to the formation of sulphuric acid.

No limits for iron are given in Table 30 because it has a low order of toxicity. At watering points, iron is rarely present in the water since, on contact with air, the ferrous salts are oxidized and they precipitate, rendering them essentially harmless to animals. However, even with a few milligrams per litre, iron can cause clogging of lines to watering troughs or an undesirable staining or deposit.

7. IRRIGATION WATER QUALITY AND WASTEWATER RE-USE

Large-scale irrigation projects can bring prosperity to an area but less desirable changes can also occur as a result of increased intensity of land and water use. One important change in the hydrological regime is that of an alteration or degradation in quality that takes place as water is used and re-used within the hydrological basin. In addition, wastewater generated by agricultural and urban sources can degrade water quality and must be considered when developing a river basin management plan.

Agricultural subsurface drainage water presents the single greatest threat to water quality. The need for drainage is often quoted as a mechanism to eliminate the hazards from waterlogging and salinity in irrigated land. A drainage scheme can be implemented for engineering or economic reasons, but in either case the drainage water created by the scheme will contain a high concentration of salts. Careful consideration must be given to its disposal so that the water supplies downstream are not polluted.

The disposal of highly saline drainage water into river courses may need to be controlled in order to meet certain minimum standards of water quality for irrigated agriculture in downstream areas. Changes in downstream agricultural practices may be necessary to adapt to the inferior water quality, or alternative schemes may need to be implemented where the drainage or other wastewater is isolated from the main water supply. Due to the high cost of transporting wastewater to a disposal site (ocean, salt-sink or river discharge), the maximum number of uses of that water should be made before discharge. At that time, disposal must be in such a way that the river-basin water quality is protected and agricultural development is not jeopardized. All wastewater should be used and re-used until no longer fit for use.

Of equal importance when protecting the quality of water supplies that are to be used as a source of irrigation water is the utilization of effluent water from domestic sources or from an agricultural processing activity. Re-using wastewater can remove a potential cause of ground or surface water pollution and, at the same time, release higher quality water for other uses. Rising demands for good quality water for domestic and industrial uses in countries with highly developed economies have already created the necessity to re-use wastewater. Many developing countries are now facing a similar situation, especially in arid and semi-arid regions where limited water availability is already a severe constraint on development.

Agriculture is the major user of water and can accept lower quality water than domestic and industrial users. It is therefore inevitable that there will be a growing tendency to look toward irrigated agriculture for solutions to the overall effluent disposal problem. Because wastewater contains impurities, careful consideration must be given to the possible long-term effects on soils and plants from salinity, sodicity, nutrients and trace elements that occur naturally or are added during use or treatment. These effects are normally manageable if associated problems with these impurities are understood and allowances made for them.

The guidelines presented in Table 1 and crop salinity tolerance values in Table 4 are sufficient to make reliable estimates of soil and crop responses to the use of wastewater where the primary limitation is the chemical constituent, such as the total dissolved salts, relative sodium content and toxic ions. On the other hand, municipal wastewater and some agro-industrial effluents which may be re-used for irrigation

Table 31 EXISTING STANDARDS GOVERNING THE USE OF RENOVATED WATER IN AGRICULTURE

	California	Israel	South Africa	FR Germany
Orchards and vineyards	Primary[1] effluent; no spray irrigation; no use of dropped fruit	Secondary[2] effluent	Tertiary[3] effluent, heavily chlorinated where possible. No spray irrigation	No spray irrigation in the vicinity
Fodder fibre crops and seed crops	Primary effluent; surface or spray irrigation	Secondary effluent, but irrigation of seed crops for producing edible vegetables not permitted	Tertiary effluent	Pre-treatment with screening and settling tanks. For spray irrigation, biological treatment and chlorination
Crops for human consumption that will be processed to kill pathogens	For surface irrigation, primary effluent. For spray irrigation, disinfected secondary effluent (no more than 23 coliform organisms per 100 ml)	Vegetables for human consumption not to be irrigated with renovated wastewater unless it has been properly disinfected (1000 coliform organisms per 100 ml in 80% of samples)	Tertiary effluent	Irrigation up to 4 weeks before harvesting only
Crops for human consumption in a raw state	For surface irrigation, no more than 2.2 coliform organisms per 100 ml. For spray irrigation, disinfected, filtered wastewater with turbidity of 10 units permitted, providing it has been treated by coagulation	Not to be irrigated with renovated wastewater unless they consist of fruits that are peeled before eating		Potatoes and cereals - irrigation through flowering stage only

Source: WHO (1973).

[1] Primary treatment of wastewater refers to the settling and removal of a portion of the suspended organic and inorganic solids.

[2] Secondary treatment refers to the activated sludge process and biological filtration (trickling filtration). It may also include retention.

[3] Tertiary or Advanced Treatment includes several processes depending on the use of the final product but usually includes clarification, activated carbon treatment, denitrification and ion exchange.

require guidelines to estimate public health hazards. The degree of risk associated with such effluents is related to the microbial characteristics.

The re-use of sewage effluent for agricultural practices is not an entirely new concept. Law (1968) cites 99 references on the use of sewage as an agricultural water resource. Some countries have developed standards for the use of effluents in terms of the treatment required and bacteriological characteristics, as presented in Table 31. A meeting of experts convened by WHO (1973) concluded that primary treatment would be sufficient to permit re-use for the irrigation of crops that are not for direct human consumption.

Secondary treatment and most probably disinfection and filtration are considered necessary if the effluent is to be used for irrigation of crops for direct human consumption. Table 32 presents the WHO suggested treatment processes to meet the given health criteria for wastewater re-use.

Table 32 TREATMENT PROCESSES SUGGESTED BY THE WORLD HEALTH ORGANIZATION FOR WASTEWATER RE-USE

	IRRIGATION			RECREATION	
	Crops not for direct human consumption	Crops eaten cooked; fish culture	Crops eaten raw	No contact	Contact
Health criteria (see below for explanation of symbols)	1 + 4	2 + 4 or 3 + 4	3 + 4	2	3 + 5
Primary treatment	X X X	X X X	X X X	X X X	X X X
Secondary treatment		X X X	X X X	X X X	X X X
Sand filtration or equivalent polishing methods		X	X		X X X
Disinfection		X	X X X	X	X X X

Source: WHO (1973).

Health criteria:

1. Freedom from gross solids; significant removal of parasite eggs.
2. As 1, plus significant removal of bacteria.
3. Not more than 100 coliform organisms per 100 ml in 80% of samples.
4. No chemicals that lead to undesirable residues in crops or fish.
5. No chemicals that lead to irrigation of mucous membranes and skin.

In order to meet the given health criteria, processes marked X X X will be essential. In addition, one or more processes marked X X will also be essential, and further processes marked X may sometimes be required.

The criteria recommended under recreation by WHO are equally applicable to irrigators who are likely to have physical contact with the effluent during irrigation.

Effluent irrigation may also lead to microbial contamination of air, soils and plants in the vicinity of the irrigation site. The extent of such contamination depends upon the degree of treatment provided, the prevailing climatic conditions, nature of the crop being irrigated and the design of the irrigation system. Where the terrain and the crop type are suitable, effluents may be applied through 'ridge and furrow' systems. These contaminate neither the air nor the upper parts of plants. Subsurface tile or trickle irrigation systems create the fewest hazards of any kind. However, the expense of utilizing such systems on a large scale severely limits their feasibility. An additional problem is the clogging of dripper nozzles and subsurface pipelines due to suspended sediments and microbial growth. Sprinklers create the greatest potential for microbial contamination of the vegetation and air.

When considering the use of effluents for irrigation, their microbial and biochemical properties will have to be evaluated. These values should then be compared with the public health standards, taking into consideration the crop, soil and irrigation system and consumption of the produce, and only when the effluent meets these standards should it be evaluated in terms of chemical criteria such as dissolved salts, relative sodium content and specific toxic ions.

In quantitative terms, the volume of wastewater available for re-use by irrigated agriculture is negligible when compared with the overall volume of water used for irrigation. However, the potential impacts associated with water quality and agricultural re-use of wastewater are so important, economically, environmentally and socially, that the need for sound planning far exceeds the relatively small quantities and areas involved. Several examples of wastewater re-use are given in Section 8.

The following list of references contains research as well as practical information on various aspects of the re-use of effluents for crop production: Eckenfelder (1980); Loehr (1977); National Research Council of Canada (1974); Sopper and Kardos (1973); and Wilson and Beckett (1968).

8. EXPERIENCES USING WATER OF VARIOUS QUALITIES

8.1 INTRODUCTION

Marginal and poor quality water is being used in several places in the world. Its use requires careful management to prevent or cope with the potential problems related to the water. Often this water is the only supply available and while crop yields may not be at a maximum, they continue to provide an economical return. In other instances, agriculture may have to re-use wastewater from both agricultural and urban sources. Awareness is growing that this wastewater must be treated and returned to supplement the main water supplies. Most of this wastewater, while degraded, is still usable and its utilization often reduces the total volume of wastewater that must be disposed of ultimately. Many irrigation projects will be faced with this re-use problem as competition increases for existing supplies.

The following summaries are of cases where such water is being successfully managed and used for crop production. The summaries are not meant to be in-depth reviews, but point out successful experiences and give references, so that the reader can judge and decide whether any of the concepts are worthy of trial in his own situation. The reader should guard against directly transferring other experiences without a thorough evaluation and field testing under local conditions. Each of the following experiences refers to a specific water quality analysis which is listed in the table, Annex I, at the end of the text.

8.2 PROTECTION OF IRRIGATION WATER QUALITY - Sacramento-San Joaquin Delta, USA

The Sacramento-San Joaquin Delta in California, USA, is the confluence of California's two largest rivers: the Sacramento River flowing south and the San Joaquin River flowing north. The Delta is a vast lowland, freshwater area which is subject to tidal intrusion from the Pacific Ocean through the San Francisco Bay. Two major water distribution systems, the Delta-Mendota Canal and the California Aqueduct, withdraw water from the Delta for agricultural and municipal use elsewhere in California. If the water withdrawals become excessive, the salinity of the remaining Delta water increases as seawater intrudes further into the Delta due to tidal action. In addition, most of the natural San Joaquin River flow into the Delta from the south is diverted upstream and the flow in the lower river for a greater part of the year consists mostly of irrigation return flows and drainage water which eventually reaches the Delta. Export of Delta water must be carefully controlled to match inflow to the Delta to prevent water quality degradation from seawater coming from the San Francisco Bay.

The Delta area has about 230 000 hectares of some of the world's most productive land. A significant portion of this irrigated land, including 60 000 hectares of organic (peaty muck) soils, is irrigated mostly by subsurface irrigation. Because of the increasing salinity in the Delta water, there is concern that maize, a major Delta crop, will suffer yield losses due to salinity. If water salinity increases, it becomes increasingly difficult to control soil salinity using subsurface irrigation. An intensive field trial was conducted in the Delta to establish tolerance of maize to salinity under subsurface irrigation management and to compare subsurface irrigation with sprinklers as a satisfactory form of management for salinity control and continued production of maize on the organic-peat soils. The field trials showed that the salt tolerance of maize was not appreciably affected by the method of irrigation as long as sufficient leaching could be achieved to control salts below the threshold level at which yield loss occurs. The 400 mm winter rainfall was generally adequate to leach surface soils free of salts and allow good seed germination. In the absence of sufficient rainfall, leaching by sprinklers or surface flooding is needed to assure germination.

An important finding of the trial was that subirrigated organic-peat soils did not show the same relatively constant degree of concentration of applied salts in the irrigation water as occurs with mineral soils (Table 3), regardless of whether sprinkler or subirrigation is used. The concentration factor for applied-water salinity to soil-water salinity for the Delta peat soils varied with the concentration of salts in the applied irrigation water. Figure 24 illustrates the change in the concentration factor for the Delta peat soils. At low water salinity the concentration factor is relatively high, but it decreases as water salinity increases. References include: United States Bureau of Reclamation (1980); Hoffman **et al.** (1983); Prichard **et al.** (1983); and Maas and Hoffman (1983).

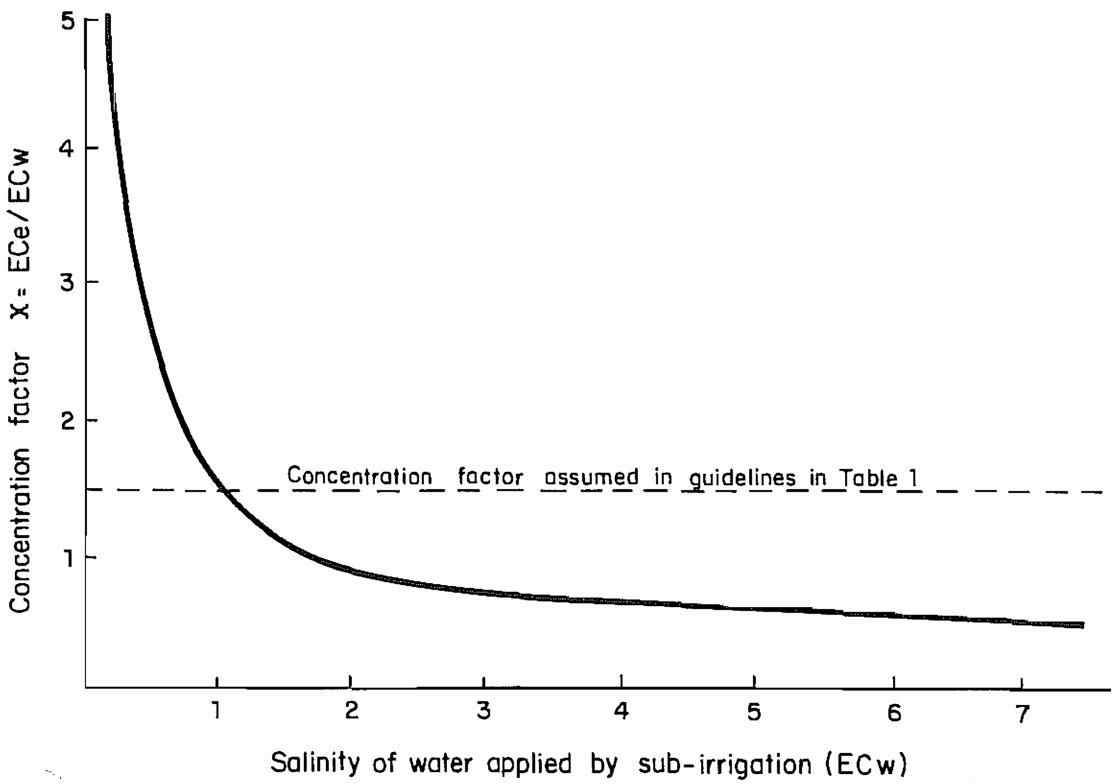


Fig. 24 Concentration factor from applied water (EC_w) to soil salinity (EC_e) under subirrigation on organic peatland in the Sacramento-San Joaquin Delta, California, USA (Prichard et al. 1983)

8.3 RE-USE OF AGRICULTURAL DRAINAGE WATER - Broadview Water District, USA

The Broadview Water District lies on the western side of the San Joaquin Valley in an area that receives less than 100 mm of annual rainfall. This 4600 hectare district receives surface water from the Delta area of California (ECw 0.3-0.5 dS/m) through the Delta-Mendota

Canal and applies approximately 0.95 metres per hectare, of which about 50 percent comes from the surface water supply and 50 percent from drainage water recirculated back into the irrigation canals. A typical analysis of the surface water, the recycled drainage water and the blended water are given in Annex I (nos. 210-212). Until 1982, this district did not discharge any of its surface return flows and since 1956 has been re-using all of its subsurface drainage water. The blended supply is considerably degraded in quality, particularly as regards salinity, boron, sodium and SAR.

The blending of water has resulted in an increased water supply to lands within the district but crops grown must be selected for tolerance to the blended water. As time has passed, the quality of the blended water has deteriorated and the cropping pattern has changed. From 1960 to 1975, the district averaged about 40 percent of the land cropped to tomatoes; by 1980, no tomatoes were planted due to yield losses caused by salinity. Crops now grown include a much larger proportion of barley and cotton, both being crops more tolerant to the salinity than tomatoes. Continued recirculation of all the drainage water causes concern regarding salt build-up. Since 1982, the district has been discharging about 20 percent of its tile drainage water in an effort to improve the blended water quality. References include: Tanji (1976; 1977).

8.4 USE OF AN EXCEPTIONALLY LOW SALINITY WATER - Friant-Kern Canal, San Joaquin Valley, California, USA

The Friant-Kern Canal transports irrigation water from the San Joaquin River, delivers it to farms along the east side of the San Joaquin Valley and extends from near Fresno to areas to the south of Bakersfield, a distance of 250 km.

The water is mostly snowmelt runoff, stored behind Friant Dam for later release for irrigation. Salinity is exceptionally low with the ECw ranging between 0.05 and 0.01 dS/m which often causes severe water infiltration problems on soils planted to moisture sensitive crops like potatoes and citrus. The water SAR by itself is not high enough to account for the poor rates of infiltration observed (SAR = 0.5).

For a potato crop, gypsum applied and disked into the soil at rates as high as 10 t/ha/year has resulted in a greatly improved rate of infiltration. Likewise, water-applied gypsum administered nearly continuously at a rate sufficient to raise the water calcium content to 2 to 3 me/l Ca has also been effective.

In a few cases, a limited quantity of an alternative, higher salinity well water has been available. In these cases, it has been possible to use the well water on the potato crop and canal water on the deeper rooted, less moisture sensitive crops like cotton, grapes and tree crops.

The Friant-Kern Canal water analysis is included in Annex I as San Joaquin River at Friant, California (see water analysis no. 230).

8.5 HIGH BICARBONATE WATER USED FOR OVERHEAD SPRINKLER IRRIGATION - Denver, Colorado, USA

Cut flowers are grown principally in glasshouses. In Colorado, USA, cut flower growers must contend with a moderately high bicarbonate concentration in their irrigation water. Wells supply their irrigation water and typical chemical analyses of two such wells are given in Annex I (nos. 228 and 229). Although the bicarbonate concentrations are moderate by agricultural criteria (Table 1), they present quality problems for marketing of a product that must have an attractive eye appeal and few blemishes. The Colorado flower growers believe that the bicarbonate ion is the cause of white deposits on leaves if they are watered by overhead spray and that it also causes plugging of localized (drip) irrigation emitters. In addition, the higher water pH accompanying the bicarbonate interferes with other ion uptake and it is thought that this may even be toxic itself to roses. From Table 11, Ca_x is at a deficiency level.

The Colorado growers do not now water any flower crop with overhead sprays. Their experience is that even with the moderate bicarbonate concentrations, overhead sprinkling or misting that wets the foliage invariably results in unsightly foliage and, in some cases, foliar damage. For overhead misting of cut flowers for market, they feel total salinity cannot exceed 0.10 dS/m (personal communication, Hanan 1980).

Most growers use spray irrigation systems which apply water to the base of the plant. Many growers are shifting to localized (drip) irrigation systems which have the advantage of not wetting any foliage. These systems are not without management difficulties; they are prone to blockage from slimes and from precipitation of carbonate or fertilizer salts. One corrective measure used to reduce HCO_3 is to reduce the water pH and reduce the bicarbonate by adding an acid. Growers feel that the sulphuric acid (H_2SO_4) raises the total salinity unnecessarily since 1 me/l of SO_4 is sufficient to meet plant requirements. If nitric acid (HNO_3) or phosphoric acid (H_3PO_4) are used, these not only lower the pH but also supply a needed fertilizer element (NO_3-N or PO_4-P). These growers use 1 equivalent of acid for each equivalent of bicarbonate. None of these acids are easy to work with but if controlled to add only what is required to change the pH to about pH = 6.5, they present little danger to metal piping systems and materially reduce the HCO_3. References include: Hughes and Hanan (1978); Schekel (1971); Hanan (1973; 1976).

8.6 USE OF POOR QUALITY WATER - Bahrain

Bahrain is an island nation off the east coast of Saudi Arabia and has an arid climate that is modified by maritime influences. The main characteristics of the climate are high summer temperatures (May-October), mild winters (November-April), high relative humidity, irregular and scant rainfall (average 70 mm) mostly in winter, and persistent winds prevailing from the northwest.

The cultivated land totals about 3700 hectares principally on the northern part of the main island. Farmers grow a wide range of crops. Date palms are most widely planted, followed by alfalfa and vegetable crops. These include tomato, cabbage, cauliflower, eggplant, peppers, celery, onions, and carrots in the winter months and melon and okra in summer.

The salinity of the groundwater used for irrigation varies but is generally high. In a survey of 47 farms, irrigation water salinity was found to range from 3.25 to 4.95 dS/m (nos. 141-144 in Annex I). In spite of the high salinity, boron was low to moderate (0.4-1.2 mg/l). Most farms surveyed were devoted to vegetable production. Because of the salinity, maximum yields of vegetable crops are not possible, but better yields could be obtained if proper attention were given to leaching and more frequent irrigation.

Experiments and trials are now underway to determine whether vegetable yields can be improved by use of greenhouses or plastic tunnels. Results to date show promise (Amer 1983). The main concern with using the present irrigation water is both salinity and sodium toxicity. In Bahrain, sodium toxicity appears to be less than might be expected, perhaps due to the abundance of calcium from carbonates and gypsum present in the soils. Boron toxicity is not expected to become a problem since most of the vegetable crops grown are sufficiently tolerant or semi-tolerant to the existing concentrations of boron.

8.7 DRAINAGE PROBLEMS - Imperial Valley, California, USA

The Imperial Valley lies in the Colorado Desert adjacent to Mexico and separated from the Gulf of California (100 km to the south) by the wide Colorado River delta (maximum elevation about 12 metres). Much of the irrigated area of the Imperial Valley is below sea level. Water diverted from the Colorado River near Yuma, Arizona, flows through the All American Canal by gravity (100 km) before delivery to the farmers in the Valley. Delivery from the main canal to the individual farms is through a very extensive network of open, lined and unlined smaller canals.

The Imperial Irrigation District maintains the system, controls the water and schedules deliveries. The water is supplied "on demand", meaning water is ordered by the user by written or telephoned request for a desired flow for a requested number of days beginning on the desired date for delivery. For example, 100 litres per second for a period of three days might be a typical water order for irrigation of a field of 20 ha planted to alfalfa.

During the early years of development (1905-1930), seepage from canals and inefficiencies of irrigation caused damaging water tables to form rapidly and place much of the best land in jeopardy due to salinity and waterlogging. Without adequate drainage, production declined and the future of the Valley looked very hazardous.

To solve the drainage problems required an extensive, valley-wide network of deep (2 to 6 metres) open drains and equally extensive on-farm buried (tile) drains to control the on-farm water tables. With the water tables under control and stabilized at depths below 2 metres, leaching to remove salts and achieve a favourable salt balance became possible. Today most of the Imperial Valley farms are tile drained (tile spacing is 60-120 metres between tile lines; depth of lines is 1.5-2.7 metres). Drainage effluent from the farm drainage sytem discharges to a district-maintained open drain and flows by gravity to the Salton Sea, a naturally occurring salt sink in the trough of the Valley where it can only evaporate. (Salton Sea elevation is about -70 m.) The on-farm drainage systems and the extensive network of main and collector drains allow the Valley to maintain a long-term salt balance.

Farmers soon learned that with adequate drainage, salts could be kept under control and a wide variety of crops could be successfully grown. They include alfalfa, vegetable crops (lettuce, carrots, asparagus, onions, sweet corn, and others), fruit crops (cantaloupe, watermelon, citrus, dates, table grapes), winter grown cereals (barley and wheat), and many other important crops such as cotton, sugarbeets, sorghum and Sudan grass.

Most of the irrigation is by surface methods (strip-check or border-check, furrow, and basin). One of the most difficult problems to manage is the high salinity during germination of salt sensitive crops.

For such crops, like lettuce, solid set sprinkler systems capable of low application rates of water (2.5-5 mm/hour) are placed in the field and turned on once or twice a day to wet and keep surface soils moist during germination and early seedling growth. This daily wetting continues for perhaps 10 to 14 days after which the sprinklers are removed to another field to repeat the procedure. Irrigation following this initial sprinkling is the standard surface method (flood or furrow).

Colorado River water (the irrigation source water) has an ECw ranging from 1.1-1.4 dS/m and an SAR = 3.1 (see nos. 219 and 235 in Annex I).

8.8 NEED FOR DRAINAGE - Tigris-Euphrates River Basin, Iraq

The Tigris-Euphrates River Plain is an area that suffers with both salinity and high water tables. This is one of the oldest known irrigated areas of the world. River water salinity for most of the irrigated area is low (ECw = 0.3-0.7 dS/m); however, salinity still became a problem. Records indicate that salinity problems were present in some areas by 2400 BC and farmers were turning from wheat to barley because barley was a more salt tolerant crop. In other areas of the Plain, salinity problems were delayed until about 100 BC (Jacobsen and Adams 1958). Early irrigators apparently understood the advantages of irrigation but did not understand the need for areawide drainage.

Most of the Tigris-Euphrates Plain today is severely troubled with both salinity and high water tables. Since the natural water quality of both the Tigris and the Euphrates has been excellent, salinity should normally not be a problem (see water analyses nos. 164 and 166 in Annex I). However, with inadequate drainage and the resulting high water tables that developed, there was no way to control and permanently leach any significant portion of the salts being applied in the irrigation water. Salts slowly accumulated and productivity declined. Drainage and reclamation projects are now being implemented and the area will no doubt again become a very productive agricultural area (Dieleman 1963).

8.9 HIGH SALINITY WATER USE - Arizona, USA

The State of Arizona has very little surface water for irrigation use and must rely on well water pumped from the underground water table, much of which is relatively saline. The Safford Experimental Station of the University of Arizona is a principal research facility in this State for developing ways to utilize higher salinity irrigation water under a hot, dry (arid) climate. Soils on the experiment station are clayey and saline. The groundwater used for irrigation during the cropping season ranges in quality from ECw = 3.1-3.5 dS/m and an SAR = 14 (no. 221 in Annex I). Crop yields reported from tests conducted at the station with cotton, barley, sugarbeets and safflower are reported in Table 33. These yields are also compared with statewide averages. In most cases, the yields from the experimental trials equal or exceed the average yield for these crops grown on commercial farms throughout Arizona.

Red Mountain Farm, a commercial farm near Dateland in southwest Arizona, uses well water ranging in salinity (ECw) from 3-11 dS/m. Soils are sandy. A survey of four fields conducted in 1982 indicated that three of the fields (Field Nos. 4, 10 and 14) were irrigated from a single canal receiving water from wells ranging in salinity (ECw) from 3-8 dS/m. The fields were planted to cotton and germinated using water from the lower salinity wells with alternate furrow irrigation.

Table 33 SELECTED CROP YIELD FROM THE SAFFORD EXPERIMENT STATION AS COMPARED TO AVERAGE FARM YIELDS[1]

Crop		Yield	Statewide Average
Cotton	(1970)	1258 kg/ha	1120 kg/ha
Barley	(1972)	4117 kg/ha	3214 kg/ha
Sorghum	(1971)	7820 kg/ha	4892 kg/ha
Sugarbeet	(1972)	56.0 t/ha	56.7 t/ha

[1] From Dutt et al. (1984).

Table 34 RED MOUNTAIN FARMS LINT COTTON YIELDS (kg/ha)[1]

		Field			
		4	10	14	29
Replication	1	1507	1076	1022	1022
	2	1668	1076	807	1130
	3	1345	861	807	1130
	4	1937	967	700	1076
Average		1614	995	834	1076
Statewide Average (kg/ha)		1238			
Applied Water Salinity (EC_w dS/m)		6.2	4.5	4.0	11.1

[1] From Dutt et al. (1984).

Irrigation after germination was with water from all wells. Seasonal average salinity of the water used and lint cotton yield is given in Table 34 for each field.

The fourth field (Field No. 29) was also planted to cotton but germinated and grown on well water with ECw = 11 dS/m. Yield of lint cotton for field 29 is also included in Table 34.

From Table 4, a water of ECw = 6.2 dS/m should be capable of producing a better than 90 percent yield and a water of ECw = 11 dS/m should be capable of at least a 50 percent yield. On that basis, a full yield from field 4 would be about 1800 kg/ha and from field 29 about 2200 kg/ha. Both these projected maximum yields are approaching reported good near maximum lint cotton yield from other areas where there are no limiting factors to production (2300-2500 kg/ha of lint cotton).

8.10 USE OF AGRICULTURAL DRAINAGE WATER FOR PRODUCTION OF SELECTED CROPS - Imperial Valley and San Joaquin Valley, California, USA

In certain areas of both the Imperial Valley and San Joaquin Valley of California, an existing high water table (less than 1½ metres) must be controlled and stabilized in order to achieve and maintain acceptable yields of adapted crops. Covered tile drain lines have been installed at about 2 metres depth with distances between lines varying from 30 to 120 metres. Drainage water is collected in open drain ditches and flows downslope to an acceptable disposal area.

Collection and transport to a distant disposal area is costly and, in some cases, wasteful of a valuable resource - the wastewater itself. Only when it is no longer usable should it go to a disposal site. Typical drainage water is relatively salty (ECdw = 3 to 6+ dS/m), contains appreciable boron (B = 3 to 10+ mg/l) and has a relatively high sodium hazard (SAR = 6 to 20+).

Trials are now underway to test the feasibility of using this highly saline drainage water for production of selected crops. To date, it seems entirely feasible to use much of this drainage wastewater to produce yet another crop. By this means, the final volume of unusable wastewater will be reduced, requiring less extensive transport and disposal facilities.

Strategies are being field tested for use of saline (brackish) drainage water for irrigation of selected salt tolerant crops while still striving to maintain full production potential of the land being so irrigated. Two field tests are underway - one in San Joaquin Valley-Westside (Lost Hills area) started in 1978; the other, in the Imperial Valley, started in 1982 (Oster and Rhoades 1983).

In the San Joaquin Valley test, a cotton crop was germinated and seedlings established using California aqueduct water (ECw = 0.5 dS/m; SAR = 2.9). After this early period, very saline water (ECw = 7.8 dS/m; SAR = 17) was used (nos. 216 and 217 in Annex I). The 1982 cotton lint yield (the fourth year of the test) was 1290 kg/ha as compared to 1570 kg/ha produced using only the low salt canal water. When only the saline water was used for both germination and production, lint yield dropped to 840 kg/ha.

The cotton planting beds were listed prior to the rainy winter season and benefited from leaching rainfall. Then, a pre-plant irrigation followed later by irrigations for germination and seedling establishment further reduced accumulated salinity to allow good germination and seedling establishment before the change-over to irrigating with the saline water. Wheat is to be the next crop, but grown with canal water only to desalinize the soil before again planting cotton (or sugarbeets).

In the Imperial Valley test (started in 1982), two crop rotations are being followed - wheat, sugarbeets and melons in one trial; in the second, cotton for several years will be followed by wheat, and then by alfalfa. For the first trial (wheat, sugarbeets, melons), Colorado River water (ECw = 1.4 dS/m; SAR = 4.9) is being used for pre-plant and early irrigations of wheat and sugarbeets and for all irrigations of melons. Later irrigations of the wheat and sugarbeets are with Alamo River (drainage) water (ECw = 4.6 dS/m; SAR = 9.9). The detailed chemical analyses of both the Colorado River water and the drainage water from the Alamo River are given as nos. 219 and 220 in Annex I. In the other trial (cotton, wheat, alfalfa), the cotton is to be grown with the Alamo River (drainage) water for all or part of its irrigations, and the wheat will be irrigated with the better water (Colorado River) to reduce soil salinity sufficiently to allow a normal alfalfa crop to be grown using the usual canal water (Colorado River). To date, one wheat crop and one cotton crop have been harvested and the highest yields were actually obtained in both cases with the treatment which received the greatest amount of drainage water substitution for Colorado River water - 75 and 100 percent respectively (Rhoades 1984a; 1984b).

8.11 USE OF MARGINAL QUALITY WATER - Medjerda Valley, Tunisia

Soil conditions and high salinity of the irrigation water make the lower Medjerda Valley of Tunisia difficult to farm. The Medjerda River flows from west (in Algeria) to east into the Gulf of Tunis in the Mediterranean Sea. About 40 km west of the town of Tunis the river enters a wide coastal plain characterized by heavy clay soils with a lime ($CaCO_3$) content up to 35 percent. The soils have a very low infiltration rate and the low salinity winter rainfall may stand on the surface for extended periods of time. During the growing season, the soils dry quickly and shrink and crack (fissures up to 5 cm wide) and water quickly enters the soil through the cracks until they swell and close.

The quality of the Medjerda River varies considerably during the year (nos. 193 and 194 in Annex I). Table 35 shows the monthly mean salinity during 1962 and 1963. The salinity (ECw) ranges from 1.3 to 4.7 dS/m. The 1962 data represent conditions of a dry year and 1963 a wet year.

Table 35 SALINITY OF THE MEDJERDA RIVER AT EL AROUSSIA, TUNISIA[1] (monthly mean in dS/m)

	1962	1963
January	3.7	2.2
February	1.3	1.3
March	2.1	2.1
April	2.5	2.2
May	3.2	2.6
June	4.1	3.2
July	4.7	4.2
August	4.2	3.5
September	4.1	2.8
October	3.0	3.3
November	2.4	3.9
December	2.6	2.7

[1] From Unesco (1970).

During much of the year, the Medjerda River water can be used for irrigation of medium to high salt tolerant crops such as date palm, sorghum, forage barley, alfalfa, rye grass, and artichokes. The soil conditions in summer (large cracks) make efficient leaching difficult, while in winter the rainfall only partially leaches salts from the top soil layer of the clayey soils (15 cm). This leaves the soil surface with such poor structure and low infiltration rate (high ESP and low ECe) that leaching the entire profile during this winter period becomes nearly impossible.

The Government of Tunisia and Unesco developed a full field research programme to assess the management needed to farm this area. The results of this programme have been useful in Tunisia as well as other Mediterranean countries that face similar problems of using poor quality water on heavy coastal soils. The main recommendation of the study was for proper timing of leaching to save water and the use of cropping patterns which include crops tolerant to the expected salinity build-up. The management principles developed during the study are transferable to other similar areas. References include: Van't Leven and Haddad (1968); Unesco (1970); and Van Hoorn (1971).

8.12 USE OF POOR QUALITY WATER FOR IRRIGATION - United Arab Emirates

The United Arab Emirates faced a number of problems when developing their national irrigation programme; a scarcity of water, moderate to high salinity in most water supplies, lack of labour, and poor farming practices. The Soil and Water Investigations Unit of the Ministry of Agriculture and FAO/UNDP initiated an extensive field programme in 1976 to improve their irrigation practices. This programme has identified several practices to improve yields while using the high salinity water. A few of these are highlighted here (the water quality is shown as no. 195 in Annex I).

a. Drip irrigation improved the general growth of tomatoes as compared to furrow irrigated tomatoes. These differences were consistent regardless of whether the tomatoes were field seeded or transplanted (Table 36).

Table 36 EFFECT OF IRRIGATION METHOD ON TOMATO YIELD (kg/ha)[1]

Drip irrigation	109 000
Furrow irrigation	65 000

[1] From Savva et al. (1981).

b. New lemon plantings showed that sprinkling reduced growth during the first 16 months as compared to bubbler, drip and basin irrigation. Extensive leaf burn and defoliation were caused by the concentrations of sodium and chloride in the irrigation water. Table 37 shows the differences in sodium and chloride concentrations in the lower leaves on trees irrigated by the four different methods. The higher sodium and chloride with sprinklers was attributed to the adsorption through leaves wetted by low angle sprinklers during the early growth stages. Eventually the trees grew above the reach of these low angle sprinklers and growth accelerated.

Table 37 EFFECT OF IRRIGATION METHOD ON SODIUM AND CHLORIDE CONCENTRATION OF THE FOLIAGE OF LEMON TREES[1] (Dry weight basis)

Irrigation System	Percent Sodium in lower leaves	Percent Chloride in lower leaves
Basin	0.39	0.88
Bubbler	0.28	0.84
Drip	0.39	0.61
Sprinkler	1.50	1.43

[1] From Savva (1981).

c. A comparison of sprinkler and furrow irrigated potatoes showed improved yield resulting from night sprinkling. There was an increase in yield of 77 percent and a water saving of 25 percent due to night sprinkling as compared to day sprinkling. Furrow irrigation at night showed no yield increase. Onions irrigated by sprinkler at night showed yield increases of 25-50 percent as compared to sprinkling during the day. The differences are attributed, in part, to lower toxicity resulting from less leaf adsorption of the toxic sodium and chloride from the applied water.

References include: Savva et al. (1978; 1981; 1984).

8.13 IRRIGATION WATER QUALITY - Lake Chad, Africa

Lake Chad is being considered for expanded development including increased diversion of the lake water for irrigation. The lake has always been considered quite unusual because the salinity level in it remains relatively low and stable. The lake is a land-locked sink with no outflow but a continued inflow from rivers discharging into it. These rivers carry varying quantities of salt.

The main river flowing into Lake Chad is the Chari River. The salinity level of the lake is dependent on the river Chari discharges and within the lake there are pronounced regional variations in salinity which chiefly depend on the position in the lake relative to the Chari discharge (Figure 25). Irrigation withdrawal sites must take these variations into account as well as fluctuations in lake levels caused by seasonal changes due to inflows and evaporation.

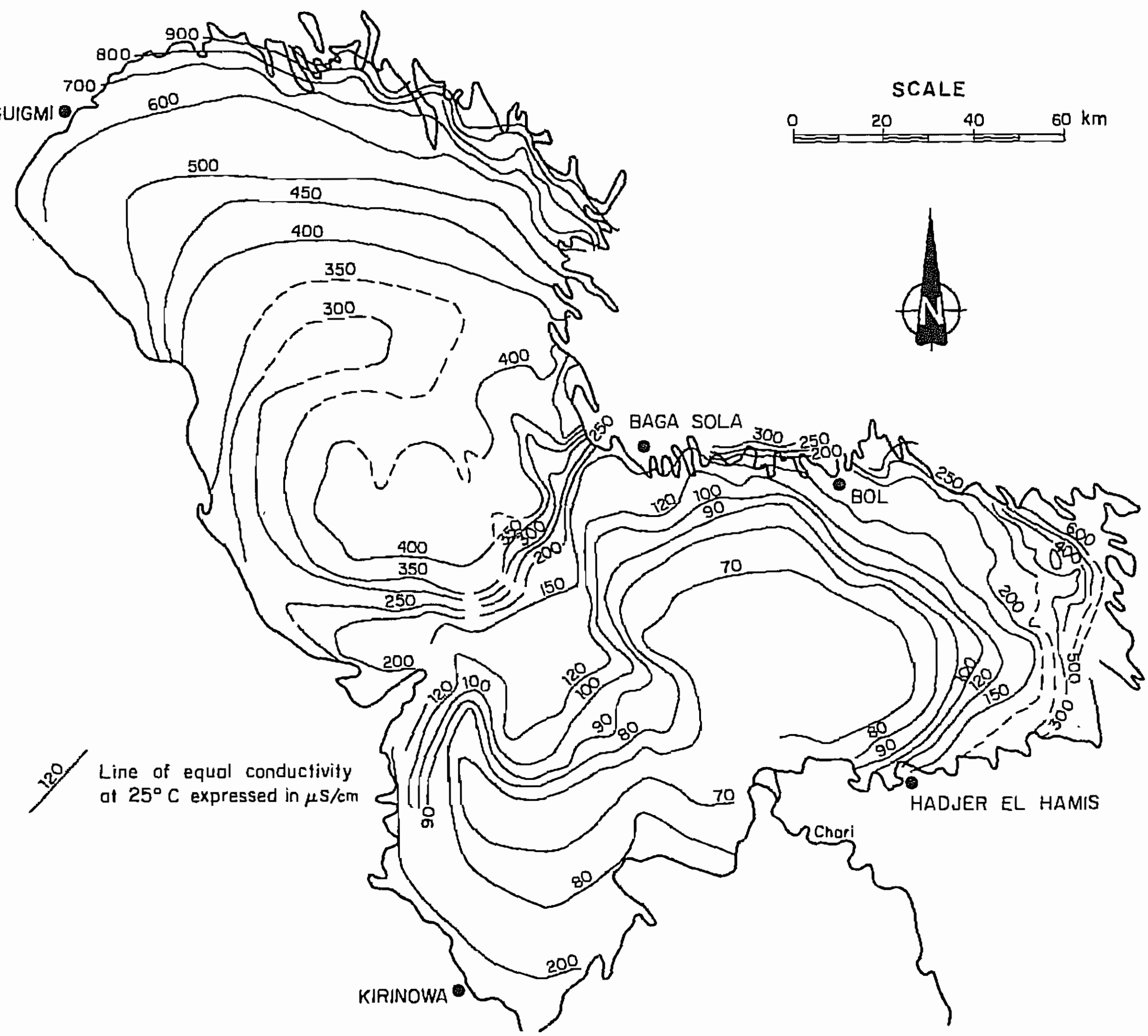


Fig. 25 Electrical conductivity of Lake Chad from 26 February to 10 April 1967 (FAO 1973)

The chemical quality of Lake Chad and two of its inflow rivers, the Ebeji and the Chari, are shown as nos. 3-5 in Annex I. It is interesting to note in Annex I that the inflow river water to Lake Chad and Lake Chad itself show no measurable concentrations of the chloride ion. This, coupled with the known leakage from the lake into local groundwater, may explain why this land-locked lake has not experienced an increase in salinity with time. The groundwater in the vicinity of Lake Chad shows the similar characteristics of high bicarbonate and low chloride. The salinity (ECw) of the groundwater generally ranges from 0.7-1.5 dS/m, except where sulphates are present and then ECw may even exceed 4.0 dS/m. Typical groundwater in the lake area is shown in nos. 6-8 in Annex I (FAO 1969; 1973).

8.14 RIVER WATER QUALITY VARIATIONS - Ethiopia and Somalia

River water quality is often inversely related to flow; dilution due to runoff in the rainy or snowmelt periods usually keeps total salt concentration low. A unique exception is the Wadi Shebelle that originates in the highlands of Ethiopia, flows south through the Ogadan plateau of Ethiopia and Somalia and discharges into the Indian Ocean.

During a greater part of the year the river flow originates mostly from the upper highlands of Ethiopia, which are a basalt formation. River water salinity from runoff originating in this upper catchment area rarely exceeds ECw = 0.75 dS/m and is often well below ECw = 0.50 dS/m (see no. 158, Annex I). With good management, such water presents few problems.

The river quality changes significantly in the periods from late April until early June and again in October and November (see nos. 159 and 160, Annex I). During these periods, river water salinity ranges from ECw = 0.75-2.0 dS/m and occasionally ECw exceeds 2.5 dS/m. The increased salinity in the Wadi Shebelle during this time is associated with high intensity rains that cause runoff from the Ogadan plateau which consists of rock formations of marine origin. The infrequent, high intensity rains on the Ogadan plateau feed the Wadi Shebelle for periods which last up to two weeks following each heavy rain. The water characteristics show a relatively high concentration of gypsum ($CaSO_4$) reflecting the rock formations on the plateau. As cropping takes place on a year-round basis in the river basin, careful management of the high salinity water is needed to ensure continued good crop production. Because most irrigation practices using Wadi Shebelle water are poor and spate irrigation is widely practised, a common management step is to avoid using the Wadi water for several days following increased river flows caused by rainfall in the Ogadan plateau (Ochtman 1975).

8.15 GROUNDWATER DEGRADATION - Wadi Dhuleil, Jordan

The Wadi Dhuleil irrigation scheme is the largest groundwater irrigation project in Eastern Jordan. The project was originally planned for 3600 donums (900 ha) but now comprises 6250 donums (1560 ha). Construction began in 1967 and irrigation began in 1970. The irrigation water supply comes entirely from the groundwater. Water pumped from the Dhuleil - Halabot aquifer was initially of good quality with ECw in the range of 0.4 to 0.6 dS/m. In the northeastern part of the project lower quality water was found with ECw ranging between 1.05 and 1.35 dS/m.

Since irrigation began in 1971 there has been a slow deterioration in water quality. For example, Well D-16, which initially showed an ECw of 0.43 in 1971, had risen to ECw of 0.80 by 1974 and to ECw of 2.52 dS/m by 1977 (nos. 170-172 in Annex I). The source of degradation is thought to be salts being leached down to the groundwater by deep percolation of irrigation water. The main sources of salt, however, are lenses deeper in the soil profile and not salt from the root zone. New wells in new irrigated areas show the same degradation trend after a few years of operation.

Salt damage to tomatoes became clearly evident after just a few years. With the increase in salinity in the applied water, the present problem is inadequate leaching to maintain soil salinity within the tolerance of the crops being grown. The wells at present being used cannot suply water in sufficient amounts to meet both crop ET and the leaching requirement in the expanded project area. A lack of adequate supply, coupled with poor irrigation practices has resulted in poor salinity control. Most investigations show that the farmers do not understand the need for increased leaching or the methods and timing of leaching applications. Other alternatives also need to be considered, such as reducing the planted area to allow adequate leaching, sprinkling at night, water applications for leaching in winter, and selecting crops more tolerant to the increasing water salinity (Natural Resources Authority 1978; and Wye College 1975).

8.16 SURFACE WATER QUALITY DEGRADATION - Yemen Arab Republic

Water quality degradation due to sequential use and re-use of a single water supply for irrigation is strikingly illustrated in the stream flow in the upper Wadi Al Hama, near Taiz, in the Yemen Arab Republic. The upper reach of the stream is of excellent quality (ECw = 0.5 dS/m; SAR = 1.0). Much of it is diverted for irrigation of valley lands adjacent to the stream and all drainage, both underground and surface, returns to the stream to be re-used for irrigated lands downslope, but in depleted volume and higher salinity.

Rainfall and runoff from surrounding rocky hillsides is almost entirely diverted for spate irrigation of terraced lands above the reach of the diverted Wadi. No surface runoff reaches the Wadi except during very infrequent periods of intensive rainfall. Within a distance of 25 to 35 km, the Wadi flow drops from an estimated 300 to 400 litres per second to a mere 15 to 30 litres per second and the salinity increases from ECw = 0.5 to near 8.0 dS/m (see nos. 203-207 in Annex I).

Cropping patterns for the irrigated crops change along the Wadi as salinity rises. Relatively sensitive beans, maize and tomatoes give way to the more tolerant sorghum and, finally, reliance is almost entirely on seasonal spate irrigation of maize or grain sorghum using runoff from nearby rocky hillsides (Hazen and Sawyer 1979).

A similar degradation pattern can be seen for other rivers from the data in Annex I: Rio Grande River, USA (nos. 222-227); Pisco River, Peru (nos. 127 and 128); James River, USA (nos. 240 and 241); Euphrates River, Iraq (nos. 164 and 165); San Joaquin River, USA (nos. 230 and 242); and the Tigris River, Iraq (nos. 166 and 167).

8.17 SEDIMENT IN THE IRRIGATION WATER SUPPLY - Ethiopia

The Awash River is the major source of irrigation water for crop production in the middle and lower regions of the Awash River Basin in Ethiopia. The water has been found to be of good chemical quality for irrigation at most of the sampling locations in the upper and middle reaches, with the ECw value ranging from 0.2 to 0.7 dS/m, and specific ion toxicity hazards are practically non-existent. However, the suspended sediment contained in this water has been a major concern to most projects utilizing it for irrigation and other uses.

In the Middle Awash region the sediment load has been monitored for quite some time and results show that the suspended sediment content of the water varies widely, ranging from less than 0.5 g/l during the dry months (December-April) to about 15-20 g/l during heavy floods.

The two major contributors of suspended sediments to the Awash River in the Middle Awash Region are the Arba and Kesem tributaries.

One of the major irrigation projects implemented recently in Ethiopia is the Amibara Irrigation Project which irrigates 10 285 ha of land through a main canal which has a capacity to carry 13 m^3/sec and is 27 km long. Water is diverted into this canal from the Awash River by means of a rockfill diversion weir, 4 m high and 100 m long. Supply of irrigation water commenced in May 1980, and in March 1981 it was estimated that 23 000 cubic metres of silt had accumulated in the upper reach of the primary canal. This volume occupied most of the canal waterway in the 2 km reach between the headworks and the first offtake. The headworks included a scour culvert which was designed to remove coarser sediment of the bed load entering the intake gates of the primary canal.

In view of the high suspended sediment load and the fact that this cannot be excluded at the intake, a settling basin (a widened canal section, 400 m long) was constructed in the primary canal head reach.

At the end of the first year of operation, sediment deposition in the settling basin and the upper reaches of the primary canal was so great that it was impossible for the project to convey the necessary amount of water at the required time. The most difficult situation encountered was with the control of intake gates which became jammed by silt building up behind them.

Various remedial measures were suggested to improve the situation, such as:

a. construction of silt ejectors;

b. flushing of settling basin; and

c. more frequent mechanical or manual clearing of silt in the silting basin and the primary canal.

All these measures add to the cost of the project and interfere with irrigation operations.

In March 1982, an enormous quantity of silt was excavated from the primary canal from the headworks right through to the last outlet (approximately 20 km), and was piled on the bank. The disposal of the dredged material has not yet been resolved and this will be an added cost to the project.

The present trend shows that de-silting of primary canals is required every year, which means that water supply is interrupted for about 2-3 months each year. Although this is planned during the period from February to April, which is after the harvest of the cotton (the major crop of the project), the unavailability of water is a serious limitation to the farms where double cropping and perennial cropping systems are practised.

Reduced permeability and surface crusting observed in the low-lying areas and along the lower portions of farms are other important ill effects of sediment-rich irrigation water. Surface crusting has been positively identified as one of the causes of poor seed germination in certain fields in the Amibara Irrigation Project.

The operation of sprinklers for pepper nurseries has been seriously affected by the Awash River water. The clogging has resulted in uneven watering and low efficiency, and has increased the cost of operation because of the need for frequent replacement of nozzles.

Another serious problem related to the 'silty water' of the Awash is the damage caused to pumping units in some of the 'old farms' where gravity supply is not available. The impellers of these pumps wear rapidly and, on average, replacement is required once in 2-3 years.

The experience in the Middle Awash irrigation projects shows that the sediment content of the water is one of the important quality criteria that should be considered in evaluating irrigation water. This evaluation should enable the engineer as well as the farmer to adopt special management practices to minimize the ill effects of sediments in irrigation water or to look for a better source (personal communication, Kandiah 1984).

8.18 HIGH FLUORIDE IN ANIMAL DRINKING WATER - New Mexico, USA

Low fluoride levels (<1 mg/l) in drinking water are beneficial to both animals and humans. High levels (>1.5 mg/l), however, can be harmful and may cause mottled teeth, and at higher concentrations can cause bone problems. The World Health Organization (WHO) Guidelines for Human Drinking Water Quality recommend less than 1.5 mg/l fluoride. Animal drinking water standards (Table 30) recommend less than 2 mg/l fluoride.

The greatest concern in drinking water supplies for animals is that shallow groundwater, commonly a major source of animal drinking water, is frequently of poor quality. Recent surveys in several countries have shown alarmingly high levels of fluoride in some shallow groundwater. For example in the province of La Pampa, Argentina, groundwater contains as much as 3 to 9 mg/l fluoride. In Ethiopia over 200 wells tested have concentrations in excess of 3 mg/l and in one area 30 percent of all wells tested indicated 12 to 30 mg/l fluoride content. In Tanzania, concentrations from 3.2 to 9.2 mg/l have been found, while in Algeria, irrigation and drinking supplies were as high as 6.0 mg/l. Kenya is now checking groundwater supplies throughout the country to determine fluoride levels.

An example of the effects of fluoride in animal drinking water comes from New Mexico, USA. Fluoride levels in groundwater in New Mexico are generally below 1 mg/l but concentrations as high as 3 mg/l are not uncommon, especially in those wells drawing shallow groundwater. A few values range as high as 26 mg/l. Three selected wells from different areas of New Mexico are given as nos. 213-215 in Annex I. Table 38 gives the trace element concentrations (including fluoride) of these wells. It is not uncommon in New Mexico and Eastern Texas, USA, to see examples of mottled teeth in cattle and horses that drink only well water over prolonged periods. The New Mexico State Veterinary Service recently reported on a case of animal drinking water that contained high fluoride levels. Their report summary states:

> "A herd of approximately 200 brangus cattle had difficulty eating. Oral examination of more than 20 animals revealed mottled, eroded, and irregular permanent incisor teeth. The molar teeth were black with irregular table surfaces. Fluoride contents of well water samples are recorded (Table 39). Three of eight water sources from the ranch had fluoride levels above 3 mg/l. Three mg/l fluoride in drinking water can cause chronic toxicity.

The stock tank water contained 4370 mg/l of sodium. The cattle should have been able to tolerate this level of sodium in the water; however, some animals were observed to drink the lagoon water which had a sodium concentration of 21 160 mg/l. It is hypothesized that evaporation of water from the lagoon resulted in its marked salinity, and that it was consumption of this extremely saline water in the absence of a non-saline water source which precipitated the episode of salt toxicosis.

This case illustrates the danger of providing saline water as a sole water source for cattle. The previous winter a group of steers had been grazed on this pasture with no problems. However, a second well had been in operation and the winter temperatures were much lower. It is interesting to note that a similar episode of heavy loss had occurred in the same pasture 5-years earlier. The water was suspected to be responsible for the losses at that time but a definitive diagnosis was not made.

It was recommended to the owner that the lagoon be drained and a new water supply be provided for the pasture.

Case 2

Approximately 200 head of yearling Hereford calves of both sexes were confined to a feed lot at the Agua Negra Ranch in New Mexico, USA, and fed alfalfa hay and a commercial protein supplement which contained a 'self-limiting' feed ingredient (1.5 percent organosulphate). The formula was not an open formula so the source of the sulphate is not known. Water was supplied in a tank from a well.

Thirty-one cattle developed signs of polioencephalomalacia; nine animals died. The protein supplement was removed and no new cases developed. The supplement was again given to the cattle at the suggestion of the feed representative. Polioencephalomalacia again developed in approximately 38 animals and 13 died. The commercial supplement was again removed and no new cases developed.

Water samples from the water tank contained 1814 mg/l of sulphate (Table 41). This is considered high. The feed supplement contained 1.5 percent inorganic sulphate which, when added to the water sulphate, may have been enough to induce brain damage. Unfortunately, brain sulphate analysis was not done in this case.

Table 41 WATER ANALYSES FOR THE AGUA NEGRA RANCH (mg/l)[1]

	Tank	Well
Alkalinity	126	143
pH	3.07	7.33
SO_4	1814	1789
Na	236.9	230
K	4.29	3.12
Cl	281.2	376.2

[1] From Hibbs and Thilsted (1983).

8.20 FRESNO IRRIGATION SCHEME USING TREATED WASTEWATER - California, USA

Fresno is located in the San Joaquin Valley, California, USA.

The Fresno wastewater treatment facility treats 1.5 x 10^5 m^3 of water daily. Approximately 275 hectares of city-owned land are farmed to cotton and maize and irrigated with the treated wastewater, as well as approximately 1350 hectares of private land adjacent to the treatment facility. The crops grown on the adjacent lands using treated wastewater include cotton, barley, alfalfa, almonds, grapes, silage maize, oats, wheat, sorghum, and seed beans.

A typical water analysis of the treated wastewater is shown in Annex I as no. 250. Trace element concentrations in the treated wastewater are shown in Table 42. Interviews with several of the farmers indicate that they apply little or no supplemental chemical fertilizers to their crops due to the nitrogen content of the treated wastewater. Also they feel that little intentional leaching is required for salt control because the water is of sufficiently good quality. The farmers have not experienced any health problems associated with the treated wastewater. In addition to the direct usage during the irrigation season, a substantial part of the treated wastewater is percolated to the groundwater. During the non-irrigation season, all the treated wastewater is percolated for recharge of the groundwater. During the irrigation season, 21 separate extraction wells pump the groundwater mound formed during this recharge. They discharge it into a main distribution canal to serve as an agricultural supply of water for farmers further away from the treatment facility. This well field supplies 37 x 10^6 m^3 per year. Percolating the reclaimed water through the soil profile and extracting it through these reclamation wells gives a form of tertiary wastewater treatment which is accomplished at a very low cost (State Water Resources Control Board 1981; and City of Fresno 1980).

Table 42 TRACE ELEMENT CONCENTRATIONS IN FRESNO MUNICIPAL WASTEWATER [1]

Element	Concentration [2] (mg/l)
Ag (silver)	< 0.001
As (arsenic	0.002
Ba (barium)	0.005
Be (beryllium	< 0.001
Cd (cadmium)	< 0.001
Cr (chromium)	< 0.001
Cu (copper)	0.013
Hg (mercury)	0.0003
Ni (nickel)	0.030
Pb (lead)	0.050
Se (selenium)	0.003
Zn (zinc)	0.041

[1] From City of Fresno (1980).

[2] < means the element, if present, was below this level of detection.

8.21 AGRICULTURAL USE OF TREATED WASTEWATER - Braunschweig, FR Germany

Wastewater utilization for crop production has been practised at Braunschweig, FR Germany, for almost 100 years. In 1954, the utilization system was expanded to 3000 ha of sprinkler irrigated cropland. The treated wastewater is distributed to about 300 farmers through a 100 km buried pipeline. The original sprinkler system was a hand-moved system, but these are now phased out in favour of self-movable spraying machines with flexible polyethylene plastic pipes. One hundred of these irrigation machines are necessary to irrigate the 3000 ha. Instead of 20 spray attendants employed in the original system, only seven are now required.

During the dry summer season, the daily flow of wastewater is not sufficient to match the water requirements of all crops (there are no storage facilities). Wells have been installed to augment the flow. The treated wastewater is sprinkled in six applications of 50 mm each - three in summer and three in winter. The six applications are an average with exact amounts applied to various crops as follows:

Potatoes	2 applications of 30 mm
Winter grain, Spring barley	3 applications of 50 mm
Oats	4 applications of 50 mm
Spring wheat, Sugarbeets	5 applications of 50 mm

The present cropping pattern in the treated wastewater use area is 25 percent winter grain, 30 percent spring grain, 20 percent sugarbeets, 10 percent asparagus, 10 percent grassland, and 5 percent potato. No problems have been experienced with the agricultural cropping pattern using the treated wastewater because the climate is mild and rainfall and over-application of water keeps salinity under control. An analysis of the treated wastewater used is given as no. 80 in Annex I. Of interest are nos. 81 and 82 in Annex I which are samples of the Oker and Erse Rivers which flow through the re-use site. These samples represent the water before it enters the re-use farming area. Groundwater samples taken inside and outside the irrigation area also show quality nearly the same as the treated wastewater used for irrigation. Table 43 gives trace element analysis for these water samples. The trace elements Manganese (Mn), Cobalt (Co) and Cadmium (Cd) in the treated effluent exceed the guidelines given in Table 21 for protection of the soil resource. Further investigation is needed to determine whether these elevated levels could cause problems in the future and whether steps are necessary to reduce their discharge to the sewage system (Tietjen et al. 1978).

Table 43 WATER QUALITY IN AND AROUND THE BRAUNSCHWEIG TREATMENT WASTEWATER USE AREA[1]

	Treated Wastewater[2]	Oker River[2,3]	Erse River[2,3]	Groundwater inside[4] the irrigation area	Groundwater outside[5] the irrigation area
	mg/l				
NH_4-N (ammonium-nitrogen)	49.0	7.0	14.2	2.8	2.9
NO_3-N (nitrate-nitrogen)	0.2	8.4	7.0	30.0	8.7
P (phosphorus)	13.0	0.9	0.7	0.5	0.4
K (potassium)	32.0	11.0	55.0	33.0	85.0
Fe (iron)	2.0	1.2	0.8	12.0	8.3
Zn (zinc)	0.9	0.6	0.5	0.4	0.7
Cu (copper)	0.15	0.03	0.04	0.06	0.05
Mn (manganese)	0.3	0.4	0.9	1.7	2.1
Co (cobalt)	0.2	0.12	0.27	0.14	0.19
Cd (cadmium)	0.02	0.01	0.02	0.01	0.02
Pb (lead)	0.04	0.02	0.03	0.07	0.04

[1] From Tietjen et al. (1978).

[2] Values given are an average of 12 or more samples.

[3] Samples taken before the rivers reach the irrigation area.

[4] Values given are an average of 242 wells.

[5] Values given are an average of 58 wells.

8.22 WASTEWATER IRRIGATION - Bakersfield, California, USA

The City of Bakersfield, located in the southern end of the San Joaquin Valley, has used treated wastewater to irrigate cropland for more than 65 years. Normal annual rainfall is 150 mm and occurs mostly in the winter months of December to the end of February. Because of the mild climate, irrigation can be practised all the year round.

The present treatment system provides primary treatment followed by aerated deep lagoons (21 ha) and storage reservoirs which can provide up to 90 days of storage, if needed. Treatment in combination with lagoons is equivalent to secondary treatment. The treated wastewater analysis is listed as no. 246 in Annex I.

The treated wastewater is used to irrigate approximately 2250 hectares of city-owned land. The city leases the land to one farmer and the lease sets very specific requirements on cropping patterns. The present crops include barley, maize, alfalfa, sorghum, and permanent pasture. Over half of the city farm land is high in salinity and sodicity. The city, through the terms of its lease, encouraged the farmer to implement a land reclamation programme that consisted of ripping to a depth of 0.8 m, followed by land grading to permit flood or furrow irrigation. For reclamation, a pre-plant leaching irrigation was given, followed later by 20 metric tons of 60 percent pure gypsum per hectare, disked into the upper 15 cm of the soil. Barley was then planted in the autumn of the first year and heavily irrigated in the winter and spring to accomplish leaching. Following the barley, a summer crop of Sudan grass or grain sorghum was planted and irrigated by border check. In late summer, the field was planted to pasture or alfalfa, and flood irrigated. Soil conditions were monitored until salinity levels reached a level safe enough to grow other crops under furrow irrigation.

In areas of higher salinity where additional leaching was necessary, the farmer planted rice as a reclamation crop. The goal was to allow the large quantities of water needed for rice to leach the high level of salts from the soil. While this practice was effective, the use of the treated wastewater in flooded rice fields created an abnormally high mosquito problem. The exact reasons are unknown, but field studies and observations by vector biologists clearly showed a significantly higher vector population in the rice fields receiving treated wastewater at Bakersfield and other sites using treated wastewater to irrigate paddy rice. Preliminary data show that the mosquitoes are attracted to standing water containing high levels of organics. Because of the concern for serious disease problems in the adjacent urban population, the use of treated wastewater for the irrigation of paddy rice has been halted in California. On other crops, the treated wastewater does not create vector problems as the fields are not continuously flooded and water does not pond for long enough to allow mosquitoes to propagate.

The amount of nitrogen in the treated wastewater is about 250 kg/ha per metre of water applied. This amount will satisfy the nitrogen fertilizer requirements of most crops. In the past, problems have occurred with certain crops such as cotton owing to excessive vegetative growth. This was probably due to the presence of excess available nitrogen in the irrigation water during the latter part of the growing season. To correct this problem, the farmer now uses the treated wastewater, with its beneficial nitrogen, during the early part of the season, and switches to low nitrogen well or canal water in the later part of the season or blends the treated wastewater with these alternate supplies to reduce the nitrogen content (Crites 1974; State Water Resources Control Board 1981; and EPA 1979).

8.23 WASTEWATER IRRIGATION - Tuolumne Regional Water District, California, USA

The Tuolumne Regional Water District collects urban wastewater, treats it and conveys the treated wastewater to private landowners for irrigation of 500 hectares of forage and pasture land. After treatment, the reclaimed water moves through a 14.2 km pipeline to a 1.85 x 10^6 m^3 storage reservoir. During the winter non-irrigation season, all the reclaimed water flows to the reservoir and is stored in it. During the irrigation season, reclaimed wastewater is supplied directly from the treatment plant to 10 farmers whose lands lie above the reservoir. If not needed for irrigation, the treated water moves to the reservoir, where it is released to farmers below the reservoir along with the reclaimed water stored during the previous winter.

The treated water can only be used for irrigation of pasture, fibre or seed crops, livestock water and landscape irrigation, and cannot be used where public contact is probable. The farmers in the area are satisfied with the quality of the reclaimed water (no. 249 in Annex I) because it presents few hazards to agricultural production. In the past, the only source of irrigation water was pumped groundwater. This was not economically feasible for the small farms. With the availability of reclaimed water, smaller sized parcels that were previously not economical are now being developed into permanent pasture.

The good quality of the reclaimed wastewater presents no potential problems and the trace element concentration is also far below maximum levels considered safe for irrigation (Table 21). The trace element concentrations for the Tuolumne Regional wastewater are presented in Table 44 (State Water Resources Control Board 1981; Tuolumne Regional Water District 1980).

Table 44 TRACE ELEMENT CONCENTRATIONS IN WASTEWATER FROM THE TUOLUMNE REGIONAL WATER DISTRICT [1,2]

	mg/l		mg/l
Ag (silver)	0.001	Fe (iron)	0.005
Al (aluminium	< 1.0	Hg (mercury)	< 0.001
As (arsenic)	< 0.01	Mn (manganese)	< 0.05
Au (gold)	< 0.01	Mo (molybdenum)	< 0.01
Ba (barium)	< 0.01	Na (nickel)	< 0.01
Be (beryllium)	< 0.01	Pb (lead)	< 0.005
Br (bromide)	0.5	Sb (antimony)	< 0.01
Cd (cadmium)	0.001	Se (selenium)	< 0.005
Co (cobalt)	< 0.01	Sn (tin)	< 0.01
Cr (chromium)	< 0.005	Ti (titanium)	< 0.05
Cu (copper)	< 0.05	Tl (thallium)	< 0.01
F (fluoride)	1.5	Zn (zinc)	< 0.01

[1] From Tuolumne Regional Water District (1980).

[2] < means the trace element, if present, was below this detection level.

8.24 IRRIGATION WITH WASTEWATER - Santa Rosa, California, USA

The City of Santa Rosa, USA, is located about 65 km north of San Francisco in a coastal Mediterranean climate. The city operates an extensive wastewater irrigation system which includes delivery of part of the water to farmers on demand. There are storage reservoirs which hold a 60-day supply and additional balancing reservoirs are located throughout the system. Twenty farmers use the reclaimed wastewater to irrigate 1600 hectares, mostly by sprinklers. The crops irrigated include maize (silage), Sudan grass, oats and winter feed for livestock. The farmers feel that the reclaimed water supplies approximately two-thirds of the fertilizer nutrients required by the crops.

The effluent supplements the winter rainfall and is delivered under contract to farmers adjacent to the pipeline. Effluent not used flows to a surface reservoir at the end of the pipeline for storage awaiting the time when demand is greater and the effluent can be re-introduced into the pipeline for use by the contracting farmers. Effluent is in surplus during the cooler part of the growing season but can be utilized both from storage and direct flow from the treatment plant during the warmer times when peak demand may exceed direct flow capacity of the pipeline.

Before the reclaimed water became available, most farmers were dry farming pasture for their dairy animals and purchasing supplemental feed. Now they are pasturing more and buying less supplemental feed.

Water analyses nos. 247 and 248 in Annex I show the influent city water (drinking water) quality and treated wastewater quality. The greatest percent change is in sodium and chloride and is typical of the change which takes place during urban usage of water in the USA. The treated wastewater salinity is ECw = 0.7 dS/m. The salinity and SAR are within the range where cropping problems are not likely to occur. No problems have been recorded as a result of using this water since 1976.

The trace element content of the wastewater, shown in Table 45, is also within the suggested limits in Table 21. One important addition resulting from detergents added during urban use is in boron which is increased significantly (State Water Resources Control Board 1981; Bain and Esmaili 1976).

Table 45 TRACE ELEMENT AND NUTRIENT CONTENT OF WASTEWATER FROM THE CITY OF SANTA ROSA[1,2,3]

	Drinking Water (mg/l)	Treated Wastewater (mg/l)
NH_4-N (ammonium-nitrogen)	0	13
NO_3-N (nitrate-nitrogen)	1.0	1.9
Total Nitrogen	-	19
Total Phosphorus	-	19
K (potassium)	1.4	10
B (boron)	0.2	0.53
Al (aluminium)	< 0.1	0.128
As (arsenic)	< 0.001	0.003
Cd (cadmium)	0.002	0.006
Cr (chromium)	< 0.001	0.003
Co (cobalt)	< 0.001	< 0.001
Cu (copper)	< 0.008	0.040
Fe (iron)	0.07	0.21
Pb (lead)	0.003	0.017
Mn (manganese)	0.02	0.068
Ni (nickel)	0.004	0.04
Se (selenium)	< 0.001	0.002
Zn (zinc)	0.02	0.06

[1] From Bain and Esmaili (1976).

[2] Composite Sample for 2 years - taken quarterly.

[3] < means the element was not present at that level of detection.

8.25 USE OF WASTEWATER HIGH IN BORON - Calistoga, California, USA

California suffered two years of severe drought during the winters of 1975-76 and 1976-77. Calistoga, a small community about 100 km north of San Francisco and in the northern part of the Napa Valley could no longer supply water to its golf course. Without water the golf greens and fairways were drying up and becoming unplayable.

Municipal wastewater was available but had to be piped about 3 km to a holding pond at the golf course before being put through the sprinkler system. Furthermore, the Calistoga mineral baths and spas use hot, mineral spring waters in their swimming pools and mud baths, and the springs flow more or less continually, discharging to the treatment plant. These mineral springs are high in boron and when mixed with the low boron domestic supply, produce a wastewater containing about 4 mg/l boron. It was therefore suspected that boron could be a problem if this water were used on the golf course.

At the beginning of the testing period to use the municipal wastewater in the holding pond at the Calistoga golf course it had a salinity (ECw) of 1.0 dS/m, boron at 3.8 mg/l and SAR = 3.5. During the two years of monitoring, boron ranged in the applied water from 3.0 to 7.8 mg/l. Boron in the root zone (saturation extract basis) of the greens ranged from 3.1 to 7.8 mg/l, and boron in the grass clippings from the greens (dry weight basis) ranged from 18 to 86 mg/kg. Frequent cutting apparently prevented any damaging accumulation of boron.

The golf greens and fairways were maintained by using the municipal wastewater for irrigation without any apparent damage from its high boron content. Conifer trees, however, in scattered plantings around the course showed appreciable leaf damage (tip burn). With the return of normal rainfall (500-800 mm/year) any potential damage due to boron has been kept to a minimum. Calistoga has continued to use the wastewater on the golf course (Donaldson **et al.** 1978).

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.)	Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/1	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
	AFRICA														
	Botswana														
(1)	Steinberg Well at Orapa Township	2.31		1.1	2.0	17.0	0.1	3.6	1.3	13	14	15	0.6	0.5	Mazor et al. 1977
(2)	Well No. 2182 at Orapa Township	2.36		3.8	4.2	16.2	0.2	12.9	3.0	8.5	8.1	9.7	0.9	1.4	Mazor et al. 1977
	Chad Republic														
(3)	Shari River at Yagoua	0.06		0.3	0.2	0.1	0	0	0.2	0.4	0.2	0.1	1.5	1.5	Grove 1972; Rache 1974
(4)	Lake Chad	0.13	8.1	0.6	0.5	0.5	0.1	0	0	1.6	0.7	0.6	1.2	1.0	FAO 1973
(5)	Ebeji River at Wulgo Bend	0.16	7.2	0.4	0.3	0.4	0.1	0	0.4	1.0	0.7	0.5	1.3	1.0	FAO 1973
(6)	Well No. T5 at Bol	0.37	7.4	2.4	0.5	1.6	0.4	0.1	0.3	4.4	1.3	1.7	4.8	1.3	Dieleman and de Ridder 1963
(7)	Well at Shuari, Chad Basin	0.90		1.3	1.6	6.6		1.2	3.8	4.4	5.5	5.9	0.8	0.9	FAO 1969
(8)	Well at Berlomga, Chad Basin	5.30		6.3	10.2	39.3		6.4	43.5	9.9	14	16	0.6	1.9	FAO 1969
	Madagascar														
(9)	Morondava at Dabara	0.20		1.4	0.4	0.3	0.1	0.2	0.5	1.6	0.3	0.3	3.5	1.7	FAO 1972b
(10)	Beritsoka at the Barrage	0.40		3.0	1.0	0.7	0.1	0.2	1.9	3.0	0.5	0.6	3.0	1.9	FAO 1972b
(11)	Andranomena at Besakay	0.06		0.4	0.1	0.2	0	0.2	0.1	0.5	0.4	0.2	4.0	1.5	FAO 1972b
	Malawi														
(12)	Shire River at Chikwawa	0.22	7.8	0.8	1.1	1.2	0.2	0.4	0	2.6	1.3	1.9	0.7	0.9	FAO 1970a
(13)	Tangazi River	0.15	7.2	0.4	0.5	0.4	0.1	0.6	0.2	1.2	0.6	0.5	0.8	0.9	FAO 1970a
(14)	Irrigation Well at Tambordera	0.37	7.4	1.9	1.1	2.6	0.1	0.5	1.2	3.6	2.2	2.4	1.7	1.2	FAO 1970a
	Mali														
(15)	Well at In Arei	2.46		14.7	6.9	3.0		0.8	19.4	2.2	0.9	1.1	2.1	8.1	Saad 1970
(16)	Well at Igdil Anta	1.12		6.9	1.9	2.3		0.8	5.2	2.5	1.1	1.3	3.6	4.2	Saad 1970
(17)	Well at Samit	1.08		6.9	3.9	1.7		0.6	4.6	7.1	0.7	1.0	1.8	2.1	Saad 1970

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.)	Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/1	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x [2]	Reference
	Mauritius														
(18)	Glacis Well	0.30	7.8	1.2	1.0	1.3	0	1.4	0.3	1.9	1.2	1.2	1.2	1.4	FAO 1965a
(19)	Dutch Well (Palmar Coast)	2.60	7.2	0.3	5.1	19.6		20.6	2.0	5.1	12	12	0.1	0.3	FAO 1965a
	Nigeria														
(20)	Well No. 3053 at Balle, Sokoto Province	1.30	7.5	6.9	4.3	4.3	0.6	3.9	12.0	0.3	1.8	1.4	1.6	15.7	Ogilbee and Anderson 1965
(21)	Well No. 3070 at Ruawuri, Sokoto Province	0.96	7.3	0.4	0.1	0.4	0	0.3	0.5	0.1	0.8	0.3	4.0	5.2	Ogilbee and Anderson 1965
(22)	Niger River at Katon Karifi	0.05	7.4	0.2	0.1	0.2	0.1	0	0.1	0.4	0.5	0.3	2.0	1.1	Grove 1972
	Senegal														
(23)	Senegal River at Wasunde	0.03	7.6	0.4	0.1	0.1	0	0	0	0.3	0.2	0.1	4.0	2.2	Grove 1972
(24)	Benue River at Garoua	0.08	7.6	0.4	0.3	0.2	0	0	0	0.8	0.3	0.2	1.3	1.1	Grove 1972
	Swaziland														
(25)	Great Usutu River at Sipofaneni	0.06	7.3	0.1	0.2	0.2	0	0.1	0	0.5	0.5	0.3	0.5	0.6	FAO 1970b
(26)	Mhlatuzane River at DS 4.4	0.15	7.5	0.2	0.6	0.5	0.1	0.3	0	1.1	0.8	0.6	0.3	0.6	FAO 1970b
	Zimbabwe														
(27)	Zambezi River above Victoria Falls	0.10	7.3	0.5	0.4	0.1	0	0.1	0.1	0.8	0.1	0.1	1.3	1.4	Mazor and Verhagen 1976
(28)	Sabi River at Birchenough Bridge	0.10	7.7	0.1	0.5	0.3	0	0.1	0.4	0.6	0.5	0.4	0.2	0.6	Mazor and Verhagen 1976
	ASIA AND SOUTH PACIFIC														
	Afghanistan														
(29)	Kunduz River at Seh Dorak	0.60	7.8	2.2	1.3	2.2	0.1	2.3	0.8	2.6	1.7	1.8	1.7	1.7	FAO 1971
(30)	Khan-Abed River at Jangal Basi	1.20	7.8	3.8	2.7	5.2	0.2	5.0	1.4	5.5	2.9	3.7	1.4	1.6	FAO 1971
(31)	Well D-92 at Kunduz	4.50	8.0	1.2	0.9	50.0	0.1	15.8	2.2	34.2	49	66	1.3	1.2	FAO 1971
(32)	Well D-73 at Kunduz	1.00	8.1	3.4	2.7	3.0	0.1	3.1	0.9	5.2	1.7	1.9	1.3	1.6	FAO 1971
(33)	Well D-7 at Kunduz-Khan Irrigation Project	1.62	7.8	3.2	3.3	9.6	0.2	7.0	0.6	9.7	5.3	6.4	1.0	1.0	FAO 1971

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
American Samoa														
(34) Well No. T-1733	0.46	8.6	1.1	0.4	2.6	0.4	1.4		2.4	3.0	3.0	2.8	1.1	US Geo. Survey 1975
(35) Well No. T-2043	1.11	7.5	0.6	1.5	7.4	0.3	7.9		1.7	7.3	6.6	0.4	1.0	US Geo. Survey 1975
Australia														
(36) Irrigation Well No. 2C at Lockyer Valley, Queensland	3.50		1.32	17.6	8.0		25.5	1.0	11.5	2.0	2.5	0.8	2.7	Shaw et al. 1981
(37) Irrigation Well No. 3F at Lockyer Valley, Queensland	2.80		9.4	16.0	5.0		19.0	0	9.4	1.4	1.6	0.6	2.8	Shaw et al. 1981
(38) Irrigation Well No. 6A at Lockyer Valley, Queensland	4.53		10.8	25.3	9.4		38.4	0.9	7.7	2.2	2.5	0.4	3.0	Shaw et al. 1981
(39) Coon Well at Lakeway	1.33	7.2	2.2	6.6	9.3	0.5	5.6	5.3	4.0	4.4	4.6	0.3	1.5	Mann and Deutscher 1978
(40) Well in Shepparton Region, Northern Victoria	3.4		0.4	2.3	26.2	0.2	21.7	1.2	7.7	23	23	0.2	0.3	Wildes 1984
China														
(41) Wongnute Ranch Near Dam Site (Surface Water)	0.50	7.3	2.7	2.1	1.2		1.0	1.3	3.6	0.8	0.9	1.3	1.6	FAO 1983
(42) Well at Wongnute Ranch	1.55		7.0	2.0	8.5		2.2	0.8	14.0	4.0	6.6	3.5	1.4	FAO 1983
India														
(43) Khor Well, Rohtak District Naryana	0.98		2.9	3.3	3.0		6.8	2.4	2.8	1.7	1.8	0.9	2.1	FAO Files
(44) Haryahera Well, Rohtak District, Naryana	1.98		2.2	2.6	15.2		6.7	2.8	10.2	10.0	12	0.8	0.8	FAO Files
(45) Brahmaputra River at Gauhati	0.15	7.1	0.5	0.5	0.6	0.2	0.2	0.2	1.7	0.8	0.8	1.0	0.8	Subramanian 1979
(46) Ganges River at Patna	0.31	7.3	1.4	3.2	0.7	0.2	0.5	1.5	2.0	0.5	0.5	0.4	1.4	Subramanian 1979
(47) Godavari River at Rajmundary	0.17	7.1	0.5	0.8	0.3	0.2	0.3	0.2	1.7	0.4	0.3	0.6	0.8	Subramanian 1979
(48) Krishna River at Kurnool	0.29	7.5	0.6	1.5	0.7	0.2	0.7	0.2	1.7	0.7	0.6	0.4	0.9	Subramanian 1979
(49) Narmade River at Broach	0.33	7.2	1.0	1.2	0.4	0.2	1.0	0.5	2.0	0.4	0.4	0.8	1.2	Subramanian 1979
(50) Lower Ganges at Kampur	0.45	8.5	1.2	0.6	2.4		0.3	0.3	3.0	2.5	2.6	2.0	1.0	Worthington 1976
(51) Rajasthan Canal	0.20	7.8	1.5	0.6	0.7		0.5		1.7	0.7	0.6	2.5	1.9	Worthington 1976
Indonesia														
(52) Well Near Bandung, Java	0.34	7.3	1.7	0.8	0.7	0.2	0.2	0.4	2.8	0.6	0.7	2.1	1.3	Pulawski and Obro 1976

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.)	Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x [2]	Reference
				----	----	----	me/l	----	----	----					
	Niue Island														
(53)	Well No. 42 at Tuila	0.40	7.7	2.8	1.2	0.3	0	0.4	0.1	4.0	0.2	0.3	2.3	1.5	Jacobson and Hill 1980
(54)	Well, Fonuakula	0.32	7.6	2.2	0.7	0.3	0.1	0.3	0.1	2.7	0.2	0.3	3.1	1.6	Jacobson and Hill 1980
	Pakistan														
(55)	Well Water at Shadman	1.12	7.5	2.7	1.5	3.3	0.1	0.6	1.2	6.0	2.3	1.3	1.8	1.2	Clarke 1980
(56)	Tubewell No. 36, Mona Reclamation Project	3.65	7.5	1.6	6.7	30.8		14.5	15.3	9.4	15	16	0.2	0.8	Mona Reclamation Project 1972
(57)	Tubewell No. 49, Mona Reclamation Project	2.08	7.6	1.3	2.1	19.1		5.7	7.0	10.0	15	16	0.6	0.6	Mona Reclamation Project 1972
(58)	Well No. BR-25 at Bari Doab	1.09	7.3	4.9	1.7	5.0		2.0	4.9	4.7	2.7	3.6	2.9	2.1	Ahmed 1972
(59)	Indus River at Attock	0.25	7.7	1.8	0.7	0.6		0.4	0.4	2.3	0.5	0.6	2.6	1.6	Ahmed 1972
(60)	Jhelem River at GT Road	0.25	7.4	1.7	0.6	0.4		0.2	0.6	1.7	0.4	0.3	2.8	1.9	Van't Leven 1964
(61)	Sutlej River at Ganda	0.34	7.6	1.8	0.4	1.2		0.4	0.8	2.2	1.1	1.2	4.5	1.6	Ahmed 1972
(62)	Tubewell No. 116, Mona Reclamation Proejct	3.60	7.7	2.5	4.0	32.0		25.0	8.9	4.5	18	19	0.6	1.7	Mona Reclamation Project 1972
	Philippines														
(63)	Matuno River at Nueva Vizcaya	0.23	7.8	1.4	0.4	0.4	0.1	0.2	0.3	2.0	0.4	0.4	3.5	1.4	National Irrig. Admin. 1984
(64)	Palsiguan River at Abra	0.29	8.3	1.6	0.6	0.5	0	0.2	1.0	1.5	0.5	0.4	2.7	1.9	National Irrig. Admin. 1984
(65)	Jalaur River at Iloilo	0.31	8.3	1.8	0.9	1.2	0	0.2	0.5	0.2	1.0	1.0	1.2	1.1	National Irrig. Admin. 1984
(66)	Diezmo River at Laguna	0.35	8.2	1.4	0.8	0.8	0.1	1.9	0.2	2.3	0.8	0.8	1.8	1.3	FAO 1975
(67)	Well No. P-18 at Laguna	0.48	7.4	1.6	1.8	1.4	0.1	0.4	0.7	3.8	1.1	1.2	1.6	1.1	FAO 1975
(68)	Well No. CL-42 at Bulacan	2.83	7.8	2.8	0.4	22.9	0.1	24.5	0.2	1.6	18	16	7.0	3.7	National Irrig. Admin. 1984
	Sri Lanka														
(69)	Well in Vanathavillu Basin	2.90		11.8	5.2	11.6		19.3	2.4	7.8	4.0	5.8	2.3	2.8	Lawrence and Dharmagunawardena 1983
	South Korea														
(70)	Well No. 40 at Cheju Island	0.14	8.1	0.8	0.1	0.7	0.1	0.7	0	1.0	1.0	0.8	8.0	1.6	FAO 1972a
(71)	Well No. TW-9 at Anyang	0.22	6.7	0.5	0.4	0.4	0	1.2	0.4	0.4	0.6	0.4	1.3	2.2	FAO 1972a
(72)	Well No. TW 67-5 at Seoul	1.06	6.3	5.1	2.7	1.2	0.2	3.2	5.6	0.6	0.6	0.5	1.9	9.6	FAO 1972a
(73)	Namba-gang River (Han-gang)	0.20		1.1	0.5	0.2	0	0.2	0.2	1.4	0.2	0.2	2.2	1.6	FAO 1972a

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/1	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
Thailand														
(74) Mae Kong River	0.28	7.0	1.7	0.5	0.5		0.4	0.4	1.9	0.5	0.5	3.4	1.9	Kobayashi 1959
(75) Mae Nam Chao Phraya River	0.30	6.8	1.7	0.5	0.7		0.5	0.1	2.5	0.7	0.7	3.4	1.4	Kobayashi 1959
EUROPE														
Cyprus														
(76) Well No. 74-74 (Gypsum Aquifer)	2.43	7.4	20.6	5.8	7.3	0.2	4.1	28.5	1.4	2.0	2.6	3.6	10.4	Krentos 1978 [3]
(77) Well No. 92/75 (Gypsum Aquifer)	3.00	7.8	30.3	9.9	5.7	0.2	5.4	36.0	4.6	1.3	1.9	3.1	8.3	Krentos 1978 [3]
(78) Well No. EB-17 (Sandstone Aquifer)	3.58	7.8	4.3	14.0	24.0	0.4	16.5	21.5	5.0	7.9	8.5	0.3	2.1	Krentos 1978 [3]
(79) Lakatamia Reservoir	1.62	7.5	1.8	3.4	11.7	0.2	8.6	2.4	6.0	7.4	8.0	0.5	0.9	Water Development Dept. 1978
Germany (FR)														
(80) Treated Wastewater at Braunschweig	1.11	7.1	4.0	2.8	3.4	0.8	3.6	2.8	4.6	1.8	2.2	1.4	1.9	Tietjen et al. 1978
(81) Oker River	0.98	7.2	4.0	2.7	3.0	0.3	4.3	4.2	1.5	1.6	1.7	1.4	3.8	Tietjen et al. 1978
(82) Erse River	1.91	7.1	8.0	5.3	4.3	1.4	12.8	6.0	0.5	1.7	1.3	1.5	16.4	Tietjen et al. 1978
Greece														
(83) Potmaia Spring, Molai Area	0.92	7.2	6.3	3.2	1.0	0	1.0	1.1	8.4	0.4	0.6	2.0	1.7	FAO 1981a
(84) Well No. E-1, Elea Area	1.18	8.0	5.7	3.3	3.4		4.2	2.2	6.0	1.6	2.0	1.5	2.5	FAO 1981a
(85) Well No. OB-1, Malai Area	0.42	7.9	2.3	2.0	0.3		0.3	0.1	4.2	0.2	0.2	1.2	1.4	FAO 1981a
(86) Well No. E-81, Elea Area	3.10	7.9	4.3	6.2	17.0		21.5	3.2	2.8	7.4	8.0	0.7	2.8	FAO 1981a
(87) Groundwater in Timbaki Basin, Messara	0.69	8.4	2.0	2.9	2.1		2.4	2.2	2.6	1.3	1.4	0.7	1.7	FAO 1972c
(88) Groundwater in Mires Basin, Messara	0.83	8.1	3.9	2.7	2.4		2.6	3.1	2.5	1.3	1.4	1.4	2.8	FAO 1972c
(89) Groundwater in Protoria Basin, Messara	0.46	8.1	1.9	1.2	1.5		1.5	0.4	2.7	1.2	1.3	1.6	1.5	FAO 1972c

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x [2]	Reference
Spain														
(90) Rio Guadalquivar at E. de Mengibar	0.89	8.2	4.2	3.2	3.7		3.5	4.5	2.8	1.9	2.2	1.3	2.7	Comisión de Recursos Hydraulicos 1974
(91) Río Segura at Cieza	0.43	8.5	2.3	2.8	1.0		1.0	2.3	2.3	0.6	0.7	0.8	1.9	Comisión de Recursos Hydraulicos 1974
(92) Río Guadiana at E. de Cijara	0.61	8.1	4.0	3.1	1.1		1.4	5.3	1.3	0.6	0.6	1.3	4	Comisión de Recursos Hydraulicos 1974
(93) Bardenas Canal at Zaragoza	0.28	7.8	2.8	0.2	0.7		0.5	0.3	2.2	0.6	0.6	14.0	2.3	Beltran 1978
(94) Irrigation Well, Bardenas-Alto Irrigation Scheme	2.7	7.6	5.6	3.9	19.5		11.7	7.5	8.7	8.9	12	1.4	1.8	Beltran 1978
Turkey														
(95) Carsamba River at Cumra	0.45	8.0	3.0	0.9	0.5	0.3	0.4	0.3	3.	0.4	0.4	3.3	1.7	FAO 1965b
(96) Beysehir Golu	0.40	7.6	3.0	0.7	0.5	0	1.0	1.1	2.4	0.5	0.4	4.3	2.3	FAO 1965b
LATIN AMERICA														
Argentina														
(97) Rio Pichanas at Cordoba	0.59	7.4	1.5	1.0	3.6	0.2	1.2	1.5	3.6	3.2	3.6	1.5	1.1	FAO 1981b
Bolivia														
(98) Rio Sulti, Angostura Irrigation Scheme	0.68		1.0	1.0	4.0	0.4	1.7	1.2	3.5	4.0	4.1	1.0	0.9	Westcot 1979
(99) Well No. BC-33 at Pampa Manata	0.43	7.4	1.1	0.9	2.7		1.0	0.5	2.2	2.7	2.6	1.2	1.2	Sagardoy 1980
(100) Well No. BC-50 at La Banda	0.40	8.6	0.6	0.7	3.3		2.3	0.6	1.2	4.1	3.4	0.9	1.2	Sagardoy 1980
Brazil														
(101) Amazon River at Abidos	0.04	6.5	0.2	0.1	0.1		0.1	0.6	0.3	0.2	0.1	2.0	1.4	Oltman 1968
Chile														
(102) Bio Bio River	0.05	7.1	0.3	0.1	0.1	0	0	0.1	0.5	0.2	0.1	3.0	1.2	Durum 1960
Columbia														
(103) Río Cauca	0.87		3.5	4.4	3.7		0.5	1.6	7.8	1.8	2.2	0.8	1.2	Pla 1984[4]
(104) Río Amaine	0.55		3.0	2.6	0.8		0.5	0.4	5.1	0.5	0.6	1.2	1.4	Pla 1984[4]
(105) Well at Hda Marsella	0.38		1.4	0.7	2.2		0.3	0.1	3.6	2.2	2.4	2.0	1.0	Pla 1984[4]

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
Dominican Republic														
(106) Río Yaque	0.71		3.0	1.3	2.7		1.7	1.8	3.6	1.8	2.2	2.3	1.7	Pla 1984[4]
El Salvador														
(107) Río Lempa at Planicie	0.22	8.3	1.1	0.7	0.9	0.2	0.4	0.4	2.1	1.0	0.9	1.6	1.2	FAO Files
(108) Río Jiboa at Planicie	0.63	8.2	1.2	0.6	4.4	0.3	3.6	0.6	2.5	4.6	4.3	2.0	1.3	FAO Files
(109) Well No. 5a at Planicie	0.42	7.9	2.4	0.9	1.1	0.3	0.8	0.2	3.7	0.9	1.0	2.7	1.5	FAO Files
(110) Río Grande de San Miguel	0.50	8.3	2.6	1.2	1.7	0.2	1.8	0.7	4.5	1.2	1.5	2.2	1.4	FAO 1964
(111) Río Calentura	0.75	7.5	2.2	2.3	3.0	0.1	3.4	0.4	4.7	2.0	2.2	1.0	1.2	FAO 1964
(112) Well No. U62-50-D at San Miguel Basin	0.40	7.5	1.8	1.8	0.8	0.1	0.5	0.9		0.6	0.7	1.0	1.2	FAO 1964
Guyana														
(113) Well near Georgetown	0.60		0.3	2.0	3.6	0.3	5.2	0.5	1.3	3.4	3.1	0.2	0.8	Arad 1983
Haiti														
(114) Well in Moustiques Region	2.8	7.5	4.2	11.2	12.0	0.3	10.5	12.2	8.5	4.3	4.8	0.4	1.5	FAO 1970c
(115) Well in Mapou Sedren Region	0.7	7.7	1.9	2.9	3.0	0.1	1.8	0	6.2	1.9	2.2	0.6	0.9	FAO 1970c
(116) Well in Desronville Region	1.1	7.1	2.3	5.1	2.8	0.1	2.8	0	7.5	1.5	1.6	0.5	1.0	FAO 1970c
Jamaica														
(117) Well Water	1.36		4.4	1.8	8.1		8.2	3.0	3.2	4.6	5.4	2.4	2.6	FAO 1974
(118) Milk Water	0.84	7.9	4.4	2.8	0.8	0.1	3.2	0.6	4.8	0.4	0.5	1.6	2.1	FAO 1974
Mexico														
(119) Canal Menor at Mexicali Valley	1.35		4.2	3.4	6.5		6.4	4.6	3.5	3.6	3.8	1.2	2.6	Payne et al. 1979
(120) Canal Presa at Morales, Mexicali Valley	1.50		2.5	4.9	9.4		6.2	7.2	3.6	4.9	5.2	0.5	1.7	Payne et al. 1979
(121) Welton-Mohawk Drain, Mexicali Valley	6.20		6.8	6.2	46.5		34.6	18.2	7.0	18	22	1.1	2.6	Payne et al. 1979
(122) Well No. IV-6, Mesa de San Luis, Mexicali Valley	1.70		4.0	2.0	12.6		14.3	2.8	1.8	7.2	7.5	2.0	3.7	Payne et al. 1979
(123) Well No. 981DER, Mexicali Valley	3.40		12.2	6.1	15.8		13.8	14.2	6.4	5.2	7.1	2.0	3.7	Payne et al. 1979
(124) Well at Valladolid, Yucatan	1.17	7.3	6.5	2.5	3.6	0.2	4.4	0.4	7.0	1.7	2.4	2.6	2.1	Back and Hanshaw 1970

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(Analysis No.) Sample Site	EC dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
Nicaragua														
(125) Well No. 5 at Masaya	3.20		14.0	3.9	12.6	0.6	16.6	10.6	5.4	4.2	6.2	3.6	4.3	Eckstein 1982
(126) Well No. 14 at Nandaime	0.48		2.0	1.1	1.4	0.3	0.4	0.1	3.9	1.1	1.3	1.8	1.2	Eckstein 1982
Peru														
(127) Pisco River (upstream) Costal Area	0.67	7.8	2.7	0.9	2.1	0.1	2.4	0.3	2.8	1.5	1.7	3.0	2.0	ONERN 1973
(128) Pisco River (downstream) Costal Area	5.83	7.7	18.0	4.5	36.5	0.4	38.5	16.9	3.5	11	15	4.0	7.6	ONERN 1973
(129) Ica River, Costal Area	0.31	8.2	1.5	0.5	0.7	0.1	0.5	0.2	2.0	0.7	0.7	3.0	1.5	ONERN 1973
(130) Majes/Camana River Costal Area	0.38	7.2	1.6	0.5	0.8	0.1	1.0	0.2	1.7	0.8	0.7	3.2	1.9	ONERN 1973
(131) Well No. 69/60-R1 at Valle del Rio Huamra	0.59	7.6	2.9	1.4	1.7	0.1	1.5	0.7	3.4	1.2	1.4	2.1	1.8	FAO 1970d
(132) Well No. 73/20-R1 at Llanura de Huacho	1.98	7.6	9.6	4.8	5.3	0.6	5.0	2.9	10.4	2.0	2.8	2.0	2.2	FAO 1970d
Venezuela														
(133) Río Limón	0.82		6.5	1.6	1.4		2.3	2.6	4.6	0.7	1.0	4.1	2.4	Pla 1984[4]
(134) Río Palmar	0.96		1.3	3.6	2.8		0.2	6.2	1.8	1.8	1.7	0.4	1.6	Parra 1976
(135) Río Unare	0.26		0.6	0.6	1.2		0.7	0.8	1.2	1.6	1.3	1.0	1.2	Pla 1984[4]
(136) Well at Coro	2.47		13.9	5.1	7.5		17.0	6.5	2.9	2.4	3.1	2.7	6.5	Pla 1984[4]
(137) Well at Carora	1.53		4.6	7.5	5.1		1.7	10.8	6.0	2.1	2.4	0.6	1.9	Pla 1984[4]
(138) Río Tinaco	0.34		1.6	1.6	0.3		0.1	0.1	3.6	0.2	0.3	1.0	1.1	Pla 1984[4]
NEAR EAST AND NORTH AFRICA														
Algeria														
(139) Well Water at Sidi	2.80	7.2	11.1	7.6	9.5	1.1	13.4	13.3	3.1	3.1	3.8	1.5	5.2	Clarke 1980
(140) Coastal Well	1.10		0.8	0.9	9.4		2.0	2.0	7.1	10	11	0.9	0.5	Anon.
Bahrain														
(141) Wadi Water	0.98	7.6	1.7	3.9	8.0	0.2	8.0	4.4	1.4	4.8	4.5	0.4	2.5	Amer 1983
(142) Budaya Well	3.62	7.2	11.0	6.9	17.6	0.7	24.0	9.2	3.0	5.9	6.9	1.6	6.2	Amer 1983

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(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
Bahrain (continued)														
(143) Well No. 10 at Barbar	5.61	7.1	21.4	11.9	32.5	1.5	38.0	25.6	3.7	8.0	10	1.8	9.2	Amer 1983
(144) Well No. 4 at Arad	3.84	7.3	11.2	7.3	18.9	0.9	28.0	7.0	3.3	6.2	7.5	1.5	5.4	Amer 1983
Egypt														
(145) Well Water at Kharga IA	0.30	6.9	0.7	0.4	1.0	0.7	1.0	0.3	1.7	1.4	1.2	1.8	1.0	Clarke 1980
(146) Mechanized Farm Canal, Pump Station I	0.98	8.1	1.5	1.5	6.5	0.2	3.4	6.5	0.3	5.3	3.3	1.0	6	FAO 1980a
(147) Mechanized Farm Canal, Pump Station II	4.13	8.0	5.1	4.9	31.3	0.3	21.1	20.8	0.3	14	9.3	1.0	18	FAO 1980a
(148) Mechanized Farm Canal Pump Station III	4.15	8.0	6.2	4.3	31.3	0.3	21.1	21.7	0.5	14	11.2	1.4	11	FAO 1980a
(149) Noubaria Canal at Mechanized Farm Canal Intake	0.6		2.4	1.1	3.5	0.2	2.8	2.0	1.5	2.6	2.5	2.2	3	FAO 1980a
(150) Nile River at Cairo	0.4		1.4	1.0	1.0		0.6	0.4	2.6	0.9	0.9	1.4	1.3	Fathi & Soliman 1972
(151) Bahwari Drain Water	5.2		4.5	15.0	30.0		41.5	14.1	4.3	9.6	10	0.3	2.5	Fathi & Soliman 1972
(152) Well Tamar No. 5, Sinai	2.80		7.6	5.0	16.8	0.6	17.5	8.1	4.5	6.7	8.0	1.5	3.7	Issar **et al.** 1972
(153) Well Nakhel, Sinai	2.20		5.8	7.6	9.6	0.5	10.0	10.0	3.6	3.7	4.1	0.6	3.5	Issar **et al.** 1972
(154) Wells in New Valley (Kharga Oasis)	0.63	7.0	1.6	1.4	1.7	0.7	3.3	0.6	1.7	1.4	1.3	1.1	2.0	Hefny 1984
(155) Well in Nile Valley, Upper Egypt	0.60	7.3	3.2	2.1	1.5	0.2	1.2	0.3	5.5	0.9	1.1	1.5	1.4	Hefny 1984
(156) Well at El Arish, Sinai	3.74	7.6	18.5	12.0	18.5	0.5	36.3	9.8	3.0	4.6	5.6	1.5	8.6	Hefny 1984
Ethiopia														
(157) Groundwater, Gode Research Sta.	3.80	8.8	32.0	4.0	8.0	3.0	9.0	18.2	10.0	1.9	3.8	8.0	4.9	Ochtman & Debele 1975
(158) Wadi Shebelle at Godi (dry season)	0.3	8.0	1.8	0.8	0.4	0	0.2	1.0	1.9	0.4	0.3	2.2	1.9	Ochtman & Debele 1975
(159) Wadi Shebelle at Godi (beginning wet season)	1.98	7.4	18.1	2.2	1.0	0.1	0.7	16.3	2.0	0.3	0.4	8.2	10.4	Ochtman & Debele 1975
(160) Wadi Shebelle at Godi (wet season)	2.30	7.5	16.5	3.6	1.1	0.2	2.1	14.2	2.0	0.3	0.4	4.6	10.4	Ochtman & Debele 1975
(161) Awash River at Melka Sadi	0.3	8.5	1.4	0.1	2.6	0.1	0.4	0	2.5	3.0	3.1	14	1.3	Sellasie **et al.** 1983
(162) Awash River at Melka Weier	0.41	8.4	1.2	0.2	3.4	0.2	1.3	0.1	4.4	4.1	4.2	6.0	1.1	Sellasie **et al.** 1983

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
Iraq														
(163) Diyala River at The Diyala Weir	0.47	8.0	3.3	1.5	0.7	0	0.5	1.9	2.8	0.4	0.5	2.2	3	MacDonald & Partners 1971
(164) Euphrates River at Al Kaim	0.73		2.8	2.3	2.0		1.8	2.8	3.1	1.2	1.4	1.2	2.0	Hanna & Al-Talbani 1970
(165) Euphrates River at Samara	1.44		3.3	3.5	4.3		4.9	3.0	4.2	2.3	2.6	0.9	1.9	Hanna & Al-Talbani 1970
(166) Tigris River at Mosul	0.46		2.7	1.8	0.5		0.7	1.4	3.2	0.3	0.4	1.5	2.0	Hanna & Al-Talbani 1970
(167) Tigris River at Qurne	1.14		3.8	3.2	2.9		3.0	3.1	3.7	1.6	1.8	1.2	2.1	Hanna & Al-Talbani 1970
Jordan														
(168) Well No. PP 433 at Majdal	0.84	7.8	2.9	4.1	1.3	0.2	2.2	1.5	4.8	0.7	0.8	0.7	1.5	NRA Jordan 1978
(169) Well No. D-6, Wadi Dhuleil (1971 - Before irrigation)	0.60	8.3	1.1	1.9	2.4	0.2	3.0	1.1	2.1	2.0	1.9	0.6	1.2	Wye College 1975
(170) Well No. D-6, Wadi Dhuleil (1974 - After irrigation)	1.38		3.8	3.9	6.0		8.0	4.1	1.7	3.1	3.1	1.0	3.7	NRA Jordan 1978
(171) Well No. D-16 Wadi Dhuleil (1971 - Before irrigation)	0.44	8.0	0.7	1.0	2.4	0.3	1.7	0.5	2.2	2.6	2.4	0.7	0.9	NRA Jordan 1978
(172) Well No. D-16 Wadi Dhuleil (1974 - After irrigation)	0.80		1.7	2.3	4.0		4.9	1.6	1.3	2.8	2.6	0.7	2.4	Wye College 1975
(173) Well No. D-16 Wadi Dhuleil (1977 - After irrigation)	2.60	7.5	6.2	9.1	7.8	0.4	18.2	3.8	1.2	2.8	2.8	0.7	6.9	NRA Jordan 1978
(175) Well No. 1 El Jafr Region (1964 - Before irrigation)	1.80	7.4	6.1	5.8	5.9	0.1	10.7	3.2	4.6	2.4	2.9	1.0	2.7	NRA Jordan 1978
(175) Well No. 1 El Jafr Region (1974 - After irrigtion)	4.35	7.1	14.5	12.6	16.1	0.1	34.0	5.0	3.9	4.4	5.3	1.2	6.2	NRA Jordan 1978
Libya														
(176) Well No. 3, Kufra Project (Desert Farm)	0.16	7.6	0.7	0.4	0.5	0	0.4	0.5	0.6	0.6	0.4	1.8	2.2	Tipton & Kalmbach 1972
(177) Well No. 4 Kufra Project (Oasis Farm)	0.48	6.8	1.6	0.7	1.7	0.1	2.3	0.9	0.7	1.6	1.2	2.3	3.3	Tipton & Kalmbach 1972
(178) Well at Sarir Project	2.0		5.4	4.5	7.6	1.1	20.8	1.2	2.1	3.4	3.7	1.2	4.1	Anon.
Oman														
(179) Irrigation Well, Kamil Wafi District, Sharqiya Region	0.62	7.4	1.7	3.1	1.8	0	1.7	1.7	3.1	2.1	1.2	0.5	1.4	FAO 1980b

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR'	adj' RNa	Ca/Mg[1]	Ca_x[2]	Reference
Oman (continued)														
(180) Irrigation Well, Kamil Wafi District, Sharqiya Region	0.68	7.7	1.0	4.0	1.8	0	1.7	1.7	3.3	2.4	1.2	0.3	0.9	FAO 1980b
Qatar														
(181) Well No. A4	0.44	8.0	3.0	1.2	1.3		1.0	0.9	3.5	0.8	1.1	2.5	1.7	FAO Files
(182) Well No. A10	1.80	8.7	5.2	5.2	10.8		9.4	7.3	4.2	4.5	5.4	1.0	2.7	FAO Files
(183) Well No. B41	2.80	7.4	17.2	10.1	14.5		11.6	23.7	3.9	3.6	5.1	1.7	5.9	FAO Files
(184) Well El Araig	5.23	7.6	14.2	10.5	33.7	0.9	41.0	14.4	2.6	9.7	11	1.4	7.4	State of Qatar 1982
(185) Barada Farmgate Well	3.10	7.8	12.0	7.4	12.2		11.8	16.2	4.0	3.9	5.0	1.6	4.7	Anon.
(186) Sulaimi Oryx Farm	2.20	7.6	8.0	4.3	10.0		8.7	10.3	4.5	4.2	5.3	1.9	3.5	Anon.
(187) IDTC No. 1 East Well	0.67	7.8	3.2	1.9	1.7		1.4	1.4	4.0	1.1	1.3	1.7	1.7	Anon.
Saudi Arabia														
(188) Well No. 2 Shaikhiya	2.00		13.5	4.9	4.7		5.1	15.6	2.7	1.5	2.0	2.8	6.5	FAO Files
(189) Well at Ashali	0.90		6.5	1.6	1.0		1.1	6.9	1.4	0.5	0.5	4.1	6.1	FAO Files
(190) Well at Ain Ghulaib	3.30		30.4	4.3	8.2		7.6	33.1	1.3	2.0	2.5	7.1	17.3	FAO Files
Syria														
(191) Khabour River at Ras-el-Ain	0.39	6.6	2.5	1.6	0.4	0.1	0.4	0.8	2.9	0.3	0.3	1.6	1.8	Burdon and Safadi 1963
(192) Well in Res-el-Ain Area	0.42	6.2	3.0	2.2	0.6	0.1	1.4	0	4.4	0.4	0.4	1.4	1.5	Burdon and Safadi 1963
Tunisia														
(193) Medjerda River at El Aroussia (Dry season)	5.30		12.8	8.8	34.0		19.6	21.2	2.2	10	12	1.4	9.2	Van't Leven and Haddad 1967
(194) Medjerda River at El Aroussia (Wet season)	0.90		3.6	2.0	3.5		4.0	3.1	1.7	2.1	2.2	1.8	3.5	Van't Leven and Haddad 1967
United Arab Emirates														
(195) Hamraniyah Station (Ras Al Khaimah)	2.3	8.2	2.5	3.9	12.4	0.4	12.6	4.6	4.6	6.9	7.5	0.6	1.5	Savva **et al.** 1984
(196) Dhaid Station (Sharjah)	0.8	8.5	0.7	1.7	3.4	0.2	2.2	0.9	2.8	1.7	3.0	0.4	0.8	Savva **et al.** 1984
Yemen Arab Republic														
(197) Wadi Sudan (Taiz)	1.90	8.6	2.0	4.6	13.5	0.1	5.1	4.9	8.2	7.4	8.1	0.4	0.9	Dewan **et al.** 1978

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
Yemen Arab Republic (continued)														
(198) Wadi Dabab (Taiz)	0.70	8.2	2.6	1.5	3.0	0.1	1.6	0.4	5.0	2.1	2.6	1.7	1.3	Dewan **et al.** 1978
(199) Wadi Resyan (Tihama Region)	2.65	7.8	5.0	4.2	22.5	0.2	14.5	10.9	5.2	10	12	1.2	2.3	Dewan **et al.** 1978
(200) Well No. 5 (Haugla Wells) Taiz	3.60	7.3	4.8	11.6	24.5	0.2	13.0	11.6	8.4	8.6	9.5	0.4	1.7	Dewan **et al.** 1977
(201) Well No. 6, Bowsan	1.31	8.6	1.1	1.0	11.0	0.1	2.8	4.3	6.0	11	12	1.1	0.7	Ozkan 1978
(202) Well No. 16, Bayt Masar	2.15	8.0	11.7	6.6	6.0	0.1	4.0	16.0	4.4	2.0	2.6	1.8	4.1	Ozkan 1978
(203) Wadi AL Haima (km 0), Taiz	0.57	8.0	3.0	2.1	1.6		0.8		5.1	1.0	1.2	1.4	1.4	Hazen and Sawyer 1979
(204) Wadi Al Haima (km 9), Taiz	2.90	8.1	5.0	10.5	17.4		11.3		11.7	6.2	7.1	0.5	1.4	Hazen and Sawyer 1979
(205) Wadi Al Haima (km 12), Taiz	4.73	8.1	5.5	18.5	34.8		20.4		14.3	10	11	0.3	1.3	Hazen and Sawyer 1979
(206) Wadi Al Haima (km 17), Taiz	5.88	8.1	1.2	5.0	43.5		5.92		12.4	25	26	0.2	0.6	Hazen and Sawyer 1979
(207) Wadi Al Haima (km 25), Taiz	8.01	8.2	1.2	4.8	63.1		8.46		12.4	36	38	0.3	0.6	Hazen and Sawyer 1979
NORTH AMERICA														
United States of America														
(208) Gage Canal in California	0.5		2.9	0.7	1.5		0.7	1.6	2.8	1.1	1.6	4.1	2.0	Bingham **et al.** 1979
(209) Salt Slough, San Joaquin Valley, CA (Irr. runoff)	1.06	7.6	2.7	2.1	5.3	0.1	4.8	2.6	2.5	3.5	3.7	1.3	2.1	US Bureau of Reclamation 1980
(210) Delta Mendota Canal in CA	0.69		2.8	0.8	3.5		2.0	3.3	1.0	2.6	2.2	3.5	4	Tanji 1977
(211) Broadview Water District Drainage Water, CA	4.81		14.5	9.0	31.0		21.3	30.0	2.8	8.9	11	1.6	7	Tanji 1977
(212) Broadview Water District Blended Supply, CA	3.23		10.0	5.5	20.0		14.0	18.5	2.4	7.2	8.4	1.8	6	Tanji 1977
(213) Well No. 1, Llano Chimayo, New Mexico	0.75	7.9	1.1	1.0	6.5	0.1	1.5	0.8	4.0	6.4	6.7	1.1	0.9	Environmental Improvement Agency 1974
(214) Well No. 1, Columbus, New Mexico	1.10	8.4	0.4	0.3	11.5	0.2	1.8	3.8	6.3	20	20	1.3	0.4	Environmental Improvement Agency 1974
(215) Well No. 4, Clovis, New Mexico	0.45	8.1	1.4	1.8	1.4	0.2	0.3	0.4	3.9	1.1	1.2	0.7	0.9	Environmental Improvement Agency 1974
(216) California Aqueduct at Lost Hills, CA	0.68		1.7	1.2	3.4	0.1	2.8	1.9	1.6	2.9	2.7	1.4	2.0	Rhoades 1984a & b
(217) Well Water at Lost Hills, CA	7.93		26.0	13.0	50.6	0.2	49.5	37.8	2.5	11.4	14	2.0	12.6	Rhoades 1984a & b

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K (me/l)	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
United States (continued)														
(218) Blended Well and Aqueduct Water at Lost Hills, CA	4.91		14.8	7.5	28.7	0.2	27.7	21.2	2.2	8.6	10	2.0	8.6	Rhoades 1984a & b
(219) Colorado River at Imperial Valley, CA	1.48	7.9	4.6	2.9	9.5	0.1	4.3	9.2	2.9	6.1	5.7	1.6	2.6	Rhoades 1984a & b
(220) Alamo River (Drain) at Imperial Valley, CA	4.64		11.4	11.8	33.6	0.3	23.5	26.9	5.0	9.9	12	1.0	4.2	Rhoades 1984a & b
(221) Well at Safford Experiment Station, Arizona	3.2	7.5	5.6	2.3	28.9	0	20.6	8.1	7.4	15	20	2.4	2.0	Dutt **et al.** 1984
(222) Rio Grande River at Otawi Bridge (km 0)	0.37		2.2	0.6	1.0	0	0.2	1.3	2.3	0.9	0.9	3.7	1.9	Wilcox 1948
(223) Rio Grande River at Elephant Butte (km 386)	0.63		2.7	0.9	2.5	0.1	1.0	2.6	2.6	1.9	2.1	3.0	2.0	Wilcox 1948
(224) Rio Grande River at Caballo Dam (km 431)	0.69		2.9	0.9	2.9	0.1	1.5	2.6	2.8	2.1	2.4	3.2	2.0	Wilcox 1948
(225) Rio Grande River at Leasburg Dam (km 512)	0.80		3.4	1.1	3.4	0.1	1.9	3.2	3.0	2.3	2.6	3.1	2.3	Wilcox 1948
(226) Rio Grande River at El Paso (km 604)	1.32		4.6	1.5	7.2	0.1	4.0	5.9	3.7	4.1	5.1	3.1	2.5	Wilcox 1948
(227) Rio Grande River at Fort Quitman (km 734)	5.82		15.6	7.0	39.7	0.2	39.2	18.5	4.8	12	16	2.2	5.8	Wilcox 1948
(228) Well Denver, Colorado (Greenhouses)	0.63	7.8	0.3	5.5	1.7		0.5	1.7	4.9	1.0	1.0	0.1	0.3	Hanan 1973
(229) Well Denver, Colorado (Greenhouses)	1.47	7.8	1.0	10.3	5.9		0.3	10.1	5.9	2.5	2.5	0.1	0.7	Hanan 1973
(230) San Joaquin River at Friant, California	0.06		0.2	0.1	0.2	0.1	0.1	0.1	0.4	0.5	0.3	2.0	1.1	USGS 1974
(231) Feather River at Nicolaus, California	0.09		0.4	0.3	0.1	0.1	0.1	0.1	0.7	0.2	0.1	1.3	1.2	USGS 1974
(232) Columbia River at Dallas, Texas	0.21	7.9	1.2	0.5	0.7	0	0.1	0.4	1.8	0.8	0.7	2.4	1.4	Durum **et al.** 1960
(233) Sacramento River at Tower Bridge, CA	0.18	7.2	0.6	0.6	0.5	0.3	0.3	0.3	1.3	0.7	0.6	1.0	1.1	Durum **et al.** 1960
(234) Snake River at King Hill, Idaho	0.50		2.3	1.6	1.3	0.1	0.7	1.1	3.5	0.9	1.0	1.8	1.5	USGS 1974

WATER ANALYSES OF 250 SELECTED IRRIGATION SUPPLIES FROM VARIOUS LOCATIONS IN THE WORLD

(Analysis No.) Sample Site	EC_w dS/m	pH	Ca	Mg	Na	K me/l	Cl	SO_4	HCO_3	SAR[1]	adj[1] RNa	Ca/Mg[1]	Ca_x[2]	Reference
United States (continued)														
(235) Colorado River at Yuma, AZ	1.38		5.2	2.6	6.4	0.2	4.0	7.6	2.8	3.2	3.7	2.0	3.4	USGS 1974
(236) Salt River at Stewart Dam, AZ	1.38		1.2	2.6	8.9	0.2	9.1	1.0	2.8	6.5	6.4	0.5	1.3	USGS 1974
(237) Pecos River at Artesia, NM	3.37		20.4	6.2	13.3	0	13.8	23.8	2.3	3.6	4.6	3.3	10.9	USGS 1974
(238) Gila River at Gillespie Dam, AZ	7.42		17.0	12.0	53.1	1.2	49.7	28.1	5.5	14	18	1.4	6.0	USGS 1974
(239) Mississippi River at Luling Ferry, LA	0.42	7.5	2.1	1.0	1.1	0.1	0.9	1.2	2.2	0.9	0.9	2.1	1.9	USGS 1950
(240) James River at Huron, SD (Before irrigation use)	1.23		3.6	3.6	5.8		2.0	5.7	5.8	3.1	3.6	1.0	1.6	Worthington 1976
(241) James River at Huron, SD (After irrigation use)	1.71		5.4	4.8	7.6		2.1	10.5	5.5	3.4	4.1	1.1	2.2	Worthington 1976
(242) San Joaquin River at Vernalis, California	0.80	7.8	2.5	1.3	4.0	0.1	3.7	1.2	2.7	2.9	2.9	1.9	2.4	US Bureau of Reclamation 1980
(243) Well in North Kern, Ca	0.17	8.0	0.4	0.1	1.4	0	0.3	0.3	1.1	2.8	1.9	4.0	0.9	DWR 1965
(244) Well near Riverdale, CA	0.97	8.2	0.3	0	10.4	0	1.1	0	9.5	27	32		0.2	DWR 1965
(245) Well near Riverdale, CA	0.49	9.1	0.1	0	4.7	0	1.4	0.3	3.0	21	15		0.2	DWR 1965
(246) City of Bakersfield, CA (Wastewater)	0.88	7.0	2.3	0.4	4.7	0.7	3.0	1.5	3.6	4.1	4.7	5.8	1.6	EPA 1979
(247) City of Santa Rosa, CA (Drinking Water)	0.31		1.3	1.3	0.4	0	0.1	0.3	2.5	0.4	0.4	1.0	1.21	Bain and Esmaili 1976
(248) City of Santa Rosa, CA (Municipal Wastewater)	0.70		2.0	1.6	3.9	0.3	3.3	1.4	2.7	2.9	3.1	1.3	1.6	Bain and Esmaili 1976
(249) Tuolumne Regional Water District CA	0.35		1.2	0.9	1.2	0	1.2	0.8	1.3	1.2	1.0	1.3	1.9	Tuolumne Regional Water District 1980
(250) City of Fresno, CA (Municipal Wastewater)	0.69	7.2	1.3	1.1	3.4	0.4	2.0	2.0	3.6	3.1	3.4	1.2	1.0	State Water Resources Control Board 1981

[1] Values shown are calculated by procedures given in text.

[2] From Table 11.

[3] Personal communication. Data supplied by Dr. V.D. Krentos, Agricultural Research Service, Nicosia, Cyprus.

[4] Personal communication.

ANNEX II

GLOSSARY

BOTULISM: poisoning from ingesting botulin (Clostridium botulinum), which affects the central nervous system producing difficulty in swallowing, visual disturbances and respiratory paralysis.

BRONZING: reddish-brown discoloration of leaves or stalks indicating a nutrient deficiency.

CHISELLING: mechanical preparation of land leaving it in a rough, cloddy condition, which helps to control wind erosion during dry periods and assists infiltration when the rain starts, or irrigation.

CHLOROSIS: yellowing or bleaching of green portion of a plant, particularly the leaves. May be caused by disease organisms, nutrient deficiencies, or other factors, e.g. low temperatures.

CORROSION (ELECTROLYTIC): corrosion (of well screens, pump components, cases or pipes) due to electrolytic action induced by metals from which the units are manufactured (see ELECTROLYTIC PROCESS).

DENITRIFICATION: the reduction of nitrates to atmospheric nitrogen and oxides of nitrogen.

DISEASE VECTOR: the living transporter and transmitter of the causative agent of a disease.

DRAINAGE WELL: a well from which water is pumped in order to lower the water table.

DRIP IRRIGATION: form of localized irrigation whereby the water is emitted from a tube or pipe in drips or drops (see LOCALIZED IRRIGATION).

ELECTRICAL CONDUCTIVITY (ECe): of the saturation paste at 25°C. The property of a substance to transfer an electrical charge (reciprocal of resistance). Used for the measurement of the salt content of an extract from a soil when saturated with water. Measured in dS/m, mS/cm, or μS/cm.

ELECTROLYTIC PROCESS: a process whereby the conduction of electricity induces chemical changes leading to solution or melting of substances.

ENCEPHALITIS: inflammation of the brain. Can be due to enteroviruses and certain arboviruses which cause serious central nervous system diseases (e.g. encephalitis). Vectors: mosquitoes (Culex), sandflies, gnats, midges and ticks.

EVAPOTRANSPIRATION (ET): rate of water loss through transpiration from vegetation plus evaporation from the soil.

EXCHANGEABLE SODIUM PERCENTAGE (ESP): the degree of saturation of the soil exchange complex with sodium; it may be calculated by the formula:

$$ESP = \frac{\text{exchangeable sodium (me/100 g soil)}}{\text{cation exchange capacity (me/100 g soil)}}$$

GYPSIFEROUS SOIL: soils that contain at least a percent of gypsum, i.e. calcium sulphate ($CaSO_4.2H_2O$). The range varies widely, e.g. 1% in Argentina and Brazil, or 5% in Syria.

LARVICIDE: a substance that kills larval stages of insects.

LEACHING FRACTION (LF): that portion of the irrigation water entering the soil that effectively must flow through and beyond the root zone in order to prevent the build-up of salinity. LF indicates that the value must be expressed as a fraction (see LEACHING REQUIREMENT).

LEACHING REQUIREMENT (LR): that portion of the irrigation water entering the soil that effectively must flow through and beyond the root zone in order to prevent the build-up of salinity. LR can be expressed either as a fraction or percentage of irrigation water.

LOCALIZED IRRIGATION: irrigation systems which wet, in particular, the area of soil at the base of the plant. Umbrella term for other irrigation systems such as: trickle, drip, drop, daily flow, micro.

LODGING: the beating down of crops by wind or rain; the tendency of certain long-stalked gramineae to collapse owing to nutrient deficiency.

LYMPHATIC FILARIASIS: infection in humans caused by filarial worms. The vectors are culicine or anopheline mosquitoes. Water habitat at larval stage.

MALARIA: infection in humans caused by four different malarial parasites (Plasmodium) introduced into the human bloodstream by the bite of an infected mosquito (Anopheles sp.) Water habitat at larval stage.

MOISTURE RETENTION CURVE: a graph showing the relationship between the amount of water remaining in the soil at equilibrium as a function of the matric suction. It is also known as soil-moisture characteristic curve.

MOLLUSCICIDES: a substance that kills molluscs (generally chemical).

NECROSIS: death of plant tissue due to disease, nutrient deficiency, toxicity, or climatic conditions, e.g. frost.

ONCHOCERCIASIS: or 'river blindness', disease caused by the filarial worm, Onchocerca volvulus. The vectors are black-flies (Simulium sp.). Water habitat at larval stage.

OSMOTIC EFFECT: the force a plant must exert to extract water from the soil. The presence of salt in the soil-water increases the force the plant must exert.

OSMOTIC POTENTIAL: the additional energy required to extract and absorb water from a salty soil.

READILY AVAILABLE SOIL MOISTURE: the depth of water between field capacity and wilting point stored in the root zone and available to the plant.

RESIDUAL SODIUM CARBONATE: a value that indicates the sodium hazard in water due to the loss of calcium and magnesium ions from the water by their reaction with bicarbonate and carbonate ions.

ROOT ZONE: the area of the soil from which the roots of a crop extract water and nutrients.

RUMINANT ANIMALS: any artiodactyl mammal of the suborder Ruminantia, the members of which chew the cud and have a stomach of four compartments; any other cud-chewing animal, e.g. the camel.

SALINITY PROFILE: a diagramatic representation of zones of varying levels of salinity, as exposed in a cut section of a field.

SALT INDEX: concerning fertilizer salts and compound fertilizers; an index of the extent to which a given amount of fertilizer increases the osmotic pressure of soil solution.

SATURATION INDEX: an estimate of carbonate precipitation from irrigation water as a function of the degree of calcium carbonate saturation of the soil solution.

SCHISTOSOMIASIS (bilharziasis): a disease caused by infestation of the body with blood flukes of the genus Schistosoma. Vector: intermediate host, snails. Water habitat or water-associated habitat.

SCHOONOVER GYPSUM REQUIREMENT TEST: a laboratory method of determining gypsum requirements of sodic soils; a method established by Mr. Schoonover.

SODIUM ADSORPTION RATIO (SAR): a ratio for soil extracts and irrigation water used to express the relative activity of sodium ions in exchange reactions with soil; expressed in me/l.

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

SOIL AGGREGATE: a single mass or cluster of soil consisting of many soil particles held together, such as a clod, prism, crumb or granule.

SOIL AMENDMENTS: a substance or material which improves soil by modifying its physical properties rather than by adding appreciable quantities of plant nutrients.

SOIL CRUSTING: soil crusts are formed as a result of compaction at the immediate surface due to an externally applied force. This force is supplied primarily by the impact of raindrops, and also by irrigation water, as the soil is wetted and the radiant energy of the sun dries the soil.

SOIL SOLUTION: the aqueous solution existing in equilibrium with a soil at a particular moisture tension.

SOIL-WATER: depth of water available in the root zone from earlier rain, snow, or irrigation which partly or fully meets the requirements of a crop.

SOIL-WATER POTENTIAL: the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation, at atmospheric pressure, to the soil-water at the point under consideration. The total soil-water potential is the sum of gravitational matric and osmotic potentials.

SPECIFIC ION TOXICITY: any adverse effect from a salt constituent in the substrata on plant growth that is not caused by the osmotic properties of the substrata.

TRANSPIRATION: rate of water loss through the plant which is regulated by physical and physiological processes.

WATER AMENDMENTS: chemicals added to water in order to improve certain soil-water properties such as increasing infiltration rates by causing a change in the chemical composition of the soil-water complex.

ABBREVIATIONS

dS/m	deciSiemens per metre
kg/ha	kilogramme per hectare
me/l	milliequivalent per litre
mg/l	milligramme per litre
mm/hr	millimetre per hour

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