Prognosis of salinity and alkalinity

FAO SOILS BULLETIN

31

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

CONTENTS

I. INTRODUCTION

The present need for more food and fibre entails reclamation and development of new land resources apart from an increase in the agricultural inputs necessary for greater production. Irrigated agriculture plays, and will continue to play, a major role in increasing the food supply - especially in arid and semi-arid regions. At present, heavy investments are being made in the development of irrigated farming in countries where the quality of either the soil or the water, or sometimes both, is not good enough to yield an economic return without the addition of reclamation measures or special management practices. Moreover, the deterioration of agricultural production on previously productive lands in the arid and semi-arid zones can be directly attributed to the evolution of salinity and alkalinity (sodicity).

There is no doubt that the early prediction of these hazards helps the timely setting up of land protection programmes. Unfortunately this concept has not been given the same attention as diagnosis and improvement. It is high time to voice clearly that protection is better than cure and to investigate the methodology of prognosis and monitoring of salt affected soils.

This Expert Consultation was held as a joint venture between FAO and the ISSS Sub-Commission on Salt Affected Soils. The meeting took place at FAO in Rome from 3-6 June 1975 and was chaired by Dr. I. Szabolcs, Chairman of the Sub-Commission on Salt Affected Soils; Prof. Dr. V. A. Kovda, past President, Dr. R. Dudal, Secretary-General and Dr. J. van Schilfgaarde, Vice-President of Commission VI on Soil Technology also participated. The Technical Secretary was Dr. Fathy I. Massoud of the FAO Soil Resources Development and Conservation Service. Thirteen experts from nine countries, a representative from Unesco and FAO staff also took part.

The purpose of the Consultation was to obtain expert advice on scientific and applied research activities in the prognosis of salinity and alkalinity with the objective of preparing a guideline for predicting salinity and alkalinity and to make recommendations on the measures needed for the implementation of the prognosis concept.

The following subjects were presented for discussion:

- extent and evolution of salt affected soils and economic land classification,
- factors to be considered for prognosis,
- methods of prognosis and monitoring,
- tentative guidelines.

During the Expert Consultation there was a short special session following the decision by the Administrative Committee on Coordination of the United Nations to entrust FAO with "the preparation of a world map of areas affected and areas likely to be affected by the process of desertification." The meeting considered the purpose of the map, having taken into consideration the constraints, and then outlined the scope of the map which, it is intended, shall be published by the end of 1976; to this end the master copy of the map should be ready by mid 1976.

Acknowledgements

The Consultation acknowledged its satisfaction with the work undertaken during its deliberations and with the recommendations formulated. It recognized the importance of this meeting as an international forum for exchanging information and promoting better understanding of the factors to be considered in and methodology of prognosis and monitoring of salinity and alkalinity. It expressed its appreciation to FAO, in cooperation with the ISSS Sub-Commission on Salt Affected Soils, for convening and servicing the meeting. The Consultation also extended its thanks to national and international institutions and organizations for releasing their experts to participate in this venture.

II. SUMMARY OF DISCUSSIONS

1. The Consultation considering the high investment involved in land reclamation and irrigation projects and the seriousness of possible failure of such projects and, recognizing that protection is better than cure, felt that proper planning should be based on:

a. sound economic and social justifications, not only on a short term basis but also on a long term one;

b. investigations on soils, hydrology, hydrogeology, topography, vegetation, climate, groundwater depth and quality, artesian water, irrigation water quality and quantity and crops;

c. surveys that are carried out regarding the land properties related to salt and water movement;

d. suitability of the land for development, not only within the project boundaries but as part of the surrounding land characteristics or the watershed area;

e. efficient management that is formulated in terms of specific environmental conditions.

2. The Consultation recognized the importance of prognosis of salinity and alkalinity which should be based on knowledge of processes involved, and realising the necessity of achieving and maintaining favourable salt balance and the value of early prediction of potential hazards, considered that measures should be taken to monitor regularly salinity and alkalinity changes by testing:

salt concentration and composition of the soil, irrigation and groundwater quality, depth to goundwater, water transmitting properties of the soil, environmental factors affecting evapotranspiration, crop performance and yield.

Also consideration should be given to using proper water management practices to push salts below the active root zone, to adequate drainage systems being provided and to desalination of the groundwater being maintained, especially where conditions become favourable for upward water movement and evaporation. Care must be taken in land levelling and other cultivation techniques, including mulching and fallowing. It was stressed that crop rotations should be considered not only in terms of their economic return, but also in terms of the suitability of crops in connection with soil and water qualities and their effect on the salt balance.

3. The Consultation took note of the new developments in the field of methodology, such as remote sensing, modelling and soil resistance measurements that facilitate the process of prognosis and monitoring. They also felt that related equipment and procedures for verification needed to be developed further. The use of the soil conductivity measurement technique was considered to be of particular interest.

4. It appeared to the Consultation that a considerable gap still exists between the basic principles available in the fields of soil and water sciences and their application to solve problems of salt affected soils. This gap was recognized to be due to inefficient application of existing sound practices or to the delay in dissemination of available knowledge. It was felt, therefore, that extension

services in soil and water management should be strengthened and that training, at various levels from planners to farmers, be stressed in the theoretical and practical aspects of causes, diagnosis, monitoring and remedies of salinity and alkalinity.

5. The discussion during the Consultation reflected the general agreement on the main factors and processes affecting salinity and alkalinity but there was a difference in views on the relative weight of some of those factors and in the methodology of prognosis. These differences in approach were due to different types of management systems. In order to make specific recommendations, avoiding risks of over generalization, it was suggested that research stations and institutes continue or initiate investigations on quantification of the various parameters of the salt balance appropriate to a regional condition. It was also felt that new methodology, such as remote sensing, should be evaluated for prognosis and monitoring of salinity and alkalinity and that modelling could serve as a tool in securing better management of irrigated lands and, therefore, its practical application should be verified under field conditions. The discussion on the methods of assessment of water quality for irrigation stressed that water quality criteria should be adapted to specific conditions.

III. RECOMMENDATIONS

The following recommendations were formulated by the Consultation on the basis of the presentation and discussion of the papers, with special reference to those dealing with methodology.

1. The Consultation, aware of the seriousness of the potential hazards of salinization and alkalization of existing and newly irrigated lands and on their environment, realizing the necessity of the early prediction of the unfavourable changes in the salt balance, recognizes the importance and need of guidelines for prognosis and monitoring of salinity and alkalinity and recommends that FAO, in cooperation with the ISSS Sub-Commission on Salt Affected Soils, continue the work in this field.

2. The Consultation recognizing that prognosis and monitoring of salinity and alkalinity needs to be based on an analysis of the processes involved and on carefully selected and quantified parameters, recommends that FAO make full use of research data available in institutions dealing with problems of salt affected soils. Furthermore, it is recommended that FAO promotes scientific and applied research, exchange of ideas, training and demonstration especially in developing countries in order to ensure experience on effective soil, crop and water management at the planning, engineering and operational levels and also on diagnosis and monitoring of salinity and alkalinity.

3. The Consultation was informed of the FAO/UNEP Project on "A World Assessment of Soil Degradation." This assessment would include salinity and alkalinity hazards besides other forms of soil degradation. The Consultation recommends that the work to be carried out on prognosis of salinity and alkalinity be closely linked and coordinated with the FAO/UNEP project on soil degradation and serves as a basis for promoting the development of monitoring activities in irrigated areas.

4. The Consultation being informed that the ISSS Sub-Commission on Salt Affected Soils would hold an in-between Congress meeting: International Congress on Managing Saline Water for Irrigation: Planning for the Future, in Texas USA in August 1976, recommends that a draft of the guideline, to be prepared by the FAO Secretariat, on prognosis and monitoring of salinity and alkalinity be ready prior to that date and be presented for comments to the meeting of the Sub-Commission.

IV. WORKING PAPERS

A. Evolution, Extent and Economic Land Classification of Salt Affected Soils

Paper 1

EVOLUTION OF SALINITY, ALKALINITY AND WATERLOGGING 1/

by

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Why are the basic principles of land reclamation and development, which have been known for a long time, not put into practice in the same way as the new knowledge we have gained? Some factors effecting this lack of application of the principles are:

i. the need for simplified presentation of the scientific material to farmers, surveyors, engineers and planners;

ii. dissemination of what is already known is lagging far behind;

iii. there is a "domination" of ignorance - almost a determination to resist change in some sectors;

iv. the lack of training and extension services;

v. the lack of infrastructures and organizational set-up;

vi. social problems.

It is the task of international organizations (FAO, Unesco, etc.) to promote ways and means to overcome these problems. They know how and have the basic information. For instance, in arid countries they should help create internal auxiliary services in topography, hydrology, soil interpretation, management and irrigation.

It is true that there are natural difficulties beyond the influence of man to delay and retard the reclamation of saline, alkali and saline-alkali soils. Examples are found in USSR as well as in Texas and other places. In the past ages great differences have been created by nature in the humid, sub-humid, arid and extra-arid areas and all these can be affected by salinization. Today we have marshalled much information on factors affecting the soils: on their fertility, their physical destruction (some of the best chernozems in USSR have suffered), salinity, secondary salinization, micro-structure, pH, soluble salt content, crusting - particularly

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1/ Notes taken during Prof. Kovda's speech.

after watering, and what could be called "vertisolization" below the arable horizon which is not due to heavy machinery.

During this work of desalinization and reclamation, the great benefit of leaching, what we call in some cases "capital leaching", was recognized. Leaching under good management conditions not only decreases salinity, but stabilizes it for future control, reduces the groundwater level and also the salinity of the groundwater.

Even when salinity has been stabilized, extensive drainage is necessary to maintain the condition of the soil. In many cases vertical drainage alone is not sufficient but must be accompanied by deep horizontal drainage (e.g. the central lowlands of Armenia). Tubewell drainage can also be of use.

Care must always be taken to desalinize goundwater and not only in the soil root zone. It has taken too long to realize the important role played by groundwater in salinization and it is about time to agree on the importance of desalinization of the groundwater. Nowadays, we know the critical concentration in groundwater and that the salt content must be kept below certain levels. It depends on the chemistry of the soil, the climate, capillary action, etc. And we also know that in reclamation work and to prevent secondary salinization the water table level must be reduced.

For many years work has been done in Tajikistan and in the heavy soils near the Caspian Sea to reclaim soils and to prevent salinization and alkalization. In these areas the reduction of the groundwater level, even to a depth of 4 m, played a major part in reclaiming them. In USSR a minimum depth of 5 m to groundwater is favoured.

We recently discovered the importance of artesian effect and as a result, in some extreme cases, it may be necessary to investigate the possibilities of reducing groundwater depths to 100 m, but this of course will be a very expensive procedure.

In the discussion it became clear that working on dissemination of available data does not mean that continuing collection of basic information for technology should stop. Rather that one must follow the other; there is much information already available, now organizations like FAO and Unesco can help to ensure that it is passed through the national infrastructures right down to the farmer and peasant who must apply it.

In this regard a suggestion was made to recommend the establishment of regional centres for land reclamation with sub-regional or national applied research institutes. Field demonstrations and experimental farms are essential in speeding up the delivery of results to farmers, planners and other users. The aim is to have a network according to the economic possibilities of the country and the variability of local conditions.

Paper 2

PRESENT AND POTENTIAL SALT AFFECTED SOILS

An Introduction

by

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The global demand for food and raw materials produced by agriculture makes the further study and optimal utilization of soil resources of the earth imperative and urgent. In science and politics the opinion prevails that the soils of different continents can supply not only the recent demands of mankind, but may fulfil all future food and agricultural product requirements of the ever-growing population. In order to meet the requirements, the further study of soil resources must be given paramount importance, with particular regard to soils and soil forming processes that are associated with unfavourable fertility.

Salt affected soils belong to those types of soils that have low fertility. They occur to such an extent in many countries that they hinder or prevent agricultural production.

The distribution of soils affected by salt at present is closely related to environmental factors such as arid or semi-arid climate, accumulation of products of weathering in groundwater near the surface, etc. On a world-wide scale there is a considerable amount of data, maps and other materials, showing the extent of salt affected soils. Among these, the FAO/Unesco Soil Map of the World (scale 1:5 000 000) should be mentioned particularly, because it is the first to give a world-wide inventory of these soils and their distribution. Salt affected soils cover such an area in many countries in arid and semi-arid regions of Asia, Africa and South America that they cause considerable problems regarding not only the natural environment of these areas, but also the national economy.

However, we do not have yet a World Soil Charter of these soils, although the approximate size of the earth's crust covered by salt affected soils is well known. Obviously, the follow-up of the resolutions adopted during the World Food Conference held in Rome in November 1974, to prepare an assesment of the land capability will help a lot in obtaining exact data on the distribution of presently salt affected soils.

In many countries the frequency of salt affected soils makes their utilization necessary, mainly by irrigation and application of chemical amendments. In other places though, where salt affected soils are not so extensive, or the country has large areas of non-salt affected lands, agriculture could be developed, apart from the salt affected areas; but not much practical attention has been paid to the reclamation of these soils. The utilization of present salt affected soils is hindered mainly by practical economic problems.

Besides soils affected by salt at present, we have to distinguish potential salt affected soils. Soils considered potentially salt affected are those which are not, or only to a very low degree, saline and/or alkaline at present but human intervention, especially irrigation, could cause their considerable salinization and/or alkalization.

Theoretically, there are many factors effecting salt affected soils, however, practically it is irrigation which leads to the formation of many millions of hectares of saline and/or alkali soils in different parts of the world. Paradoxical situations can often happen in irrigation systems established even after thorough work and expensive planning and construction, the soils, instead of increasing in fertility, transform into poor saline land. This process is known as secondary salinization and/or alkalization, which is as old as irrigated agriculture.

Many thousands of km^2 of fertile irrigated lands were transformed into saline and alkali deserts during the history of mankind by the influence of improper irrigation. Unfortunately, this has happened not only in the past, but secondary salinization and/or alkalization is showing a disastrous increase, parallel with the construction of new irrigation systems in many countries all over the world, particularly in arid and semi-arid regions, or in regions with mineralized groundwater near the soil surface.

The extent of irrigation - influenced by the demand for an increase in food production - makes it imperative to pay attention to potential salinization and/or alkalization in order to study and characterize this process, as well as to predict and prevent it everywhere if possible.

It is well known that the majority of irrigated territories in the world are exposed to the hazard of secondary salinization, alkalization and waterlogging. According to estimates by the UN and affiliated agencies (FAO, Unesco, etc.) more than 50% of all irrigated lands of the world have been damaged by secondary salinization, alkalization and waterlogging. In the same estimation, many millions of productive hectares in irrigation systems have to be abandoned yearly owing to these causes.

While existing salt affected soils can be recognized on the basis of a few morphological, chemical and physicochemical observations and determinations, the recognition of potentially salt affected soils as well as determination of the long-term hazard of salinity or alkalinity on any given territory necessitates special survey and methods.

Due to the paramount importance of irrigation and the close relationship existing between irrigation, drainage and the salinity and/or alkalinity of soils, it was deemed necessary to delineate on the maps of salt affected soils, whenever possible on the basis of available data, those areas which are exposed to the hazard of salinity or alkalinity owing to the introduction, the present practice, or the further extension of irrigation. The Map of Salt Affected Soils in Europe (sponsored by Unesco, FAO and ISSS) shows the areas where potential salt affected soils are developing. This map demonstrates that even in Europe, where the extent of salt affected soils is smaller than in some other continents, the surface covered by potentially salt affected soils is equal or more than the territories where soils at present affected by salt occur. Evidently, in continents with more arid conditions this rate is much higher.

Secondary salinization and alkalization take place mainly in one or more of the following situations:

i. accumulation of salts from poor quality irrigation water;

ii. increase in the level of groundwater:

   a. the salt content of the groundwater accumulates in the deeper soil layers;

   b. the rising groundwater transports the salts from the deeper soil layers to the surface or surface layers, or

   c. the rising water table limits natural drainage and hinders the leaching of salts.

iii. lack or low effectiveness of drainage systems in irrigated soils.

A possible hazard from salinization and/or alkalization in irrigated areas or areas to be irrigated can be influenced by the following factors:

a. climatic, such as: temperature, rainfall, humidity, vapour pressure and evaporation and their fluctuations and dynamics;

b. geological, geomorphological, geochemical, hydrological, hydrogeological and hydrochemical, such as: natural drainage, depth and fluctuation of water table, direction and velocity of horizontal groundwater flow, salt content and composition of the groundwater, etc.;

c. soil, such as: soil profile, texture, structure, saturated and unsaturated water conductivity, soluble salt content, salt composition and salt profiles, exchangeable cations, pH, etc.;

d. agrotechnics, such as: land use, crops, cultivation methods, etc.

e. irrigation practices, such as: the amount of irrigation water: method, frequency and intensity of irrigation, salt content and composition of irrigation water, natural and artificial drainage, etc.

The above-mentioned factors determine the aims and methods of the preliminary soils survey in order to define the degree or the existence of potential salinity and/or alkalinity. But it is also evident that the enrivonmental conditions on one hand, and the methods of utilization of the territory in question on the other hand should be taken into consideration when an area is evaluated in this respect. Due to this fact different limit values and different methods, based on uniform principles, should be selected in the course of this procedure. For example, in arid regions, in deserts and semi-deserts practically all irrigated areas are potentially salt affected owing to the arid climate as well as to the high accumulation of salts in the soils and waters of these areas.

The basic aims of the survey and study of potentially saline or alkaline soils are to predict the harmful processes and to elaborate, whenever possible, methods suitable to prevent the occurrence of secondary salinization and alkalization. In order to develop a reliable method of predicting salinization and alkalization the following problems have to be solved:

1) the main sources of water soluble salts (irrigation water, groundwater, surface waters, salty deep soil layers, etc.) must be identified;
2) the main features of the salt regime must be characterized (salt balances); and the whole range of natural factors influencing the salt regime must be analysed;
3) the effect of irrigation and drainage on the water and salt regimes of the soil must be predicted and determined.

Consequently, an exact salinity and/or alkalinity prognosis must be based on an evaluation of many natural and human factors and a knowledge of the existing soil processes, as well as the pattern of planned soil utilization.

In the books on salinization, alkalization and waterlogging widely used in soil science, some contain valuable data and information on the methods of studying the former two processes. For instance: Diagnosis and improvement of saline and alkaline soils. Handbook No. 60. US Department of Agriculture, Washington, 1954. The most recent and up-to-date approach and methods concerning the problem are condensed in Irrigation, Drainage and Salinity. An International Source Book. FAO/Unesco, Hutchinson/FAO/Unesco. 1973. (Ed. V.A. Kovda, C. van den Berg and R.M. Hagan).

In technical literature numerous publications describe general and local methods for the prediction and prevention of the above processes. For instance, based on these principles (see details in: Symposium on the Reclamation of Sodic and Soda-Saline Soils. Agrokémia és Talajtan. 18. Suppl. pp. 351-376., 1969.), a special survey was made in the eastern part of the Hungarian Lowland in order to predict the influence of existing and projected irrigation schemes on soil salinity and alkalinity. In spite of the many achievements in this field, we still lack a coordinated international guideline and practical handbook describing the necessary methods of assessment in order to fulfil the growing demand by soil science for preliminary survey of irrigated territories.

During the preliminary study of irrigated areas, or areas to be irrigated, in order to elaborate the proper prognosis and possible prevention methods, besides the natural factors, the projected pattern of farming-systems should be taken into consideration mainly in respect to such factors as methods of irrigation, possibility of drainage, economical aspects, etc.

Following the preliminary survey of irrigated areas and their environment, a special survey is necessary parallel with the construction of irrigation systems. In this survey the thorough study and determination of all essential soil and water properties should be included, checking the data and conclusions of the preliminary survey. During the exploitation of irrigation systems, the regular monitoring of factors influencing salinization and alkalization processes is indispensible. All these are pre-conditions for effective prognosis and for the possibility of preventing secondary formation of salt affected soils in irrigated areas.

ECONOMIC LAND CLASSIFICATION FOR THE PREVENTION AND RECLAMATION OF SALT AFFECTED LANDS

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1. INTRODUCTION

The prevention and reclamation of salt affected lands are of paramount importance in meeting the food crisis and helping man. The opportunities and ways and means for accomplishment are great despite the multitude of diverse and complex factors and interactions. Further, responsibilities in providing for social well-being and obligations to assure favourable environmental interactions can be accomplished. The investigations for exploration and analyses integrate the activities of the several disciplines including water quality, plant science, drainage, environmentalism, engineering, sociology, geology, soil science, economics, and land and water use and management. Important to these studies is coordination of their independent activities into a meaningful framework of analysis. From the evaluations, alternative plans are developed to indicate required programming, operation and reclamation procedures conforming to area needs and policies. Analysis is made of land use problems and opportunities associated with alternative plans, recognizing the natural and modified resource base; existing and potential land use patterns; zoning regulations; and general relationship to environmental, social and economic aspects and benefits. In this regard, economic land classification is a tool for identifying needs, establishing opportunities and selecting lands for water and salinity control.

The process is somewhat analogous to eating at a large cafeteria or shopping at a large supermarket. The choice of items and combinations are numerous but somewhere along the line, someone has to pick up the "tab". Choices are influenced by the funds available and financing capability. The cost of investigations for planning is also very important.

Most of the developing countries are not in a position to go "carte blanche". The exception would be some of the oil producing countries where, in addition to having ample and ready finances, the governments, in order to meet goals to become self-sufficient in food production, are more likely to subsidize on-farm development and operations in addition to project features.

The classification system described in this paper can be adapted to serve needs for various goals, land characteristics and conditions, farm enterprises and financing arrangements irrespective of water supply or control methods; i.e., it is applicable to both rainfed and irrigated lowland or upland agriculture under either private or government ownership and management.

2. LAND SELECTION

The prevention and reclamation of salt affected lands largely involve providing for control of water movement including soil-water and groundwater. This is accomplished through installation and operation of facilities and implementation of measures; i.e., water supply and distribution, water and land use, management and drainage. Formulation of plans can be efficiently guided by an effective system of economic land classification which avoids a rigid or fixed procedure. The general principles followed in the Bureau of Reclamation are applied to fit land classification to the specific environmental situation including economic, social physical and legal patterns existing in the area.

The physical, soil, topographic, drainage, climatic and water quality factors and their interrelationships influence the needed control facilities and measures related to crop production inputs and yield outputs. These are, in turn, controlled by technological levels, economic conditions, social organization, resourcefulness and motivation of people, the goals of development, and means and availability of financing. Planning is accomplished by using the land classification survey as a systematic, integrating process for the determining elements in the plan (Maletic, 1967; and Maletic and Hutchins, 1967).

2.1 Principles

The classification should conform to modern classificatory principles and practice (Sokal, 1974; Tversky and Kahneman, 1974). The system should be based on a single factor or set of factors, and the factors to be classified should be selected and adhered to for the entire classification. This principle is basic and extremely important. It is preferable that the chosen factor or factors be unifying. This principle and the unifying aspect are logically and conveniently met by selecting economic factors to reflect goals. For this purpose, unifying factors such as benefits, net income, or payment capacity to be generated by means in accomplishing goals are generally used.

In addition, four other basic principles are followed in structuring the classification to needs and goals for specific areas (Maletic, 1962). These are the principles of prediction, economic correlation, permanent-changeable factors, and arable area - service area analysis.

2.1.1 Prediction principle

Under the prediction principle, the classes in the system express the land-water-crop and economic interactions appraised to prevail after resource and management modification. This involves identifying and evaluating the changes anticipated to result from development or reclamation and management.

Examples of changes that can be brought about by modifying water control measures and management are variation in depths to water tables and associated soil moisture, salinity and aeration conditions affecting tillage and crop growth; modification of slope and microrelief by landforming; and alteration of soil profile characteristics by deep ploughing, chiselling or addition of amendments. Soil texture may be modified by sediment in water entering the soil.

The manner and magnitude of water control can effectively serve to regulate salt effect on lands, crops, social and economic conditions, and the environment. The concentration and composition of salts in the soil solution and associated exchangeable ion status on soils can be influenced by numerous factors, including the composition of water applied, the rate of water application and leaching, dissolution and precipitation of soil solution constituents, and the rate and amount of drainage.

Flooding of soil, as practised under rice cultivation, sets in motion a series of physical, microbiological and chemical processes which influence crop growth (Ponnamperuma, 1965). These include retardation of gaseous exchange between soil and air, reduction of the soil, and the electrochemical and chemical changes accompanying the reduction. There is a decrease in redox potential, increase in pH under acid conditions and decrease under alkaline condition, and an increase in specific conductance. Also, the flooding causes dentrification, accumulation of ammonia, reduction of manganese, iron, and sulfates, accumulation of the products of anaerobic organisms and other secondary effects of reduction. Cate and Sukhai (1964) have attributed the decrease in soil acidity upon flooding to the precipitation of aluminium hydroxide, the reduction of ferric iron and the absorption of ferrous iron by the clay.

Water supply and control and related salinity control are determinants of successful agriculture with respect to either diversified upland cropping or wetland rice production. Regulation of water inflow and outflow largely controls salinity, sodicity, acidity, reduction products and aeration. Thus, the prediction principle should be concerned with the quality of water, the soil, subsoil and substrata characteristics and conditions, drainage, and land use and management - all under specific plans. In prediction, the classification also deals with water requirements, soil productivity following landforming and expected soil profile modification practices, flood hazard, soil erosion, quality or return flow and crop production inputs and outputs.

2.1.2 Economic correlation principle

The economic correlation principle involves relating, within a given setting, the physical factors of soil, topography and drainage with an associated economic value. The economic basis for the land classification is usually chosen to contribute toward determining the feasibility of water control planning for increasing net farm income, to achieve benefits and to evaluate the interrelationships of investment feasibility and the water use.

More specifically, the economic values chosen to define land class depend upon the purposes to be served by the land classification. As applied to the United States, the economic value is defined in terms of net farm income and payment capacity. Net farm income measures the benefits directly accruing to the farmer, while payment capacity after making allowances for farm returns represents the residual available to defray the cost of water (USDI Bureau of Reclamation Manual, 1953). For initial planning studies in the developing countries, it has generally been the policy to use direct benefits (net farm income), as the economic parameter in land classification rather than payment capacity (USDI Bureau of Reclamation, 1967). This is done to eliminate the need for immediate resolution of the repayment policies and the extent of irrigation subsidies that might be applicable. With newly developing countries, it can be expected that in the early period of project investigation, the development of a repayment capacity is not sufficiently firm to base confidently the land classification on repayment criteria.

With land classes defined as economic entities, a set of relevant and mappable land characteristics is chosen for the time and place to provide a physical definition of the land specifications. The land class determining range of these characteristics varies with the economic, ecological, technological and institutional factors expected to prevail in the area. As a consequence, land classes express, in terms of economics, the local ranking of land for modified use; e.g., best suited, moderately suited, poorly suited and unsuited for irrigation development.

2.1.3 Permanent-changeable factors principle

The permanent-changeable factors principle recognizes that changes in land arising from water and land development impose a need to identify characteristics that will remain without major change and also to identify those which will be significantly altered. This identification permits construction of a consistent set of land class determinig factors assuring uniform appraisal of land conditions by the various disciplines engaged in making the land classification surveyed. Most land factors, including soil depth, are changeable at a cost. Typical changeable factors include salinity, sodicity, titratable acidity and exchangeable aluminium, depths to water table, relief, brush and tree cover, rock cover, drainage and flood hazard. Particle-size distribution of subsoils and substrata occuring at depths not disturbed by tillage and landforming is about the only factor that may not be altered.

Whether given characteristics will be changed usually depends upon economic considerations. The land classification survey thus deals with two aspects of this principle. Can the change be accomplished, and what degree of change is economically feasible? This is largely dependent on the climatic and economic setting of the project. For example, a large investment may be made to reclaim a saline, sodic or acid soil which after improvement will yield a net farm income of US$500 per hectare. In another setting, where net income after improvement would only be US$75 per hectare, the soil having similar conditions would be regarded as non-reclaimable. In the latter case, it may be infeasible to make the change.

2.1.4 Arable area - service area analysis principle

The arable area - service area analysis principle relates to the selection of lands to be served and involves a two-step process. In the initial step, land areas of sufficient productivity to warrant consideration for service are identified. Upon this determination, there is superimposed the selection of the lands to be specifically included in the plan of development. The former may be termed arable lands and the latter service area or lands selected for service. The selection of arable lands is guided by farm production economics; i.e., the economic value such as benefits, net income or payment capacity, as chosen to define the land classes. The service area or land selected for service is guided by the economic goals selected to guide plan formulation. The scope of plans may be influenced by relationships to purposes served other than water supply to lands such as in the case of multipurpose projects.

The application of plan formulation criteria to the classification generally leads to successive elimination of identifiable increments of arable lands from the plan of development. Typical adjustments include (i) elimination of non-economic increments such as those that are too costly to serve, drain or manage; (ii) conformance of land area to utilizability, serviceability and manageability; (iii) exclusion of isolated segments, odd-shaped tracts and severed areas that cannot be efficiently fitted into the farm unit pattern; (iv) deletion of proposed public rights-of-way; and (v) elimination of areas unable to meet minimal criteria for economic returns under the plan. Of these factors, items (i) and (v) are goal-dependent.

2.2 Water Suitability

Water quality evaluations are approached by analysis of the environmental setting in the context of predicted water use (USDI Bureau of Reclamation, updated 1975). The determination of the suitability of water involves integrating land and water factors. In this process, land classification surveys are utilized to delineate land classes that would favourably respond to a water supply of a given quality. This selection of land as a potential part of a water development is then tested as to feasibility by application of plan formulation criteria.

Water quality standards *per se* are not applied in appraising the usability of water for irrigation. As has been stated by Fireman (1960): "Its usability depends on what can be done with the water if applied to a given soil under a particular set of circumstances. The successful long-term use of any irrigation water depends more on rainfall, leaching, irrigation water management, salt tolerance of crops and soil management practices than upon water quality itself."

2.3 Application of Methodology

The application of procedures for planning requires thorough study to assure fitting resource developments to the goals and social, economic and physical settings. Methodology should be developed for application to local needs using the principles previously discussed. In several countries, there has been a tendency to adopt rather than adapt, i.e. to attempt transfer of procedures rather than develop systems based on the principles. Usually, the transfer approach will not work satisfactorily, thus it is essential to go through the rigours embodied in applying the principles.

The system is also applicable to either state or privately owned or operated farm enterprises irrespective of subsidies involved. This is accomplished by defining the land classes in terms of relevant economic parameters. Therefore, it is necessary to explore fully and consider the controlling policies in structuring and implementing the land classification for local application.

The system is applicable to either diversified cropping and wetland rice production for all situations and ranges in water supply and control including rainfed agriculture, irrigated agriculture, water regulations in flood plains and reclamation of marshlands and tidelands. The principal differences in requirements are the source, quality and control of water. All the principles and components, particularly economics with respect to productivity, land development, flooding and drainage are highly relevant.

The major basis for physically, chemically and economically differentiating diversified croplands from wetland ricelands is the ability of the soil to attain optimum soil submergence, susceptibility to soil puddling and control of water table (Grant, 1964). Therefore, the differentiating characteristics of wetland rice classes are primarily predicated on water control as related to soil characteristics and conditions of adequate drainage and differentiating soil characteristics that have a strong influence on the yield and cost of producing diversified crops.

Many of the soil parameters, especially with respect to prediction and productivity, are different in classifying lands for the two types of irrigated cropping. In contrast to upland agriculture, the classification of soils for paddy rice production involves the prediction of ultimate soil conditions that will occur from flooding. Some of the conventional soil tests used in surveying soils for diversified crop production are not applicable to the characterization of soils for paddy rice production because of the drastic changes in soil properties, their dynamic state and the wide differences among soils produced by flooding (Ponnamperuma, 1965).

In regard to productivity, the ability to attain optimum soil submergence or saturation and control of water tables would be requisite for rainfed wetland rice production on soils high in neutral salt exchange acidity (in cases where the exchangeable aluminium and other acidity can be sufficiently neutralized by processes associated with reduction). Income from rice grown under upland conditions on such soils could be affected by reduction in yields of variations sensitive to the prevailing acidity or the cost of neutralizing the acidity with amendments. Acid sulphate soils could require amendments for flooded rice culture. The predictive and permanent-changeable factors, along with land development costs, are very important in land levelling and terracing operations exposing subsoils. Flooding and inadequate drainage are major factors affecting cultural practices and production of paddy rice in vast areas of Monsoon Asia. These can be highly significant economically from the standpoint of either living with the situation or providing measures for water control measures. Numerous other facets could be cited.

In the case of non-irrigated diversified or upland crop production in arid or humid areas, the land class determining features would include soil, topography, drainage and associated management factors influencing ranges in productivity with available moisture plus any land development measure to be taken to modify productivity or ease production. In appraising land potential of swamps, land development costs for drainage and tree removal would enter into the classification as well as productivity of the lands after reclamation. The structuring of the land classification depends on the purpose of the survey, constraints and conditions.

Economic studies and consultations with international agencies, governments involved and other authorities assist in determining economic and financial criteria to be used in project planning and developing land classification specifications. These include period of analysis, interest and discount rates, repayment capacity and means of financing. It is also necessary to estimate the approximate project cost, operation and maintenance cost, and farm costs and returns. These elements provide the information needed to establish the minimum level of land quality which should provide benefits sufficient to meet project costs. As a product of this determination, also provided are the maximum permissible land development costs. After this cutoff point is established, it is possible to finalize the land classification into ranges of net income.

Before the land classification is started, the matter of handling land development costs is determined. Methodology between countries may vary according to whether the government expects the farmer or landowner to pay for all development costs or the government does all of the on-farm development with no direct cost to the farmer. The land classification is varied to show a reduced payment capacity in net farm income and lower land class where land development costs are borne by the farmer. When development costs are handled as a government expense, they do not influence the land class except when the maximum permissible expenditure would be exceeded.

After identifying with the policies to prevail, the classification is guided by a series of somewhat interrelated stages. These may be identified as the pre-survey, survey and post-survey stages.

2.3.1 Pre-survey stage

The pre-survey stage involves study of the land resources, associated productivity and drainage capability experiences in a fully developed area having physical and climatic conditions similar to the area of investigation. In developing, fitting and testing the land classification specifications to project conditions, farm enterprise studies are made to determine the net farm income for the various classes (Seldon and Walker, 1968). Establishing these standards for classifying land for net farm income, involves the projection of representative farm enterprise and representative levels of farm management. These, of course, must stem from information of the present day situation and trends in the development and application of technology in agriculture. In the latter regard, it is recommended that adaptive research programmes be undertaken to help guide the land classification work by providing answers to questions pertaining to management systems, fertility, amendments, water management practices and other factors.

The characteristics and qualities of lands which determine suitability for warranting modification in water supply, control, management and use vary with each project. The land class determining factors represent selected and correlated ranges for such characteristics as texture, depth to bedrock, hardpan, sand, gravel, caliche or other root-limiting influences, structure, consistence, colour, and mottling, kinds and amounts of coarse fragments, and kind, thickness and sequence of horizon. In addition, the prediction aspect of selecting arable lands requires many laboratory measurements. Performance qualities are also either measured or inferred. These would include factors such as fertility, productivity, erodibility and drainability, as well as such measurable factors as infiltration rate, hydraulic conductivity, moisture characteristics and moisture-holding capacity.

In investigating lands consisting of highly leached and weathered soils, a strong soil characterization programme should be conducted. The chemical status of such soils needs to be carefully evaluated along with observable characteristics in making sound selections of irrigable land. The problems met with these soils are usually fertility related chemical characteristics requiring special appraisal. They include status of weathering of the clay minerals, soil acidity, charge status, soluble and exchangeable iron, aluminium and manganese, base saturation, and nutrient status of the soils. Such characterizations identify infertile soils having limited suitability for continuous crop production because of high inputs of both money and management. On other soils they indicate the type and level of production inputs required to attain specified yield levels of particular crops. Of course, other soil characteristics such as texture, structure, depth, water-holding capacity, infiltration rate, permeability and claypans are evaluated as are water quality, climate, topography and drainage conditions. Salinity reclamation and control can be a factor in high rainfall areas including the tropics.

In considering low base status soils, Sanchez- and Buol (1975) recommend that: "related inputs should be optimized by (i) selecting crop varieties and species more tolerant to nutritional deficiencies or toxicities, (ii) applying fertilizers at lower rates than those recommended by classic marginal analysis, and (iii) increasing the efficiency of applied fertilizers in such soils." Should such criteria be adopted, the analyses need to be made in relation to the economics of water control for specific settings. The ranges in soil properties comprising land classes can vary among and within countries.

Topographic characteristics considered consist of the degree of slope, relief and position. These factors are evaluated as they influence land development needs and costs, method of water distribution, design of on-farm conveyance systems, erosion hazards, crop adaptability, drainage requirements, water use practices and selection of management systems. It is necessary to make decisions regarding the extent to which slope and relief will be modified by landforming, and to make estimates regarding the amount, type and cost of land development.

2.3.2 Survey stage

In the survey stage, appropriate land classification specifications are applied in the performance of the arable classification. This involves field traverse, soil and substrata observation and sampling, laboratory analysis of soil samples, delineation of the land classes, subclasses, informative appraisals and the related procedures necessary to accomplish the field survey work. Performance of the fieldwork is guided by the type of investigation being performed. These may be of appraisal, feasibility, pre-construction, post-construction or post-development grade. If the appraisal studies show promise of achieving the development goals, then more detailed studies are subsequently performed.

The requirement for investigative detail is set not only by the type of investigation being formed but also by the complexity of the landscape being investigated. In accomplishing the field survey, the Bureau of Reclamation generally uses not more than five land classes defined on the basis of their range in payment, capacity or net income. In short growing season areas, fewer land classes are sufficient. Class 1 lands have the highest level of suitability. Class 2 lands have intermediate suitability. Class 3 lands have the lowest suitability for general farming. Class 5 is used as a temporary designation for lands requiring special studies before a final land class designation can be made, and class 6 is land not suitable for development.

Subclasses are used to indicate the reasons why land is placed in classes lower than class 1. This is shown by appending the letter s for soil deficiency, t for topographic deficiency and d for drainage deficiency to the land class designation. Subclasses of the land classes 2, 3, 4, and 6 are s, t, d, st, td and std. The mapping unit symbol also provides for showing the present land use productivity level development cost, water requirement, drainage requirement and, as needed, special appraisals to indicate specific deficiencies.

For drainage evaluation purposes, the fieldwork involves numerous observations and measurements of conditions of the substrata as well as the true solum and superficial parent materials. Observations to a depth of 3 metres or less in case of a barrier are used in all investigations for irrigated diversified cropping, and to greater depth as needed depending upon the particular type of landform encountered.

2.3.3 Post-survey stage

In the post-survey stage, the arable land classification may be modified as additional pertinent physical, engineering, hydrologic and economic information is obtained. Arable classification adjustments are needed if the final project plan and costs for water and drainage are significantly different from original estimates. During the post-survey stage, application is made of tests for engineering feasibility and project formulation criteria of benefits and costs, repayment, and the operation, maintenance and replacement costs as needed to select the plan and related service area under the development goals.

Results of the land classification are applied to (i) selection of service area, (ii) determination of water management requirements, (iii) selection of land use and size of farm, (iv) determination of project payment capacity, (v) determination of water control benefits, and (vi) development of layouts for water supply and drainage system.

2.4 Laboratory Support

In addition to field measurements for water movement and retention in soils, a certain amount of characterization by laboratory methods is required to support the land classification. Because laboratory studies should serve to substantiate field appraisals, it is essential that laboratory work be closely coordinated with fieldwork. The number and type of studies are determined by the controlling project or area specifications and needs. There should be a joint plan between field and laboratory investigations before taking samples if maximum use is to be made of data obtained. Problems should be studied rather than standard or routine tests made.

This testing can be very expensive. Unfortunately, the results are frequently misleading. In many areas, there has been a tendency to "overtest," i.e., perform too many or unnecessary tests on certain soils at the expense of not performing essential or critical testing on particular soils. Also, there have been shortcomings in proper interpretations.

In submitting soil samples for laboratory characterizations, the laboratory should be furnished with pertinent field appraisals including soil textural class along with the tentative land class designation. The soil samples should represent genetic horizons with no more than 60 cm depth per sample.

2.4.1 Approach

The first priority in laboratory characterization should be directed toward direct and indirect measurements that evaluate soil structure and its stability, effective soil cation exchange capacity and soil reaction. After this is accomplished then consideration should be given to testing that confirms, explains the causes of phenomena previously observed or predicted, reveals the presence of toxic elements (salinity level, boron content, sodicity, acidity, reduction products, etc.), and indicates what and how much is required to cope with the soil deficiency under eventual field conditions with water control and management.

The laboratory testing might include determinations for soil structure stability by measurements of floc volume and hydraulic conductivity of fragmented samples; moisture retentivity at 15 bars pressure; soil reaction by measurement of pH in 0.01M calcium chloride (1:2) and pH in water (1:1) or (1:5); soil salinity by measurement of specific electrical conductance of soil-water extracts; soil acidity by measurement of exchange acidity including exchangeable aluminium (that portion of soil acidity that can be replaced with a neutral-unbuffered salt); titratable acidity (amount of acid neutralized at a selected pH); soluble aluminium; soil solution concentrate and composition including sodium and calcium plus magnesium; exchangeable cation status; organic matter; available phosphorus; and others.

Laboratory operations and characterizations for moisture retentivity at pressures lower than 15 bars are not recommended unless suitable correlations with field conditions are developed and then only in relation to diversified cropping. In general, the nonroot zone depth soil samples need not be characterized for acidity hazards. Soils of near neutral or basic reaction need not be characterized for exchange acidity. In the initial screening of samples for screenable characterization, soil-water suspension of 1:1 ratio may be substituted for the time-consuming saturated soil pastes. The blanket laboratory analysis for soil textural class is neither required nor desired.

Particle size analysis should be limited to master size characterization, the occasional confirmation of field textural appraisals and the training of new employees.

2.4.2 Screenable testing

After establishing interrelationships that exist for various properties, it is usually desirable to implement screenable testing. Depending on the relationships and degree of correlation, a procedure for sequence of testing and screening of samples might encompass the following phases. Under phase I of the scheme, all samples would be characterized for soil structure stability through measurement of hydraulic conductivity on a fragmented sample basis during an initial and elapsed time interval and volume of wet settled floccules.

In the second phase of testing, all samples from the root zone depth, i.e., those depths that would prevail after land levelling, would be characterized for moisture retentivity at 15 bars pressure; electrical conductivity of 1:1 soil-water ratio extracts; and soil pH in water (1:1) or (1:5), and $CaCl_2$ (1:2). Samplings of greater depths in the case of barrier situations should be appraised on salinity levels.

In the third phase, selected root zone samples suspected through the testing results of phases I and II to be highly acid, low in base saturation, or low in cation exchange capacity, should be further characterized for neutral salt exchangeable acidity, aluminium, sodium and calcium plus magnesium. Also, in the third phase, selected root zone soil samples suspected through the testing results of phases I and II to be salt affected should be characterized for electrical conductivity of the saturation extract and sodium absorption ratio and residual gypsum.

In phase IV, selected samples having been characterized during phaces I, II and III to be saline-acid would be characterized for soluble aluminium. Also selected soil samples coming from potential ricelands and found to be acid in phase III testing would be characterized for active iron and manganese and organic matter content.

Concurrently with the screenable testing, the master site samples should be characterized on a complete analysis basis, i.e., all samples from all depths should be characterized for the items previously mentioned.

The field and laboratory soil scientists should study the results of field and laboratory characterizations for possible correlation, especially with respect to soil genesis, soil morphology and clay mineralogy.

USING NATURAL SYSTEMS

Many workers trained in mapping natural bodies have great difficulty in initial attempts to adopt and adapt to economic land classification. The difficulty seems to be in conceptualizing the landscape under the conditions expected to prevail under the new land use regime through economic reasoning and installation of control structures. Another difficulty concerns notions that boundaries of natural bodies will coincide with class boundaries, ranking land for use suitability. This rarely occurs because kinds of soil having natural boundaries are commonly found in contrasting economic environments or vice versa. The location, size of tract and other economic characteristics of land are highly significant in land classification.

It can be very difficult to rely upon natural body mapping, as commonly made, for classifying a given area particularly on complex and problem lands consisting of soils and substrata requiring extensive and intensive field and laboratory characterization. Although logical procedures can be advanced for accomplishing the required integration, experience has shown that the procedures necessary for a land classifier to establish class boundaries related to natural body mapping units can be nearly as time consuming as the conduct of a basic land classification without benefit of a soil survey. This is not to imply that soil surveys are not useful. Natural soil bodies, because of their information content, can provide much essential information, including bases for deriving predictions.

The Soil Resources Development and Conservation Service of the Food and Agriculture Organization of the United Nations, Rome, Italy, under the leadership of Dr. R. Dudal, is to be commended for recognizing needs and implementing revised soil survey procedures to serve water resource planning better.

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Paper 4

NATURAL FACTORS

by

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1. INTRODUCTION

Soluble salts form a formidable menace to irrigated farming and so their occurrence and movements deserve a careful and intensive study. Among the various factors involved in soil salinization, the natural factors were clearly put forward several years ago by Kovda. He observed that salinity is not a phenomenon occurring at random, but is encountered in definite locations only, and that it is closely connected with the geomorphology of the area.

This is indeed what is to be expected, as soluble salts are easily moving substances. Salt movement, therefore, may be considered as the fundamental process behind all phenomena of salt accumulation and leaching, in nature as well as under conditions controlled by man.

2. MOVEMENT OF SALTS

Obviously soluble salts will move with the water in which they are dissolved. So we might use as a first approximation the principle that dissolved substances are carried along with soil moisture flows and groundwater currents. We might also use this principle in reverse: measuring the movement of dissolved substances allows an estimation of the displacement of soil moisture and groundwater. The latter hypothesis forms the background of most work concerning the application of tracers for measuring soil moisture flows or groundwater currents; in many cases these techniques yield excellent results.

However, there are many examples where soluble salts and water do not travel together, or at least not at the same velocity. The most obvious case is evaporation, where water is lost, but salts remain. Salts, therefore, tend to concentrate in places where water evaporates, a simple fact that is behind most of our considerations about salinity and salinization.

Less conspicuous is diffusion, by which salts may move whereas the water does not. Also dispersion has a tendency to uncouple the transport of water and salts, so that they may move at different rates.

The composition of salts is influenced by ion exchange, by precipitation of salts and perhaps also by osmotic phenomena. Moreover, large differences in salinity between different waters may cause density currents or layers of fresh water to float on top of saline water, as is often the case in coastal aquifers.

All these processes cause salt distributions which are often hard to explain.

3. TRANSPORT

3.1 Transport versus Dispersion and Diffusion

Dispersion and diffusion tend to blurr any sharp boundaries between waters of different quality. The vague transition zones produced by these processes will also be moved by groundwater currents. In many cases the times of residence can be estimated by considering transport only: this is especially true for transport in groundwater systems.

If transport only is active, a sudden breakthrough of "new" water at the end of a column will be observed. In reality this breakthrough is a more gradual process, but the time at which the outflow is composed of 50% "old" and 50% "new" water is still correct. This adds to the usefulness of calculations based on pure transport only. Pure transport is often denoted as "piston flow".

3.2 Times of Residence in Simple Transport Systems

a. In a steady-state system, the time of residence is defined as:

$$T = \frac{\text{volume of system}}{\text{flux through system}}$$

b. For a column of soil:

$$T = \frac{\varepsilon . A . L}{Q} = \frac{\varepsilon L}{v}$$

where v can be found from Darcy's Law:

$$v = -k\nabla h$$

T:	time of residence	s
ε:	volume fraction of water	–
A:	cross section	m
L:	length of column	mm
Q:	flow through column	$m^3 s^{-1}$
$v = Q/A$:	flux density	$m\ s^{-1}$
k:	permeability	$m\ s^{-1}$
h:	hydraulic head	m

c. In porous media the velocity of transort V is larger than the flux density:

$$V = v/_{\varepsilon}$$

V:	average velocity of flow	$m\ s^{-1}$
v:	flux density	$m\ s^{-1}$
ε:	volume fraction of water	

d. For a well in the centre of a circular island, with yield Q (taken positive):

$$T = \frac{\varepsilon \cdot \pi R^2 \cdot H}{Q}$$

R:	radius of island	m
H:	thickness of aquifer	m
Q:	yield of well	$m^3 s^{-1}$

e. If the "old" and the "new" fluid are of different viscosity, complications arise. If a more viscous liquid is replaced by a less viscous one, instability ("fingering") occurs. With waters of different salinity, variations in viscosity may be neglected; in oil-water systems, they are very important.

3.3 Times of Residence in More Complicated Transport Systems

In many systems T varies, even when diffusion and dispersion are neglected. If a well W near a canal is pumped, the shortest stream-lines (like AW) have by far the shortest times of residence; the travel time along BW is much longer.

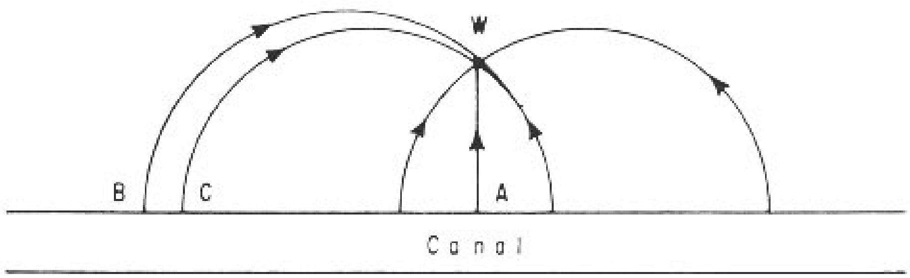


Fig. 1 TIMES OF RESIDENCE IN STREAM-LINES

A simple method of solution is the following: from models or from calculations we derive the pattern of stream-lines and the corresponding stream functions (e.g. from 0 to 100% of the total flow). If CW and BW are two stream-lines of which the stream function differs 1%, 1% of the total flow towards the well occurs between CW and BW. For this area therefore:

$$T = \frac{\varepsilon OH}{Q/100}$$

T:	time of residence	s
ε:	volume fraction of water	-
O:	area BCW (in reality!)	m^2
H:	thickness of aquifer	m
Q:	yield of well (positive)	$m^3 s^{-1}$

The area O can be found by using a planimeter and the scale of the model.

Example: scale of model 1:1000

O (measured in model) $\quad$ 15 cm^2

1 cm in model = 1000 cm = 10 m in reality

1 cm^2 " " $= 10 \times 10$ m = 100 m^2 in reality

O = 15 cm^2 " " = 1500 m^2 in reality

If Q = 0.05 $m^3 s^{-1}$; H = 10 cm ; = 0.25 we have between BW and CE:

$$T = \frac{0.25 \times 1500 \times 10}{0.05/100} = 7\,500\,000 \text{ s or } 89 \text{ days.}$$

A more direct method is the use of hydraulic models with coloured solutions (e.g. a Hele-Shaw model) or electrical models with coloured ions like $Cu(NH_4)_4^{++}$. For simple cases analytical solutions are available.

Example: flow through aquifer towards a drain D

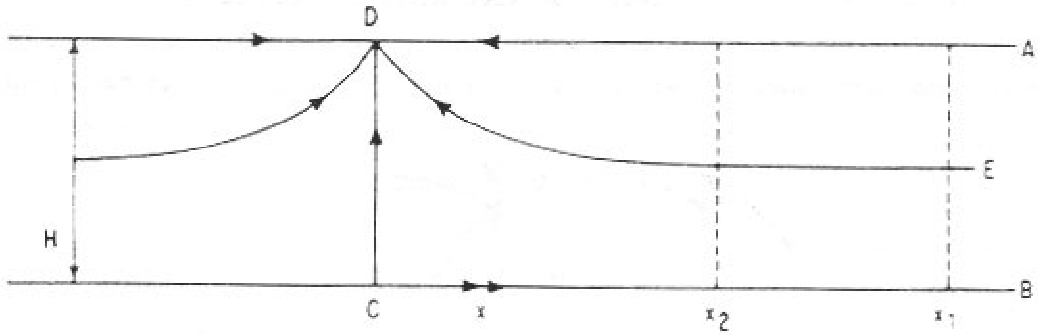


Fig. 2 FLOW THROUGH AQUIFER TOWARDS A DRAIN, D

Q: total flow towards drain (positive, from both sides)

H: thickness of aquifer

x: horizontal distance from drain.

along AD $\qquad T = \frac{4\varepsilon H^2}{\pi Q} \ln \cosh \frac{\pi x}{2H}$

along ED $\qquad T = \frac{2\varepsilon H^2}{\pi Q} \ln \cosh \frac{\pi x}{H}$

Along BCD no flow will ever reach the drain, because C is a "stagnation point". Far from C flow occurs along BC, but the water particles will deviate from BC towards the drain and complete stagnation occurs in the dead corner C.

Between two distances x_1 and x_2 ($x_1 > x_2$) we have:

along AD $$T = \frac{4\varepsilon H^2}{\pi Q}\left[\ln \cosh \frac{\pi x_1}{2H} - \ln \cosh \frac{\pi x_2}{2H}\right]$$

" ED $$t = \frac{2\varepsilon H^2}{\pi Q}\left[\ln \cosh \frac{\pi x_1}{H} - \ln \cosh \frac{\pi x_2}{H}\right]$$

" BC $$T = \frac{4\varepsilon H^2}{\pi Q}\left[\ln \sinh \frac{\pi x_1}{2H} - \ln \sinh \frac{\pi x_2}{2H}\right]$$

3.4 Times of Residence in a System with Recharge (approximate)

Example: recharge, due to percolation of excess irrigation water is drained towards parallel canals (fully penetrating). We take x = 0 midway between two canals and suppose all flow to be horizontal.

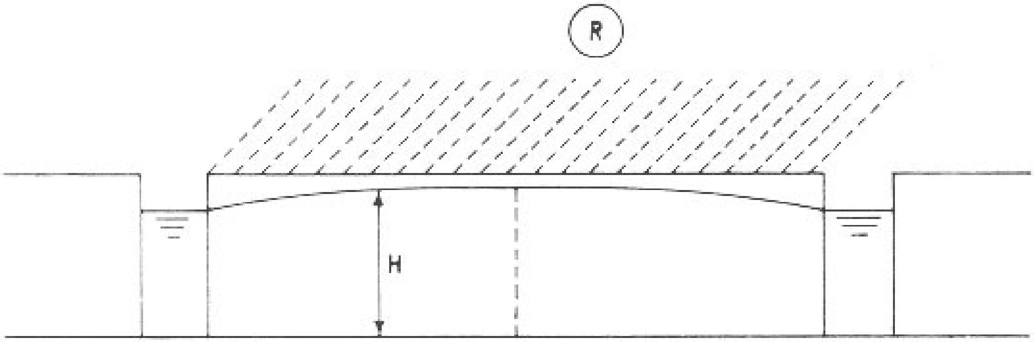


Fig. 3 TIMES OF RESIDENCE IN RECHARGE SYSTEM

x:	distance from divide	(m)
L:	distance of canals	(m)
H:	thickness of aquifer (~constant)	(m)
ε:	volume fraction of water	(-)
R:	recharge rate	($m\ s^{-1}$ or /day)
T_x:	time of residence between x and canal	(s or days)
Q_x:	flow at distance x from divide	($m^3 s^{-1}$ or m^3/day)

The flow at point x is $Q_x = R.x$

The flow from the left towards the canal at x = L/2 is RL/2

Total flow towards the canal (from both sides) is RL.

Between x and x + dx we have:

volume of system	$\epsilon H \; dx$	m^3
flow through system	Q_x	
time of residence	$dT = \frac{\epsilon H \; dx}{Q_x} = \frac{\epsilon H}{R} \cdot \frac{dx}{x}$	

Time of residence between points x_1 and x_2 $(x_1 < x_2)$

$$\Delta T = \frac{\epsilon H}{R} \int_{x_1}^{x_2} \frac{dx}{x} = \frac{\epsilon H}{R} \left[\ell n \; x_2 - \ell n \; x_1 \right] = \frac{\epsilon H}{R} \; \ell n \; x_2/x_1$$

If $x_1 = 0$ (midway between canals), the time of residence is infinite and stagnation occurs.

Between a point at distance x from the divide and the canal, the time of residence is:

$$T_x = \frac{\epsilon H}{R} \; \ell n \; \frac{L}{2x}$$

Example: In an irrigated area R = 1 mm/day ; L = 200 mm ; H = 5 m ; ϵ = 0.25.

x = 0	1	10	50	90	m
T_x = ∞	5756	2878	886	132	days
T_x = ∞	16	9.9	2.4	0.4	years

From the example, we see that within about 10 years nearly all the "old" groundwater in this shallow aquifer has been replaced by "new" water derived from irrigation. This is quite common, at least in well-drained soils and just below the root zone. Therefore the initial composition of the groundwater will not affect the development of salinity after irrigation; this process will be dependent upon the quality of the irrigation water.

DIFFUSION

Small particles are constantly moving. In liquids and gases, where particles are rather free, these random movements result in diffusion. If there is a difference in concentration, more particles will move from places of high concentration towards places of low concentration than in the reverse sense, because the probability of such a movement is greater.

Macroscopically diffusion is described by Fick's Law:

$$J = D \nabla c$$

J :	flux density	$kg\ m^{-2}s^{-1}$	or	$kg\ m^{-2}yr^{-1}$
D :	diffusion coefficient	m^2s^{-1}	or	m^2yr^{-1}
c :	concentration	$kg\ m^{-3}$		
∇c :	concentration gradient	$kg\ m^{-4}$		
x :	distance	m		
t :	time	s	or year	

The minus sign indicates that the flux is opposite to the direction in which the concentration increases.

Fick's Law is equivalent to the Laws of Ohm (electricity) and Darcy (groundwater flow).

If the movement is in the x-direction only:

$$J = -D \frac{\partial c}{\partial x}$$

For NaCl in water: $D = 1.52 \times 10^{-9}\ m^2s^{-1}$

For NaCl in soils: $D = 0.57 \times 10^{-9}\ m^2s^{-1} = 0.018\ m^2yr^{-1}$

In soils D is lower, because the pathways (pores) are tortuous. For different soils (clay, silt, sand) the mutual differences are small, because D is not dependent on the size of the pores (unless they become of molecular dimensions), but on their tortuosity, which is not very different in different soils.

4.1 Diffusion in Soils, Flooded with Fresh Water

We assume a saline soil which is suddenly brought under a layer of fresh water. By renewing the water, its salinity is kept low and the soil continues to loose salt by diffusion. No movement of water through the soil is supposed to occur.

This situation arises in rice cultivation on saline soils and also at the bottom of salty lakes, which suddenly turned fresh by human interference.

For the salt concentration in the soil, we have:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \qquad \text{where } x \text{ is depth below surface}$$

In the cases mentioned, the solution appears to be:

$$c = c_o \text{ erf } u \qquad \text{with} \qquad u = x/2\sqrt{Dt}$$

$$\text{erf } u = \frac{2}{\sqrt{\pi}} \int_0^u e^{-u^2} \cdot du$$

If t is expressed in years, $D = 0.018\ m^2/\text{year}$, x in metres we find c at any depth and time. Diffusion appears to be a slow process (see Figure 4).

Rice growing on saline soils is possible if a continuous stream of fresh water is maintained across the fields to remove the salts entering the water by diffusion. The topmost centimetres of the soil soon become fresh enough for root growth. The desalinization of deeper layers, however, is extremely slow; therefore rice growing is not a good measure for reclaiming saline soils.

An example is the Guadalquivir marshes in Spain, where rice on highly saline clay soils yielded 5 000 kg/ha if a continuous stream of fresh water was available. The salt content of deeper layers, however, was hardly changed.

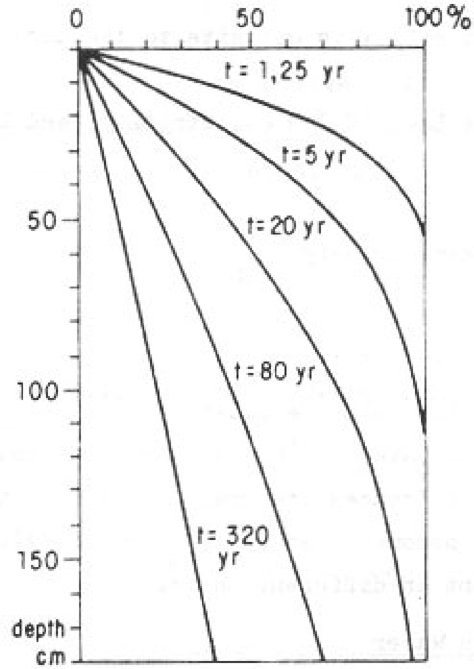


Fig. 4 THEORETICAL RELATIONS BETWEEN DEPTH AND SALINITY IN THE BOTTOM OF A LAKE WHICH TURNED FRESH AT $t = 0$

The diffusion process in the bottom of Lake Ijssel closely followed the laws mentioned above. This lake was separated from the sea in 1932 and turned fresh soon afterwards.

4.2 Diffusion from a Thick Clay Layer towards a Thin Sandy Aquifer

We may suppose a thick clay layer underlying a thin sandy aquifer. In the aquifer water is circulating, but the clay is considered impermeable. Both the sand and the clay are of marine origin.

Initially both the sand and the clay are filled with connate salt water of concentration c_o, but at a time, $t = 0$, fresh water begins to enter the sand with c flux density v. Due to this recharge, the salt water in the sand is replaced by fresh water, but at the same time diffusion from the clay starts. Due to this process, the aquifer will continue to yield brackish water for a long time.

The water in the aquifer is supposed to be completely mixed over its cross-section, but no dispersion occurs in longitudinal direction. This is a good approximation for thin aquifers extending over large distances, but for aquifers of great thickness dispersion processes (transversal as well as longitudinal) must be taken into account.

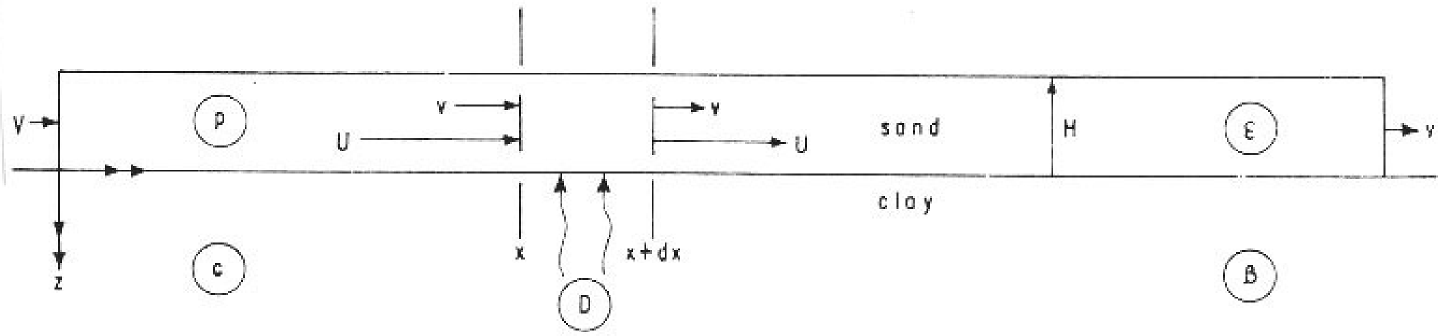


Fig. 5 DISPERSION IN AQUIFERS

The salt concentration in the aquifer is:

$$p = c_o \operatorname{erf} \frac{\beta Dx}{2\varepsilon HU\sqrt{D(t-x/U)}}$$

The salt concentration in the clay is:

$$c = c_o \operatorname{erf} \frac{\frac{\beta Dx}{\varepsilon H} + zU}{2U\sqrt{D(t-x/U)}}$$

p	:	salt concentration sand	kg m^{-3}
c	:	" " clay	"
c_o	:	" " initial	"
x	:	distance	m
z	:	depth in clay	"
t	:	time	s or yr
β	:	porosity clay	-
ε	:	" sand	-
H	:	thickness sand 1/	m
D	:	diffusion coeff. clay	$m^2 s^{-1}$ or m^2/yr
U	:	true velocity	m s^{-1}
v	=	εU: flux density	m s^{-1}

1/ See also point following

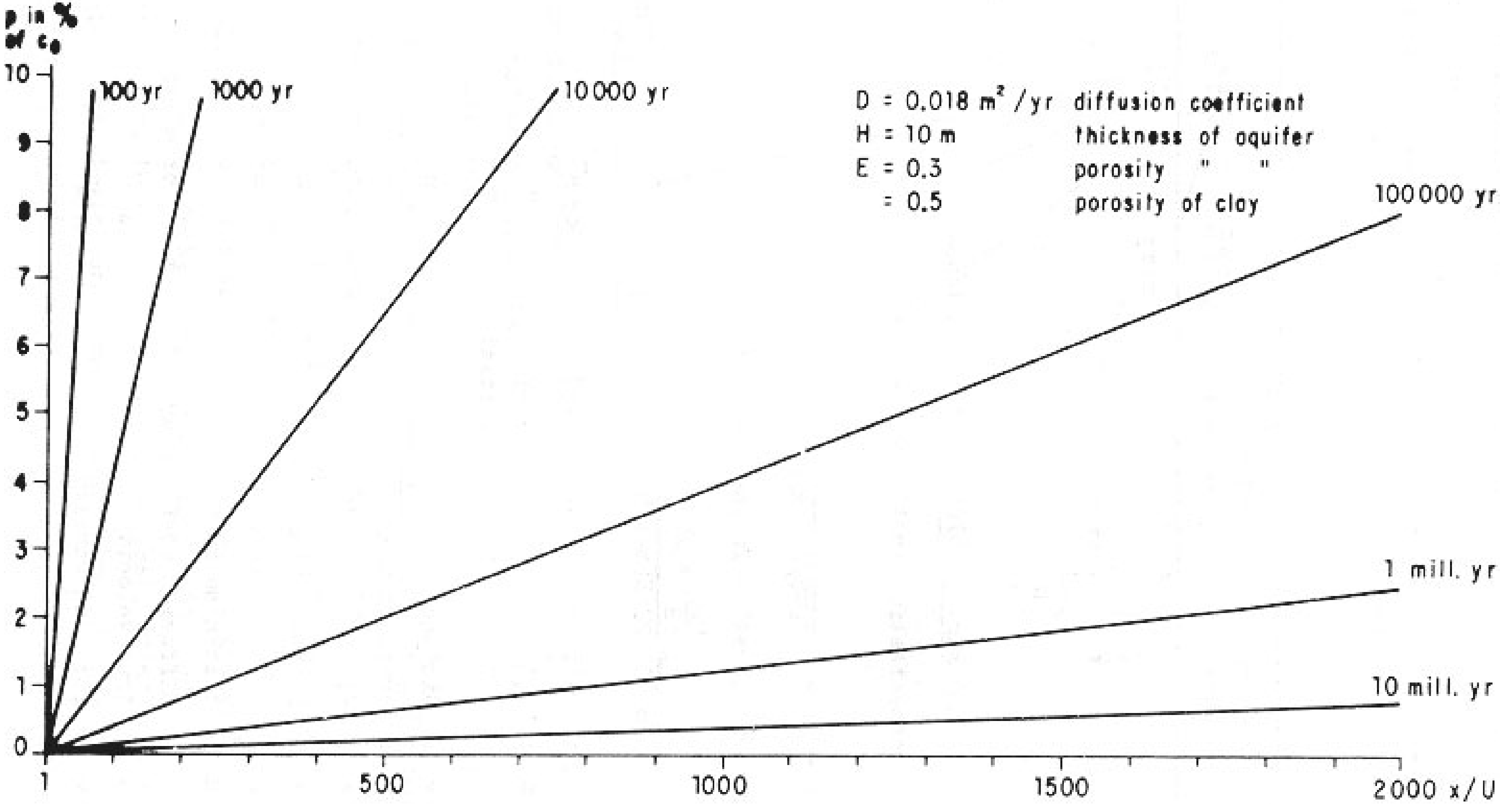


Fig. 6 DESALINIZATION OF AN AQUIFER IN CONTACT WITH SALINE CLAY OF GREAT THICKNESS

For H = 10 m the salt concentrations we' calculated. The results are
D = 0.018 m²/yr given in the figure. For large distances and low velocity
ε = 0.3 (x/U > 1000) the aquifer yields brackish water for very
ε = 0.5 long periods.

If the aquifer is confined between two initially saline clay layers of great thickness, H must be taken as half the thickness of the aquifer.

The theory explains the increasing salinity along the path of flow, as encountered in many aquifers. A similar theory has been developed in heat flow (Carslaw and Jaeger, p. 296).

5. DISPERSION

5.1 Mechanism of Dispersion

In porous media, like the soil, water moves through a complicated network of tortuous channels. In soils, the grains cause a frequent separation of water filaments which re-unite later on. The movement is very irregular on a microscopic scale, but on a macroscopic scale it shows a distinct direction and velocity of flow.

In places, where two or more pores unite to form a cavity, the water coming from different directions is mixed by molecular diffusion. It can be shown that in soils this process is rap. enough to reduce any existing differences in concentration to less that 1% of their original value during the time that the water is present in such a cavity. Therefore, the entire movement can be considered as flow through a series of interconnected, small but well-mixed reservoirs with dimensions of the same order as the soil particles. From each reservoir smaller pores lead into different directions; a water particle from such a reservoir chooses one of these pathways, in the general direction of the macroscopic flow.

Another cause for dispersion is the irregular flow within the pores. In a capillary tube, water flows faster in the middle than near the walls, this leads to longitudinal dispersion.

In soils, the pores are of different size, and water flows faster through the larger pores. Later on, such fast filaments re-unite with slower ones and molecular diffusion again causes exchange. Also this mechanism is mainly operative in the direction of the macroscopic "stream lines". Therefore longitudinal dispersion is larger (often 3-8 times as large) as transversal. This is in contrast with diffusion, which is equally active in all directions.

Elaborate models for dispersion have been worked out by Scheidegger, Bear, and others.

Dispersion is characterized by a dispersion coefficient D_x ($m^2\ s^{-1}$ or m^2/yr), which plays the same part as the coefficient for molecular diffusion D. As dispersion is different in longitudinal and transversal direction, we must distinguish between:

D_L ($m\ s^{-1}$ or m/yr) for longitudinal dispersion

D_T ($m\ s^{-1}$ or m/yr) for transversal dispersion.

Both are approximately proportional to the average velocity of flow in the pores, V; they are often written as

$$D_L = (\lambda + 2\mu)\, V \qquad V = v/\epsilon$$

$$D_T = V$$

λ, μ	:	constants (lengths), of the same order as the irregularities in the soil	m
V	:	average velocity in the pores in direction of flow	$m\ s^{-1}$ or m/yr
v	:	flux density ("filtration velocity")	$m\ s^{-1}$ or m/yr
ϵ	:	porosity (volume fraction)	

From

$D_L = (\lambda+2\mu)\ V$ and $V = v/\epsilon$ we have:

$D_L = k.v$ where $k = \frac{\lambda+2\mu}{\epsilon}$ is again a constant, the "characteristic length".

5.2 One-dimensional Dispersion

If all changes occur in the direction of flow (x-direction), longitudinal dispersion only is operative. This is the case in the desalinization of a soil by rainfall or irrigation, where the direction of flow is vertical.

This leads to the differential equation

$$\epsilon \frac{\partial c}{\partial (vt)} + \frac{\partial c}{\partial x} - k \frac{\partial^2 c}{\partial x^2} = 0$$

For desalinization of a semi-infinite soil column, the conditions are:

$x > 0$	$t = 0$	$c = c_o$	(initial salt content)
$x = 0$	$t > 0$	$c = 0$	(boundary condition)
$x \rightarrow \infty$	t finite	$c = 0$	(infinite depth)
x finite	$t \rightarrow \infty$	$c = 0$	(infinite time)

The solution conforming to these conditions can be found by using the Laplace-transformation. It is:

$$c(x,t) = \frac{c_o}{2}\left[\operatorname{erfc} \frac{vt-\epsilon x}{2vt}\sqrt{\frac{vt}{\epsilon k}} - e^{x/k} \operatorname{erfc} \frac{vt+\epsilon x}{2vt}\sqrt{\frac{vt}{\epsilon k}} \right]$$

where

$$\operatorname{erfc} z = 1 - \frac{2}{\sqrt{\pi}} \int_0^z e^{-u^2} .du$$

v	:	flux density	($m\ s^{-1}$)
t	:	time	(s)
c(x,t)	:	salt concentration	($kg\ m^{-3}$ of soil moisture)
c_o	:	initial salt concentration	($kg\ m^{-3}$ of soil moisture)
ϵ	:	pore fraction filled with solution	(-)
k	:	characteristic length	(m)
x	:	depth	(m)

This solution was proposed by Glueckauf for laboratory columns; with k = 0.05 m it gives a fair description of the desalinization of silt-loam soils under the influence of rainfall. Recently Frissel and Reiniger (1974) found k = 0.03-0.07 m for soils leached by sprinkling.

The solution mentioned applies only to substances which remain in solution: the Cl'-ion is a good example. For substances entering in ion exchange or precipitation reactions solutions have been worked out by Reiniger and Bolt (1972).

A simpler model consisting of a series of completely mixed reservoirs, each with a thickness 2k gives almost the same results; for practical cases this model is extremely useful (see section 6).

5.3 Two-dimensional Dispersion

If salts enter an aquifer, dispersion occurs in longitudinal as well as transversal directions. If an aquifer, overlying a salty clay layer (cf. 4.2) is thick, this dispersion cannot be neglected.

For certain cases, especially when a constant salinity is maintained at the clay surface, the problem of dispersion has been solved (Verruijt, 1973). For a combination of diffusion (from clay towards aquifer) and dispersion (within the aquifer) no exact solution has yet been found. Preliminary calculations, compared with observations in the thick Pleistocene aquifer of the Netherlands show that the irregularities (which govern the values of λ and μ) are of the order of 1-2 metres. Obviously dispersion is governed by irregularities in the aquifer rather than by sand grain effects, which would cause values of λ and μ of the order of one millimetre (Meinardi, 1973).

6. MIXED RESERVOIRS IN SERIES

6.1 Series of Reservoirs as a Model for Aquifer Behaviour

A simpler model is obtained by considering aquifers or soils as composed of a series of well-mixed compartments. Diffusion and dispersion act as mixing processes, whereas the dimensions of the compartments are a measure for their activity; with small compartments transport dominates, with larger ones mixing processes gain importance.

With compartments or reservoirs of equal size, originally saline and losing their salt by leaching, we have:

For the first compartment $c_I = c_o \cdot e^{-t/T}$

" " second " $c_{II} = c_o \cdot e^{-t/T} (1 + \frac{t}{T})$

" " third " $c_{III} = c_o \cdot e^{-t/T} (1 + \frac{t}{T} + \frac{t^2}{2 \cdot T^2})$

" " N-th " $c_N = c_o \cdot e^{-t/T} \left(1 + \frac{t}{T} + \dots + \frac{t^{N-1}}{(N-1) \cdot T^{N-1}}\right)$

where T is the time of residence in each compartment.

The results are almost the same as for the dispersion theory treated in 5.2, if the thickness of each compartment is taken equal to 2 k.

6.2 Reservoirs with Bypass

In irrigated soils, leaching is often not fully efficient. Such soils usually have cracks, root holes, etc., through which part of the water passes almost unchanged. The model for such cases is a mixed reservoir, provided with a bypass, through which part of the water flows unaltered towards the next compartment.

The leaching efficiency in irrigated soils is represented by the relative importance of such a bypass. It ranges from zero (all water passing through the bypass) to one (all water passing through the reservoir).

In practice, this leaching efficiency is lower for heavy soils than for light-textured ones: under sprinkling it is higher than under surface irrigation systems.

7. ORIGIN OF SALTS

7.1 Sources of Salts

The primary source of salt is the weathering of rocks. Rocks contain Na, K, Mg and Ca in the form of silicates. Chlorides are rare; sulphur is mainly present as insoluble sulphides, which may be transformed into soluble sulphates after oxidation.

Weathering occurs under the influence of CO_2 from the air and especially CO_2 produced by decay of organic matter. This process gives rise to soluble carbonates of Na, K, Mg and Ca. Also Cl and SO_4 are removed by leaching and in the humid tropics dissolution of silicates is an important process.

The hydrological cycle transports the dissolved salt to the ocean, which is enriched with Na, K, Mg, Cl and SO_4. In the sea, Ca is precipitated by organisms as shells and limestones; therefore the sea water has a low Ca content.

7.2 The Salt Cycle

The amount of soluble salts, carried by the rivers, is sufficient to give the ocean its present salt content within a geologically short time. As the ocean is much older, a salt cycle must exist, comparable to the hydrological cycle, but proceeding at a slower rate.

Rain and salt spray from the waves bring salt towards the continents. The amounts are considerable near the coast, but rapidly diminish further inland, as shown in the following table.

SALT CONTENT OF RAIN WATER IN GERMANY (RIEHM and QUELLMALZ, 1959)			
Location	Distance from coast km	Cl mg/l	Na mg/l
Westerland	0.2	37.6	18.5
Schleswig	50	4.9	2.4
Braunschweig	450	1.9	0.8
Augustenberg	800	0.9	0.5
Retz	1250	0.3	0.1

All marine sediments are by origin saline. In the case of pore water (connate water) also the salts are trapped in the sediments. In dry climates the salt concentration may become far higher by evaporation. Along the Gulf of Cambay (India) large tidal flats are only flooded at spring tide. Between two inundations the salts become concentrated by evaporation and consequently the salt concentration of the soil moisture is several times higher than in sea water. By uplift of marine sediments, considerable amounts of salt are removed from the sea.

Under special circumstances (bays in a dry climate, separated from the sea by a narrow and shallow entrance) evaporites are formed: gypsum, halite (NaCl), finally K and Mg salts. Such evaporites may reach a great thickness: in the Zechstein (Permain) hundreds of metres of evaporites were formed in N.W. Europe and similar formations of different geological age occur elsewhere.

Under high pressures (overburden of more than 1 000 m thickness) salt becomes plastic and starts to flow. Thick salt layers (of more than 300 m in thickness) form domes, which often rise another 1 000 m over the original position, forming slender pillars or walls. Sometimes such salt diapirs reach the surface, where they may form "salt glaciers" in a dry climate (Iran). In other cases the surface is not reached but the salt diapirs may become exposed by later erosion. Erosion of salt domes is a major source of salinization or rivers in mountainous areas (Karpathians and N. Africa, where Triassic salts influence the quality of many rivers).

If the salt diapirs remain buried, part of their salts will dissolve in the groundwater. The impurities in the salt are left behind as a "caprock" of clay or anhydrite ($CaSO_4$), which is nearly watertight. Due to such caprocks, the salt domes of the northern Netherlands do not influence the recent groundwater, but in other areas (e.g. across the German border) highly saline groundwater is found near diapirs. Where such groundwaters rise to the surface, saline soils occur, characterized by a vegetation of halophytes.

Old marine sediments may still contain saline waters. The water pumped from coal mines in the Netherlands and Germany is often brackish; this is perhaps due either to marine transgressions during the Carboniferous or to later transgressions of the sea.

Permeable marine formations on the continents (sands, sandstones, limestones) often become fresh due to leaching by rainwater. Water from such formations may be used for domestic purposes or for irrigation water.

Examples:

1. The Tilburg water supply draws water from a layer of marine shells dating from the Pliocene. In later periods this ancient "beach sand" has become fresh.
2. Many limestones of marine origin are excellent sources for irrigation water.

However, if such permeable formations are in contact with marine clays, which are still salty, diffusion of salt from the clays often influences the water quality in the aquifer, a process which may continue for geological periods. As a consequence, the water in the aquifer becomes increasingly brackish in a downstream direction. In the long run the entire formation will become fresh, but this process may require geological time.

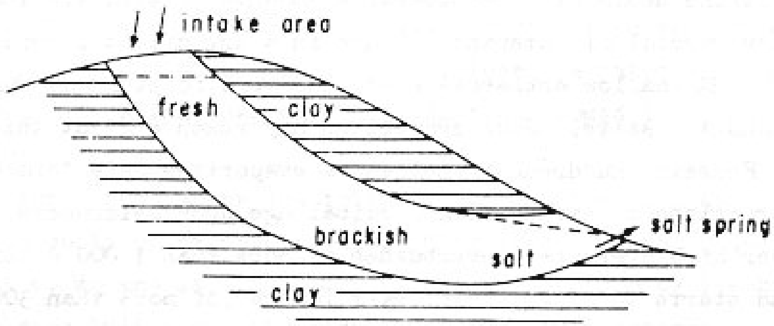


Fig. 7 INFLUENCE OF DIFFUSION OF SALT FROM MARINE CLAYS ON WATER QUALITY

7.3 Kinds of Salts

The chemical composition of the salts depends on the geochemistry of the region. In coastal areas, Cl usually dominates, due to cyclic salts carried with the rainfall and due to former marine transgressions.

In limestones and calcareous sands (many coastal dunes) Ca and HCO_3 dominate, due to dissolution of $CaCO_3$ in water containing CO_2. Such waters are "hard"; they are useful for irrigation, but present problems in domestic use and especially in industry. Ion exchange may cause natural softening of such waters, converting them into waters of $NaHCO_3$ type, which are less favourable for irrigation.

In some areas B is present. This element forms soluble borates, which may concentrate in borax lakes ($Na_2 B_4O_7 \cdot 10H_2O$). Boron is a minor element in plant nutrition, but excess leads to damage, especially in fruit trees. Such B toxicity is probably confined to areas of volcanic influence.

Other volcanic rocks are rich in Na (some basalts contain Na zeolites, some igneous rocks contain Na silicates) and give rise to waters high in Na, with a high SAR value.

In the centres of the continents ions other than Cl usually dominate: either SO_4 or HCO_3 - salinization occurs. In tropical regions HCO_3 and silicates dominate, but the total concentration of the waters is extremely low. The few cations present in the soil are taken up by the tropical rain forest and return via falling leaves and dead wood. This cycle is almost closed and few cations escape by leaching. If the forest is cut, the elements are rapidly leached. Therefore, in regions with shifting cultivation the concentration of the river water is markedly higher than under natural conditions, where total dissolved solids are about 50 g m^{-3} (mg/l).

In other cases SO_4 is the dominant anion, giving rise to sulphate salinization. In combination with Ca it leads to waters, rich in gypsum, which are of excellent quality for irrigation.

7.4 Pollution with Inorganic Compounds

In industrialized and densely populated regions pollution (both organic and inorganic) often dominates the natural water quality. An extreme example is the Rhine river, with a Cl content of about 250-300 mg/l, whereas the natural content is about 20 mg/l.

The following are examples of pollution with inorganic compounds:

- <u>mining</u>: the potash mines of the Elzas cause considerable pollution of the Rhine with NaCl, which is a useless by-product from these mines. In addition, coal mines pump salt water into the river.
- <u>irrigation:</u> drainage water of irrigated areas is often salty. If discharged into a river, it may damage other areas further downstream. In arid regions, this may become one of the major problems in stream basin development, especially in regions far from the sea.

- municipal waste water: contains several kinds of salts, like chlorides, nitrates and phosphates. Groundwater under old human settlements contains more Cl and NO_3 than natural waters; in dry climates $NaNO_3$ crystallizes around such old settlements.
- industry: soda industries convert NaCl into Na_2CO_3 according to the overall reaction:

$$2\ NaCl + CaCO_3 \rightarrow Na_2CO_3 + CaCl_2$$

  The calcium chloride is a useless by-product and is discharged.
- drainage of polders causes seepage currents. In coastal areas the seepage water is often saline. In the Netherlands this is an important cause of salinization.
- cooling water, if pumped from great depth, may be saline. In Delfland district (Netherlands) a special pipeline has been constructed to convey saline cooling water from industries at Delft towards the sea.

8. INFLUENCE OF GROUNDWATER CURRENTS AND CAPILLARY RISE

8.1 Seepage Currents

From the foregoing it will be clear that movement of water causes movement of salts. Salts, therefore, are transported from places where water is infiltrating towards places where it evaporates. They accumulate in places where groundwater rises to the surface, a phenomenon denoted as seepage.

Seepage is common along the foot of a hill or natural terrace and in valleys. In humid climates, hydromorphic soils (gley soils) are found in such locations, in arid climates saline soils occur instead. If semi-permeable (semi-confining) layers are present in a valley near the surface, extended seepage of low intensity occurs over large areas; if they are absent seepage is concentrated near the foot of the slopes. (Fig. 8 A and B.)

In irrigated areas, leakage of water from unlined canals gives rise to seepage in their neighbourhood and often causes severe salinization of a strip along such a canal. (Fig. 8C.)

Extremely widespread is seepage from irrigated fields towards adjoining dry fields. Under irrigation, water tends to move downwards and there is little danger of acute salinization, but under non-irrigated fields water moves upward and evaporates, so that salts accumulate. Due to this movement, we often find a rim of highly saline soils around small irrigated areas or around villages. (Fig. 8.)

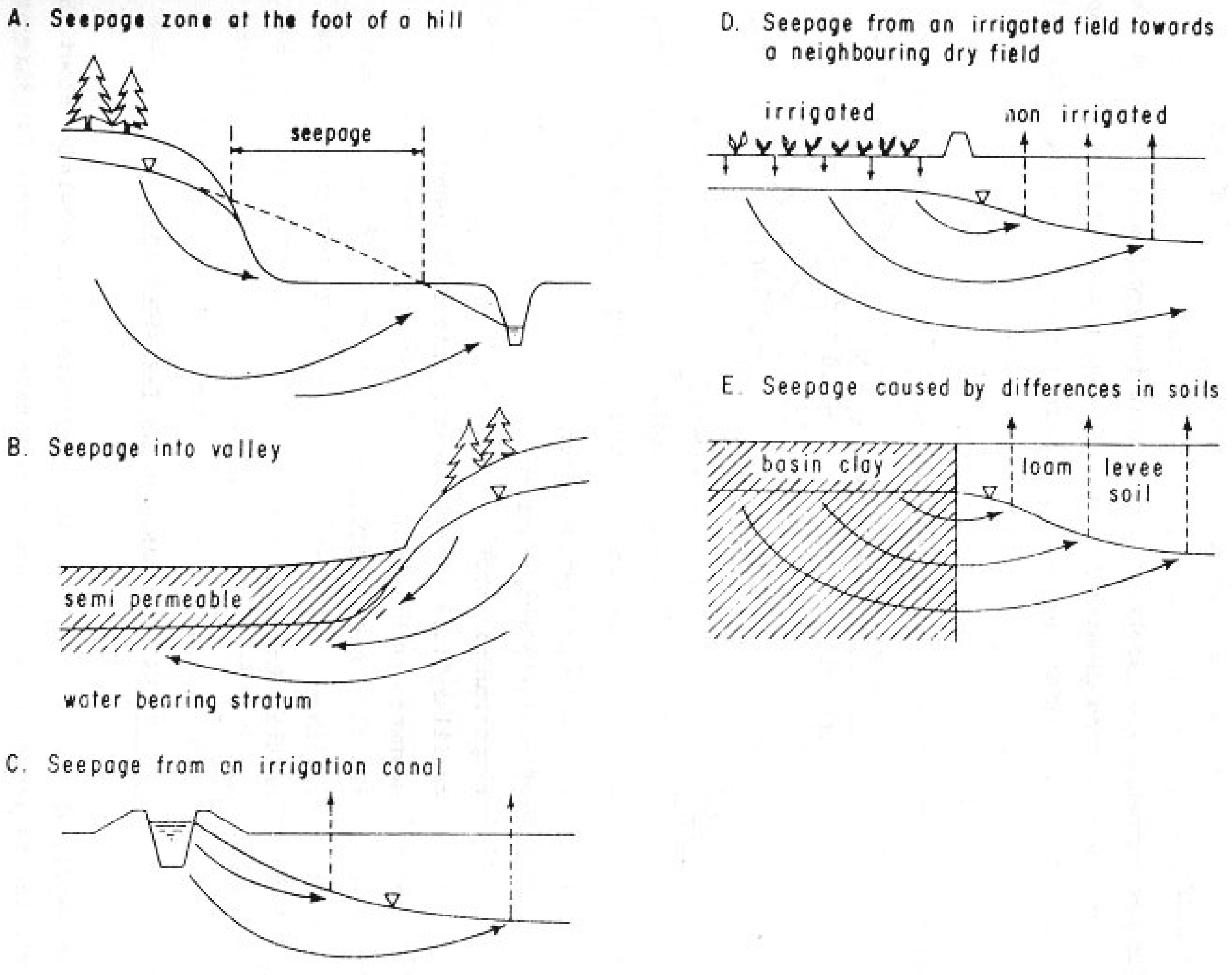
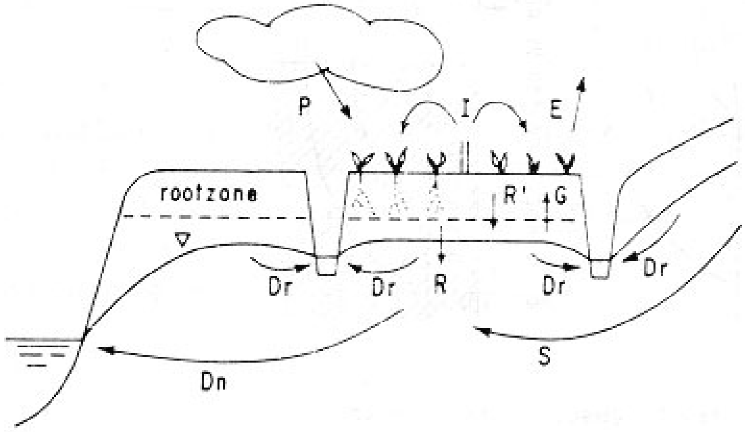


Fig. 8 SEEPAGE PHENOMENA

If soils with different capillary characteristics border each other, seepage currents may be set up, directed towards soils of higher capillarity. This may cause natural differences in salinity, due to variations in soil texture. Slight differences in elevation may have similar effects. (Fig. 8E.)

8.2 Capillary Rise

Seepage currents are rarely so strong that the groundwater reaches the surface. Usually an unsaturated zone remains present, through which water rises by capillary action towards the soil surface or towards the root zone of plants. (Fig. 9).



I	:	effective irrigation water
P	:	effective precipitation
E	:	evapotranspiration
G	:	capillary rise of groundwater into root zone
R'	:	downward percolation
R = R'-G	:	net downward percolation
Dr	:	drainage
Dn	:	natural drainage
S	:	seepage

Fig. 9 WATER BALANCE OF AN IRRIGATED SOIL

The nature of capillary rise is well understood and knowledge about the soil characteristics is increasing. Several models have been proposed for this process, among these the model of Rijtma-De Laat is useful for practical purposes. In this model the non-steady process is approached by a succession of steady states. Recently this model was applied to saline soils by **Varallyay** (1974). The model predicts that capillary rise will lead to a lowering of the groundwater table. This in turn, will cause a decrease in the upward flow and finally the process will come to a standstill. The depth of the groundwater after a prolonged dry period is a fair indication of the depth over which capillary flow is active and may be used as a check on the calculations.

The limiting groundwater depth, mentioned above, is only indicative if neutral groundwater conditions exist, i.e. if neither natural drainage nor seepage occur. If natural drainage is present, the groundwater will fall below this level and capillary rise will stop earlier. If seepage is present, the groundwater will be maintained at a higher level. In this case, an equilibrium is reached in which the capillary rise becomes equal to the amount of seepage. The amounts of salt transported by this process are usually considerable and may lead to severe salinization. Therefore, attention should be given to groundwater currents and especially to measures that prevent seepage water from reaching the surface, among these leaching and drainage are of most importance.

9. SUMMARY AND CONCLUSIONS

Salts move with the water; this transport is modified but usually not profoundly altered by diffusion and dispersion.

Ion exchange, precipitation or solution may change the proportions of individual ions.

The occurrence of salinity under natural conditions can be explained from a study of the geo-hydrology of the area. Such investigations also form the base for predicting the changes introduced by irrigation.

Phenomena of seepage and capillary rise greatly influence salt transport and accumulation. For these processes, useful models have been developed; their application is hampered by a lack of knowledge about the soil constants, like saturated and unsaturated hydraulic conductivity. Work should be concentrated on methods to obtain such constants rather than on further refinement of the models.

The "salt cycle" concept may be helpful in understanding phenomena of salinization and leaching.

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2. Man-made Factors

Paper 5

a. WATER MANAGEMENT AND SALINITY[1/]

by

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1. INTRODUCTION

Permanent agriculture under conditions of insufficient precipitation depends on water management so that excessive salts do not accumulate in the root zone. When rainfall is insufficient to satisfy evapotranspiration and the plants must depend on drawing from a water table for part of their water supply, the only question is how soon the soil will salinize, not whether. When irrigation water is supplied, there is a twofold question: whether sufficient supplemental water is applied to provide the required leaching, and whether the drainage network (natural or man-made) has the capacity to remove sufficient water with its associated salts. In other words, to prevent salination, a net downward flux of water is mandatory.

In this discussion, I propose to distinguish between maintaining a favourable agriculture under irrigation and reclaiming excessively saline (or sodic) soils.

2. MAINTAINING A FAVOURABLE ROOT ENVIRONMENT

One of the criteria that is often applied to predict whether a soil will salinize is the so-called "critical water table depth". As I understand it, the basic concept of a critical depth is rather simple, but its application extremely complex. As described by Talsma (1963), it was first introduced by Polynov in 1930 and defined as that maximum height above the water table to which the salts contained in the groundwater can rise under natural conditions both by capillary rise and diffusion. We understand better now than we did in the 1930s that the level to which water can rise in soils is essentially unlimited, as long as we do not specify the rate of rise. Within the framework of this concept, however, numerous observations have been made, often associated with detailed field studies. They have led to estimates for critical depth varying from 1 to over 3 m, depending on soil

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1/ Contribution from the Agricultural Research Service, USDA, U.S. Salinity Laboratory, Riverside, California.

morphology, climate, quality of the groundwater, cropping patterns and other factors. Kovda (1961), for example, makes clear and specific distinctions based on salt content of the groundwater. Talsma (1963) concluded, from his own field studies and data in the literature, that it was reasonable to specify that the upward flux should not exceed 0.1 cm/day. If the soil physical properties are known, this maximum flux permits, in theory, the calculation of a minimum depth to water table.

Even though numeric standards can be readily found in the literature, the determination of the critical depth remains a judgement, rather than a rational derivation. Szabolcs, Darab and Varallyay (1969) took an important step to rectify this shortcoming and proposed a method for calculating the critical depth from a salt balance model. Whereas their method has merit, it also suffers from a fundamental weakness. In effect, these authors assume that there is an influx, x, of salt to the root zone equal to the amount in the irrigation water, and an influx, z, from the capillary fringe. The salt concentration, C_3, in the capillary fringe is derived from the groundwater, plus any residual salt. The influx z is determined by assuming a constant upward water flux at concentration C_3, independent of water table depth. Since the total salt flux into the root zone is assumed constant, it follows that the calculated concentration in the soil solution increases as the depth D_1 of the root zone is decreased by a rise of the water table. These calculations completely ignore the dynamics of water flow (see Fig. 1). Another problem with the model is the assumption of a "salt regime coefficient", or a natural, constant leaching rate expressed as a percent of soil per year. To the extent that such a rate can be estimated, it should be a function of the concentration of the soil solution near the lower boundary of the root zone and the water flux, rather than of the salt content of the soil and, thus, the depth D_1. Varallyay (1974), in recognition of this problem, carried the work further by determining, in the laboratory and by computer, the maximum height to which water could rise at prescribed rates for different arrangements of layers of soil with widely varying properties.

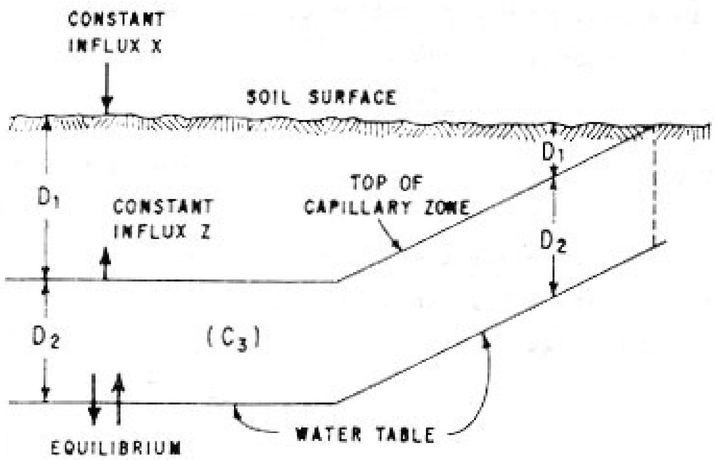


Fig. 1 SCHEMATIC ILLUSTRATING SOME OF THE IMPLICATIONS OF CRITICAL WATER TABLE DEPTH MODEL BY SZABOLCS et al. (1969)

If we may look back to the concept advanced by Gardner (1958) and further developed by Raats and Gardner (1974), a constant upward flux from a water table can only be maintained as long as a limiting height is not exceeded. Starting with the steady state flow equation in the form

$$q = k(1 - dh/dz), \qquad [1]$$

where q(cm/day) is the flux, k(cm/day) the hydraulic conductivity, h(cm of water) the pressure head, and z the vertical coordinate, with positive direction downward, we may solve for z:

$$z = \int (1 - q/k)^{-1}\, dh. \qquad [2]$$

If the relation between k and h is known, the integration can be performed, be it sometimes with difficulty. For many soils, the k(h) relation can be adequately represented by (Raats and Gardner, 1974)

$$k = \frac{K}{(h/h_{K/2})^n + 1}, \qquad [3]$$

where K represents the conductivity at saturation, $h_{K/2}$ the pressure head at which $k = K/2$ and n a constant varying from 1 to around 15. This relationship is equivalent to Gardner's (1958)

$$k = a/(S^n + b) \qquad [3a]$$

with $S = -h$, $K = a/b$ and $-h_{K/2} = b^{1/n}$. Another relationship, particularly convenient for analytical work, has the form

$$k = K \exp(\alpha h). \qquad [4]$$

Here α (cm^{-1}) is a soil property that describes the relative rate of change in k with respect to the pressure head:

$$\alpha = (1/k)\, dk/dh. \qquad [4a]$$

Gardner (1958) and before him Wind (1955) showed that there was a maximum upward flux from the water table that could be sustained over a given distance. This seems to be true wherever the integral $\int_0^{-\infty} k(h)dh$ is finite, whatever equation is used to describe k(h). In Raats and Gardner's (1974) notation, using Eq [3], one finds, for $q \ll K$,

$$-q_{max} = K[h_{cr}/(z-z_o)]^n \qquad [5]$$

or, exactly,

$$\frac{-q_{max}/K}{(1 - q_{max}/K)^{1-n}} = \left[\frac{h_{cr}}{z-z_o}\right]^n \qquad [5a]$$

Here z_o is the elevation at which k = K (water table) and $h_{cr} = h_{K/2}\, \pi/n \cdot \sin(\pi/n)$ represents the critical pressure head introduced by Bouwer (1964).

$$h_{cr} = (1/K) \int_0^{-\infty} k(h)dh. \qquad [6]$$

Note that, because of our sign convection, q_{max} and $z-z_o$ will be negative.

If Eq [4] is chosen instead of Eq [3] to represent k(h), one can integrate Eq [1] to obtain

$$\alpha z = \ln\left[(k - q) / (K - q)\right]. \qquad [7]$$

This, in turn, yields the limiting value (with z = 0 at h = 0)

$$z_{max} = -\alpha^{-1} \ln (1 - K/q_{max}). \qquad [8]$$

For this case (Eqs [4] and [6]), $h_{cr} = -1/\alpha$.

Thus Eqs [5] and [8] represent two relations that permit the determination of the minimum depth of the water table below a sink of given strength in a uniform soil.

Table 1 gives some z_{max} values for illustrative soil parameters taken from the literature. Note, that, in the range of q of importance for the present purpose, the approximate Eq [5] gives essentially the same result as the exact Eq [5a]. Eq [8], on the other hand, matches well only when n has a value close to 2.5, giving rather different results for n deviating substantially from that value. This latter point is especially clear in the more general comparison given in Fig. 2, showing the relationship between the dimensionless ratios z_{max}/h_{cr} and $-q_{max}/K$ for various values of n in Eq [5a] and for Eq [8].

Table 1 CRITICAL DEPTH (z_{max}) CALCULATED FOR FOUR SOILS BY MEANS OF THREE EQUATIONS, ASSUMING $-q_{max}$ = 0.1 cm/day

Soil type	K sat cm/day	$-h_{K/2}$ cm	n	z_{max} -cm Eq [5]	Eq [5a]	Eq [8]	α 1/ cm^{-1}
Banno sand 2/	26.5	6.6	1.5	659	658	89	0.0625
Yolo 1 3/	1.0	20	2	99	95	75	0.0318
Pachappa f.s.l. 3/	12.3	30	3	180	179	175	0.0276
Sand 4/	40.0	18	4	89	89	120	0.0500

1/ Calculated from $-\alpha^{-1} = h_{K/2}\pi/n\cdot\sin(\pi/n)$

2/ From Talsma (sand overlying clay) (1963)

3/ From Gardner and Fireman (1958)

4/ From Wind (1961)

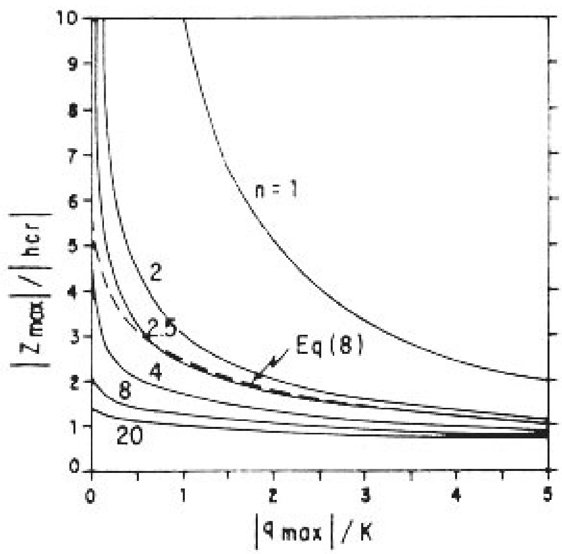


Fig. 2 DEPENDENCE OF MAXIMUM HEIGHT OF RISE ABOVE WATER TABLE ON FLOW RATE FOR A RANGE OF VALUES OF n in Eq [5a] and for Eq [8]

For non-uniform soils, thus in many field situations, the above approach is limited. Varallyay's (1974) numeric approach provides as yet the only available solution for layered soils. The other requirement of the theory, a given sink strength, raises two dilemmas: its magnitude and its location. Talsma (1966) advances several reasons for selecting $-q_{max} = 0.1$ cm/day, including that it seems to work satisfactorily in practice, that the nature of the k(h) curves often results in an abrupt change in required critical depth around this value, and that the potential evapotraspiration rate normally is higher. It appears indeed a reasonable choice, if the critical water table depth is used at all, and if it is kept in mind that over time any upward rate will salinize a soil. The question of the location of the sink is another matter. For bare soil, the sink is simply the evaporative flux from the surface, but for cropped soil, it becomes a distributed sink due to a variable root water uptake pattern. As a first approximation, one might estimate the depth of the rooting zone and use that value as the boundary for the upward flux calculations. This clearly is not a very satisfactory solution. The interaction between root uptake patterns and soil water and solute fluxes is a complicated subject in which only limited progress has been made to date, at least in the present context. One approach to an analytical evaluation will be deferred till later in this discussion. In any case, no matter how sophisticated the analysis, depth to water table cannot uniquely predict accumulation of salt in the soil profile.

Are there alternatives to the use of a critical water table depth as a criterion for maintaining a favourable root zone? The objective, achieved in whatever way, is to maintain a net downward flux sufficient in magnitude to prevent excessive accumulation of salts in the soil solution. Even with a high water table, upward flow will only occur when there is an upward gradient; an appropriate irrigation regime, in principle, can prevent such a gradient. Possibly more to the point, one must ask the question what factors cause the creation of a water table. In some cases, drainage from surrounding geologic formations causes a lateral inflow from natural sources; in others, excessive irrigation upstream may result in adverse conditions. Artesian pressure in a semi-confined aquifer may be caused by recharge hundreds of kilometres away, as is the case in the Red River Valley in North Dakota. In this valley, efforts at controlling salinity through cultural practices, tile drainage and soil management were only marginally effective because artesian pressure in a saline aquifer some 100 m deep caused a slow but continuous upward flow. Doering and Benz (1972) demonstrated, through theory and field tests, that a simple solution to the problem consisted of rather widely spaced wells, pumped at a low rate just sufficient to reverse the hydraulic gradient.

In most cases, however, irrigation excessive to the drainage capacity causes the rise in water table. To prevent this rise, one must either increase the drainage rate by artificial means, reduce the amount of irrigation water, or a combination of these. It is my view that the water table height should be viewed as a consequence of water management, rather than as the independent variable causing water management problems.

A clear example is offered by the Wellton-Mohawk region in Arizona, part of the Gila River drainage basin. Irrigation has been practised in the Valley since the 16th century by surface diversion and, later groundwater pumping. Geologically a closed basin, only severely limited surface drainage is provided naturally. When upstream development reduced river flow, increased pumping lowered the water table, restricting drainage even more, and return flow salinized the groundwater. This in turn, led to importation of water from the Colorado River some twenty years ago, with a concomitant increase in area irrigated, often at excessive rates. Shortly thereafter, a rising water table caused severe problems, requiring the construction of over 100 drainage wells and a lined conveyance channel for disposal. From 1970-72, the irrigation efficiency (crop consumptive use/water delivered to farms) was estimated to be 56% (Adv. Comm. Irrig. Eff., 1974). Whatever the irrigation efficiency the same problems would have cropped up. However, the rate at which the problems developed, and the rate of drainage needed, thus its cost, depended strongly on the irrigation efficiency.

In most instances, drainage theory and practical experience are sufficiently well advanced to design a system for a given drainage requirement. This requirement must be established by consideration of i) the natural drainage rate, ii) the amount of water to be removed from extraneous sources, and iii) the amount of irrigation water in excess of crop needs that must be removed. The latter is strongly affected by management. Returning to the Wellton-Mohawk, it has been conservatively estimated that 10% of the water diverted for irrigation is lost in transit, an amount equal to about 20% of the total drainage water pumped. Also, using primarily current practices of the better farm operators as a guide, it was determined that the farm efficiency could be raised from 56% to 72%, without significant technological problems. Thus good management can have a substantial impact on reducing the drainage requirement. Canal lining, use of pressurized delivery systems and scheduling irrigation water delivery on demand can reduce distribution system losses as well as facilitate high on-farm efficiencies.

An important factor in determining the drainage requirement is the leaching requirement, or the amount of irrigation water needed in excess of crop consumptive use to maintain a favourable salt balance. The most common practice is probably to determine the leaching requirement (LR) from the relation (USSL Staff, 1954)

$$LR = EC_{iw}/EC_{dw} \qquad [9]$$

where EC_{iw} and EC_{dw} represent the electrical conductivities of the irrigation and drainage waters, respectively. Drainage water, in this context, means the water draining below the root zone. It is customary to select for EC_{dw} in Eq [9] the conductivity, EC_{e-50}, of the saturated soil extract at which a 50% reduction in crop yield was obtained in experiments with uniform salinity throughout the root zone. This usage results in a safe value that allows for relatively poor uniformity of water distribution in both time and space and may well be justified when water and energy are plentiful and drainage easily obtained. Recent findings (van Schilfgaarde et al., 1974) however, suggest that far lower LRs may suffice with precise water management. Based on extensive experiments with alfalfa by Bernstein and Francois (1973), it is hypothesized that the older data can be reinterpreted in the manner shown in Fig. 3. Extrapolating the yield reduction curves to zero yield leads to a value of EC beyond which roots are not able to extract water against the osmotic gradient. To convert the values in the figure from EC_e to EC_{sw} (from saturation to field water content) one must multiply EC_e by the ratio θ_{fc}/θ_s, where θ_{fc} and θ_s are the volumetric water contents at field capacity and saturation. The EC thus obtained can be used in the denominator in Eq [9]. This interpretation of the data results in permissible salinity levels at the bottom of the root zone around 3 to 4 times those previously recommended. Whether or not the reasoning used here will stand the test of time in detail, there seems no question that far lower LRs than customarily recommended are entirely adequate, as long as proper management practices are used.

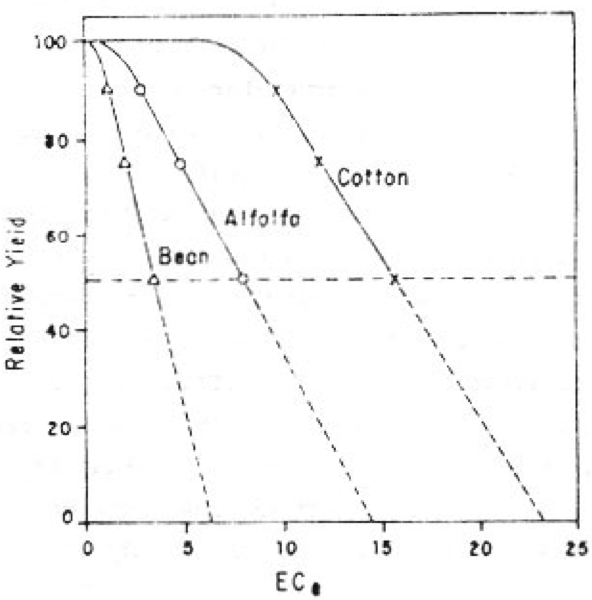


Fig. 3 REINTERPRETATION OF CROP YIELD REDUCTION DATA AS A FUNCTION OF THE SALINITY OF THE SATURATION EXTRACT (EC_e)

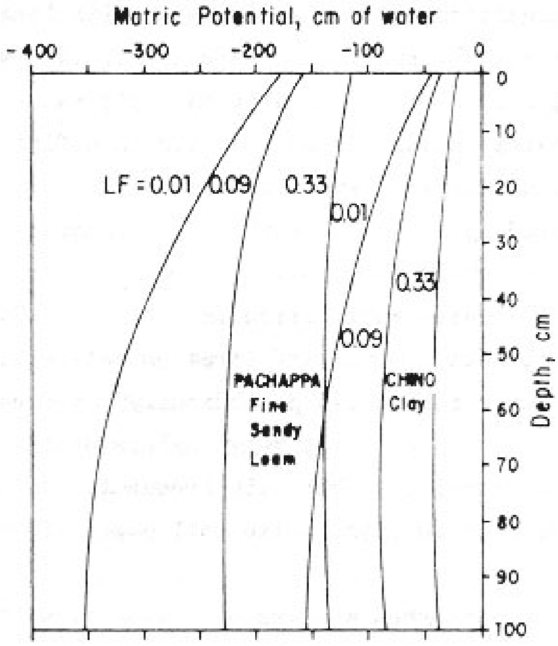
The importance of irrigation management, in this connection, has two aspects. First, if it is planned to operate an irrigation scheme at low leaching, it becomes especially important to obtain uniform water distribution over the field, because the margin of permissible error is far smaller; and it becomes desirable to maintain more nearly uniform conditions over time, because with long intervals between irrigation, the water and osmotic stress in the soil solution will build to excessively high levels. Secondly, in order to be able to apply water in quantities, or at rates, that are accurately enough known to assure a definite, but low, leaching fraction, the irrigation system must permit accurate control. Meeting both of these requirements is enhanced by frequent, low rate irrigation applications and, especially, by means of pressurized systems.

When the rate of water application is less than the infiltrability – the potential rate of infiltration – the infiltration rate will be independent of soil properties. Even if water is applied periodically but frequently (say once a day), the fluctuations will be damped out at very shallow depth so that an essentially steady state condition prevails. Thus with frequent, low rate water applications, the control over water distribution in the soil passes from the soil to the irrigation system.

Raats (1974) has analysed a class of steady flows through soil profiles in the presence of plant roots. He solved the flow equation, Eq [1], for a k (h) distribution as in Eq [4], assuming that the rate of water uptake by the roots ι could be described by

$$= (T/\delta) \exp(-z/\delta), \qquad [10]$$

where T (cm/day) represents the total root uptake, or transpiration rate, and δ (cm) is a characteristic length that corresponds to the depth above which 63% of the water is taken up. From this analysis, Fig. 4 was developed. It illustrates the point just made that, over a wide range of leaching fractions, the pressure head (or matric potential) does not vary much. The soil remains less than saturated and the pressure remains within the tensiometer range. Raats' analysis can also be used to evaluate the effect of a water table. In the limiting case without plant roots, the results reduce to Eqs [7] and [8], as they should. With roots present, his analysis leads to a relationship between k or h and z as a function of depth of water table, z, and the ratio q/T, representing the fraction of the water uptake supplied from the water table. This is illustrated in Fig. 5. Figure 6 further illustrates Raats' analysis by comparing various percentages of flow supplied from the water table. When $-q/T = 1$, all the plant need is satisfied from below; when it is zero, all is supplied from the surface. In this example, when the water table depth $z = 10\delta$, only 0.2 of the transpiration demand can be supplied from the water table. Furthermore, Raats interprets his analysis in terms of salt distribution, neglecting effects of precipitation or dissolution and of dispersion and diffusion. Accounting for these phenomena is a project now underway.



<u>Fig. 4</u> MATRIC POTENTIAL AS FUNCTION OF SOIL DEPTH FOR TWO SOILS AND THREE LEACHING FRACTIONS WITH T = 1 cm/DAY AND δ = 15 cm (i.e., 91% OF WATER TAKEN UP ABOVE 36 cm)

RECLAMATION

Thus far we have considered maintaining a salt balance, or a quasi-steady state. Now consider the situation where a soil needs to be reclaimed, or where excessive salts are to be removed. The only reasonable way to accomplish reclamation seems to be by applying water to the surface for leaching, with or without chemical amendments, depending on soil chemistry.

The subject of amendments will not be discussed. Two other interrelated questions remain: the amounts of water to be applied and the manner of water application. Numerous field tests and detailed theoretical analyses have been reported in the literature. This experience verifies that leaching does not take place by simple piston flow displacement. If that were the case, one would need to apply only an amount equal to one pore volume displacement to obtain complete reclamation. Several factors cause the actual flow to be more complicated than simple displacement, including diffusion and variations in the localized flow velocities in the soil pores; they tend to reduce the leaching effectiveness. As

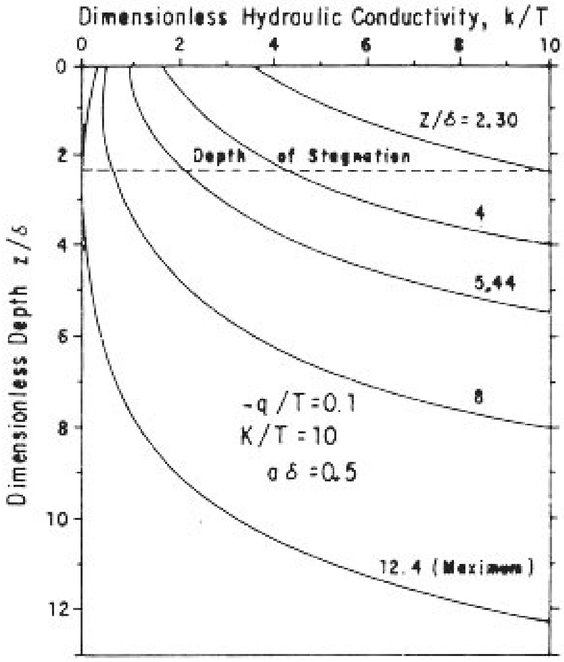


Fig. 5 HYDRAULIC CONDUCTIVITY AS A FUNCTION OF DEPTH FOR SOME UPWARD FLOWS. IN EACH CASE, THE WATER TABLE SUPPLIED 10% OF THE CROP TRANSPIRATION; THE CURVE PARAMETER INDICATES WATER TABLE DEPTH. TYPICAL VALUES FOR δ MAY BE TAKEN AS δ = 15 cm

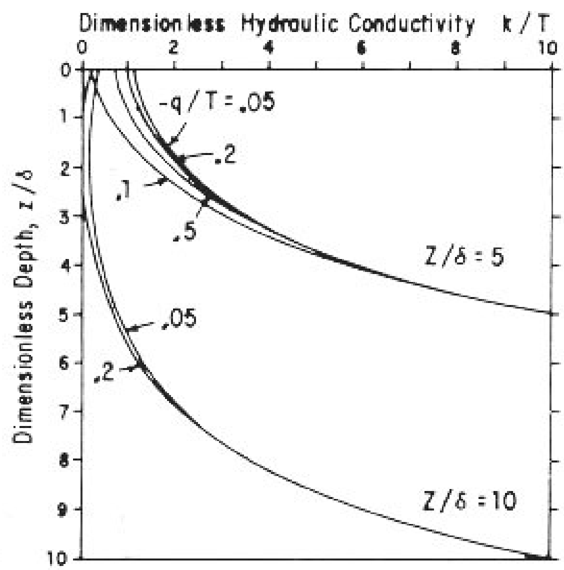


Fig. 6 EFFECT ON HYDRAULIC CONDUCTIVITY DISTRIBUTION WITH VARYING IRRIGATION RATES $(1 + q/T)T$ for $K/T = 10$ and $\delta\alpha = 0.5$. TYPICAL VALUES OF δ are 10 and 20 cm

suggested by Biggar and Nielsen (1967), leaching should be more efficient, in terms of amount of water needed, when it takes place at water contents below saturation.

Comparing the results of several investigators, a relatively consistent picture emerges. Van der Molen (1956), in an excellent paper, adapted the theory of ion exchange columns to the removal of salt from soils and compared it to field observations in Holland after the seawater inundation during World War II. He showed that he could describe the changes over time of the chloride profiles very well with the error function relationship he derived. Similarly, Gardner and Brooks (1957) developed a somewhat different theory and compared it with data from laboratory column studies. In both cases quoted, the leaching took place at water contents less than saturation. Reeve et al. (1955), in a field experiment, compared the effect of different amounts of leaching water ponded on the surface, but since they applied the water in relatively small increments intermittently, they again were dealing with predominantly unsaturated flow.

Reeve et al. concluded that one unit depth of water was required per unit depth of soil to reduce total salinity by about 80%. [In their field experiments, adequate leaching of boron required substantially more water.] Since the volumetric water content, based on their data, was probably near 50%, this amounts to $p = 2$, where p is the number of pore volume displacements. Van der Molen's relationship requires that 50% of the choloride is removed when $p = 1$; assuming $N = 10$ in his expression (N = number of mixing layers), one obtains $p \approx 1.9$ for 80% salt removal. Gardner and Brooks' analysis yields, for 80% removal, about $p = 1.5$. Thus, for practical use, it seems entirely adequate to use Reeve et al's value $p = 2$, or their rule of thumb that one unit depth of water is required for every unit depth of soil to be reclaimed.

Oster et al. (1972) compared the effectiveness of continuous ponding, intermittent ponding and intermittent sprinkling for leaching under field conditions. They found that half as much water was required with intermittent flooding as with continuous flooding for the same reduction in salinity, with sprinkling intermediate. To reduce salinity by 70%, they applied 0.5 cm water per cm depth of soil on the intermittently flooded fields and 1.2 cm/cm on the continuously flooded.

As pointed out earlier, one reason for the greater effectiveness of intermittent or nonponding methods of leaching is the predominance of unsaturated flow and the consequent reduced "bypass", or the "microgeometry" of flow. Another can be the "macrogeometry" of the flow pattern. Kirkham (1949) demonstrated that, for a ponded field with parallel underground drains, the surface infiltration rate near the drains is very much higher than near the centre between drains. Thus essentially no leaching takes place on a large section of the land, even if it is kept ponded for an extended period. Besides methods such as intermittent ponding or sprinkling, another possible approach to increasing the uniformity of infiltration is to modify the field surface geometry appropriately. Leaching by means of furrows or diked basins, if they are oriented parallel to the drains, should be highly advantageous.

Earlier reference was made to the leaching requirement. Boumans and van der Molen (1964) (see also van der Molen, 1973) have introduced a modification in determining the LR by considering that part of the water used for leaching bypasses the root zone without removing salt, the remainder being effective. Thus they introduce a leaching efficiency, f. When applied to the case of reclamation, or one-time salt removal, the use of the factor f has the same consequence as the use of a prescription based on displacement, such as $p = 2$. Although the physical models that led to the two methods may differ, the practical results are equivalent. I have serious reservations, however, about the suggestion, as interpreted by Bouwer (1969), that numeric values can be assigned to f based on soil texture. As pointed out by van der Molen (1973), f can be expected to depend significantly on the method of water application. More important is the need to distinguish between leaching for reclamation and leaching by over-irrigation.

When uncropped land is reclaimed by flooding or sprinkling, the theory of miscible displacement, verified in field and laboratory, predicts an efficiency well below 100%. The presence of root holes, cracks and animal burrows in the surface soil, combined with continuous large pores, also would lead one to predict substantial bypass in that superficial region. The use of an efficiency factor in such cases appears quite adequate for many practical situations. Even then, the example quoted above of the 2:1 ratio in water requirements for two methods of application indicates the need to take account of more than the soil texture in assigning a value to the efficiency.

On the other hand, when leaching is accomplished by continuous or intermittent over-irrigation of cropped land, an entirely different situation prevails. The average water content will be lower than in the previous case, and the activity of the roots should lead to substantially lower rates of downward flow. The extreme of piston displacement, by flooding, may now be contrasted with the opposite extreme under continuous trickle irrigation, of a steady state replenishment of the root zone water supply. While reclamation strives for deep percolation of 100% of the water applied, leaching for maintenance strives for, say 10%. I propose that, under such circumstances, the use of an efficiency factor is not warranted. Lysimeter, field plot and field-scale experience at our Laboratory tends to support this view.

The foregoing discussion has been devoted to physical and engineering aspects of water management for salt control. Aspects of soil and water chemistry have not been touched. The models of van der Molen and Raats, for example, can only be applied with integrity to simple systems with nonreacting salts such as

NaCl. In principle, the concepts presented can also be applied to more complicated systems, containing, for example, carbonates. In general, such applications require numerical solution by computer. Other problems, such as boron removal, require different approaches. To keep this presentation within bounds, none of these will be discussed.

Suffice it to reiterate that the primary objective of water management for salinity control is to maintain a downward flux. Provision of adequate drainage together with precise irrigation management is the key to success.

ACKNOWLEDGMENT

The helpful cooperation of Dr. P.A.C. Raats, USSL, is gratefully acknowledged, both in formulating many of the ideas presented here and in preparing the material for the illustrations.

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Paper 6

b. ASSESSING THE SUITABILITY OF WATER FOR IRRIGATION: THEORETICAL AND EMPIRICAL APPROACHES 1/

by

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1. INTRODUCTION

Numerous schemes have been proposed for classifying waters with respect to their suitabilities for irrigation. These have ranged from general schemes designed for average use conditions (USSL Staff, 1954; Rhoades and Bernstein, 1971; EPA, 1972) to specific schemes for restricted regional conditions (Thorne and Thorne, 1951 ; Handa, 1964). While some of these schemes may be useful for indicating the potentials of arbitrary waters for irrigation, the actual suitability of a given water for irrigation depends on the specific conditions of use. These specific conditions include the crop grown, various soil properties, irrigation management practices, especially leaching fraction (LF) (the fraction of infiltrated water that passes beyond the root zone), and frequency of irrigation, climatic conditions and certain cultural management practices.

The effects of irrigation frequency on water suitability have not been incorporated in any of the general water assessment schemes. Yet increasing irrigation frequency can markedly affect crop yield (Bernstein and Francois, 1973a; Mantell and Goldin, 1964), and one of the commonly used practical rules of salinity management is: when irrigating with saline waters, irrigate frequently. This recommendation implies that crop response is related to the sum of osmotic pressure, π, and matric suction, τ, in the root zone and that this sum, σ, can be minimized by increasing the irrigation frequency. For a given quantity of salt in the soil, both π and τ can be minimized by keeping the water content high by irrigating frequently. Wadleigh and Ayers (1945) and Richards and Wadleigh (1952) demonstrated that the effects of salinity and irrigation frequency on bean and "guayule" yield could be normalized by relating the crop response to the sum of π and τ integrated over the root depth and the experimental period under conditions of general salinity where sodicity, nutrition and toxicity were negligible. Taylor (1952b) showed that alfalfa and sugar beet yields were significantly correlated with average seasonally integrated

1/ Contribution from the Agricultural Research Service, USDA, U.S. Salinity Laboratory, Riverside, California.

τ with variable irrigation frequency. An increase of 1 atmosphere integrated τ within the range 0.4 to 4 atmospheres reduced established alfalfa and sugar beet yield between 0.27 and 0.65 and 0.78 to 2.45 t/a/yr respectively. Although salinity was not included as a variable in this study, Taylor suggested that the integrated π could be obtained by measuring the π of the soil water as a function of time and depth and water content and that it could be added to τ before integration. Yaron et al. (1972), Bresler and Yaron (1972), and Zur and Bresler (1973) have evaluated the interactions of irrigation regime, level of soil salinity, water and climatic conditions, absence of leaching and short-term use of variably salinized irrigation waters on grapefruit and groundnut yields by both statistical and computer simulation techniques. They concluded that, for non-steady state, short-term conditions and a given level of climatic stress, π is overwhelmingly dominant on fruit yield of these crops with condition of short irrigation intervals (3 days). For such intervals, the irrigated τ was only 10 to 15 percent of the integrated σ at longer irrigation intervals (about 20 to 30 days). They also found that irrigation water quality and initial level of soil salinity became less important as compared with τ, on time-integrated $\emptyset$, as the irrigation interval increased becoming nearly negligible at the longest irrigation intervals. The integrated π achieved nearly a constant value - irrespective of the irrigation interval. From these observations they concluded that the pre-irrigation salt concentration of the soil water mainly determines the value of the time-integrated π under conditions of short-term irrigation with saline water without leaching. For this reason, they prescribed using an extra allotment to pre-leach and reduce the soil salinity level at the beginning of the crop season, rather than using such water for leaching during the irrigation season.

Under conditions of long-term use of waters for irrigation (steady state conditions) with leaching, the interaction of salt concentration of the irrigation water and the leaching fraction determines the level of soil salinity, as well as the depth-integrated π, of the root zone soil water. This latter conclusion can be deduced from the equation developed by Bernstein and Francois (1973b) to describe the mean salinity against which water is absorbed by the plant, $\overline{C}$,

$$\overline{C} = \frac{-1}{V_{iw} - V_{dw}} \int_{V_{iw}}^{V_{dw}} C \, dv = \frac{C_{iw}}{1 - LF} \ln \left[\frac{1}{LF}\right] \qquad [1]$$

where V_{iw}, V_{dw} are volume of infiltrated and drainage water, respectively, and C_{iw} is the concentration of the irrigation water. Equation [1] applies only to the condition of conservation of mass, i.e., $C_{iw}V_{iw} = C_{dw}V_{dw}$ where C_{dw} is the concentration of drain water. Raats (1974) has shown that $\overline{C}$ is independent of the water uptake profile, for conditions of piston displacement, but not where dispersion and diffusion affects the distribution of salinity in the root zone appreciably. Under the assumption of piston flow, $\overline{C}$ is also independent of frequency and time, because it is only the relation between concentration and volume during evapotranspiration that affects $\overline{C}$ as the unit volume of applied water passes through the root zone. The degree of volume reduction and concentration increase during this passage is determined by the leac ing fraction and is independent of time or the extent to which the soil is dried between irrigations. This agrees with the observational and model findings of Zur and Bresler (1973). Since concentration and osmotic potential are closely related, Eq [1] can also be used to calculate π weighted in proportion to water uptake. Ingvalson et al. (in press) have modified Eq [1] to account for the effects of salt precipitation and dissolution.

$$\overline{C} = a - \frac{b}{(1 - LF)} \ln (LF) + \frac{c}{(LF)} \qquad [2]$$

where a, b, and c are constants of the second-order polynomial equation describing the concentration of the water as a function of $\left[\frac{1}{LF}\right]$ derived from the chemical model of Oster and Rhoades (1975). Thus, the water uptake weighted π, $\overline{\pi}$, may be estimated as a function of C_{iw} and LF.

Since $\overline{C}$ is more strongly a function of C_{iw} than of LF, Bernstein and Francois (1973) concluded that crop growth is very sensitive to EC_{iw} and that high salinity levels in the lower depths of the root zone have little effect on yield. This conclusion overlooked the approximate additivity of effect that τ and π may have on crop response. In the case of negligible τ, like under conditions of high frequency or trickle irrigation regimes, $\overline{C}$ is probably a better index of salinity for evaluating expected crop response than under conditions of infrequent irrigation. As reviewed by Slatyer (1969) and Rawlins and Raats (1975), time of exposure to salinity or salinity exceeding some "critical" value may also affect crop response. Correlations have been observed between such total water potential "stress days" and crop yields. Such time of exposure to salinity stress is also ignored in Eqs [1] or [2]. Bower et al. (1969, 1970) concluded that crop response is primarily to average root zone salinity. Ingvalson et al. (in press) correlated alfalfa yield obtained under conditions of non-uniform root zone salinity to various indices of salinity including (i) irrigation water salinities, (ii) space averaged, soil profile salinities, (iii) soil water salinities weighted in accordance with water uptake by the crop, and (iv) time and space integrated soil water salinities. The expressed reason for the latter experiment was that "the assessment of irrigation water quality and the adoption of appropriate irrigation management procedures require an adequate knowledge of how crops respond to non-uniform soil salinity". In this experiment alfalfa yield correlated best with lower root zone depth, time-integrated soil water EC ($r = 0.89$, although yield also correlated reasonably well with average root zone soil salinity ($r = 0.78$) and $\overline{C}$ ($r = 0.71$). The chemistry model used to determine $\overline{C}$ in this latter study was previously tested with respect to its ability to adequately predict the drainage water composition of these same lysimeters resulting from the use of eight widely varying waters for irrigation and leaching fractions of 0.1, 0.2 and 0.3 (Oster and Rhoades, 1975). The predicted compositions and salt loads agreed very closely with those determined experimentally (Rhoades et al., 1973, 1974).

The ulimate method of assessing the suitability of waters for irrigation will require the attainment of our capability to: 1) predict the composition, the osmotic and matric potentials of the soil water and the corresponding exchangeable cation composition of the soil, both in time and space, resulting from the use of any arbitrary irrigation water under any given soil-crop-water management system and climatic conditions, and 2) interpret such information in terms of effect on crop response. The need for such an approach to assessing the suitabilities of waters for irrigation rather than the presently used tables of empirical values assumed to describe water suitability under hypothetical average-use conditions has been previously discussed (Rhoades, 1972). Obviously such a task would be very complex. Even if we could satisfy number 1, we doubt that our present knowledge would enable us to accomplish number 2. We especially do not understand the mechanisms by which salinity (as indicated in the preceding discussion), sodicity or toxicity affect crop response nor can we accurately predict, on the basis of any developed theory, the changes in soil hydraulic conductivity under field conditions, as affected by water and soil properties. Yet, there seems room for improvement of past conventional schemes of water assessment based on generalized empirical findings that have often proven insufficient in practice.

Because of the reasonably good correlations obtained between alfalfa yield and average root zone salinity and $\overline{C}'$, and because of the ability of the chemistry model to predict either of the latter two indices of salinity, apparently such a chemical model could serve as a basis for assessing the suitabilities of waters for irrigation. It would be even better if the model could be modified to predict soil water salinity compositions throughout the root zone and if the effect of τ and irrigation frequency could somehow be incorporated with π to estimate an adequate total water potential index of the crop root zone with which to predict crop response.

With the above in mind, a water quality assessment model was developed and the concepts and utility of this model are discussed here. The chemistry part of the model will be recommended for adoption to aid in assessing sodicity hazards of irrigation waters and in the interim, (until a verified model capable of predicting the time and space varying total soil water potential is developed and information gained on how to quantitatively relate this to crop response) to aid in assessing salinity hazards of irrigation waters. The matric and total stress parts of the model are crude but do qualitatively demonstrate the effects of irrigation frequency, soil water retentivity characteristics, time leaching fraction and irrigation water salinity on time and space-integrated soil water potential. It also gives evidence to support our recommended method for assessing the salinity hazards of irrigation waters.

An improved model of this type, but more capable of calculating what this model can only approximate, is needed to advance our present, limited ability to assess water suitability for irrigation. For these reasons the matric and total potential parts of this model are included even though these parts of the model are not recommended for adoption in their present form.

2. CRITERIA FOR ASSESSING IRRIGATION WATER SUITABILITY

Criteria for assessing irrigation water suitability must include those chemical, physical and biological characteristics of soils, waters and crops which must be quantified and may have to be controlled for specific uses of irrigation waters. The suitability of waters for irrigation should be evaluated on the basis of criteria indicative of their potentials to create soil conditions hazardous to crop growth or crop use.

Besides the factors already discussed, many additional factors affect water suitability for irrigation. In this treatise we limit ourselves to salinity and sodicity hazards associated with water use for irrigation. Salinity is defined as the general effects of salts on crop growth thought to be largely osmotic in nature and related more to total salt concentration than to specific salt species. Sodicity is defined as the effect of an excessive amount of exchangeable sodium in the soil on soil permeability and structure deterioration, and a direct toxic effect of exchangeable sodium on plants specifically sensitive to sodium. The variables that affect water suitability for irrigation considered herein are: chemical composition of irrigation water, leaching fraction, irrigation frequency, soil water retentivity characteristics, crop tolerances to π, τ and ϕ, and allowable limits of EC–SAR with respect to soil permeability.

3. DESCRIPTIONS AND ASSUMPTIONS OF THE WATER SUITABILITY MODEL

3.1 Predicting Soil Chemistry Distribution

The chemistry model developed by Oster and McNeal (1971) and modified by Oster and Rhoades (1975) was used to estimate the distribution of salinity and sodicity in the soil profile based on an assumed water uptake pattern and a CO_2

distribution in the crop root zone as described later. Electrical conductivity of the soil water, EC_{sw}, or of the saturation paste extract, EC_e, will be used as the index of salinity and the sodium-adsorption-ratio, SAR,[1/] will be used as the index of sodicity. Briefly, the model calculates the resultant equilibrium chemical compositions of waters assumed to be concentrated from their initial compositions by the factor ($1/LF_a$) appropriate for a given fractional interval of the root zone. The pH of the solution is assumed to be governed by soil carbonate equilibria. Soil $CaCO_3$ is assumed to be present in sufficient quantity to saturate the soil solution before concentration begins. The model calculates equilibrium solute activities using the Debye-Hückel theory, taking into account ionic strength and ion-pair formation constants, and precipitation of $CaCO_3$, $MgCO_3$ and $CaSO_4$ by iteration processes so that the final composition meets all the simultaneous equilibrium constants of the considered solid phases, ion-pairs and carbonate species for an assigned partial pressure of CO_2. Briefly the iterative process involves repeated calculation of: (i) the ionic strength of the solution; (ii) single ion-activity coefficients; (iii) the molar concentrations of all 16 ion pairs and appropriate calculated ion activities, and (iv) the molar ion concentration of single ion species by difference between the analytical concentrations and the sum of their ion-pair concentrations. SAR is calculated from the total soluble concentrations of Na, Ca and Mg left in solution, including those in ion-pair forms, after the equilibrium composition is obtained. The electrical conductivity (EC) of the solution is then calculated by the third-order polynomial fit method (No. 2) of McNeal et al. (1970).

The input requirements for the model as used here include irrigation water concentrations of Ca, Mg, Na, K, CO_3 + HCO_3, Cl and sulphate, and P_{CO_2} and leaching fractions by depth through the profile, LF_a. Leaching fractions at any depth in the root zone are calculated from known or estimated water uptake patterns through the root zone from

$$LF_a = 1 - \frac{f\,V_{cu}}{V_{iw}} \qquad [3]$$

where $f\,V_{cu}$ is that part of the total volume of consumptive use taken up above the depth in question. From an examination of the water uptake patterns of crops, we chose to use the values 40, 30, 20, 10, except as noted, as representative general percentages of total water uptake by fractional quarters of the root zone for use in Eq [3]. Such uptake patterns are affected by irrigation frequency and leaching fraction, as shown by Mantell and Goldin (1964) and Ingvalson et al. (in press).

1/ SAR = $Na/\sqrt{(Ca + Mg)/2}$, where the concentrations of Na, Ca and Mg are expressed in meq/litre.

However, results obtained with the model using reasonable but different water uptake patterns show that variations in water uptake distribution do not appreciably change the resultant salinity (EC) or sodicity (SAR) profiles. Furthermore, as discussed earlier, water uptake pattern does not appreciably influence $\bar{\pi}$, unless dispersion and diffusion effects are marked. Soil air P_{CO2} levels of 1.6, 3.3, 4.6 and 5.3 atm were used in the model, except as noted, for successively deeper quarterly fractions of the root zone. Deviations from these P_{CO2} values are not expected to alter appreciably calculated EC and SAR values for most water compositional types. Soil water composition was calculated at quarter points in the root zone.

From the steady state water compositions through the crop root zone we calculate: 1) $\bar{\pi}$ by the method discussed earlier (Ingvalson et al., in press) using Eq [2] or by summing the products of water uptake proportion and π for each depth increment and dividing by the sum of the fractional water uptake in the root zone, using the calculation procedure described later in Section 3.2, and 2) the various EC–SAR combinations through the root zone. Comparisons of such latter combinations with the threshold EC–SAR values of Quirk and Schofield (1955) or McNeal and Coleman (1965a), etc., or preferably from known values established for the soil in question allow the sodicity hazard of the water to be evaluated for the specific leaching fraction. While not discussed here, other parameters of chemical composition can also be predicted for suitability evaluation with this model, like Cl concentration, Ca/Mg ratio, etc. (Oster and Rhoades, 1975).

To test the applicability of this predictive chemistry part of our water quality model for the above-stated purposes, predicted and determined values of EC and SAR were compared where eight widely different waters (Table 1) were used to irrigate and alfalfa crop in soil filled lysimeters at leaching fractions of 0.1, 0.2 and 0.3. The experimental set-up has been previously described (Rhoades et al., 1973). Briefly, alfalfa (*Medicago sativa* L., var. Moapa) was grown in 36 outdoor lysimeters filled with Pachappa fine, sandy loam soil. The seeds were germinated and the plants were established while receiving small irrigations of deionized water each day for about 3 weeks. The lysimeters of one set of treatments (eight irrigation waters with three LFs) contained non-calcareous Pachappa soil, while those of the other set of treatments contained Pachappa soil to which $CaCO_3$ was added to total 1% by weight. Salt sensors were installed at the 40 and 80 cm depths to monitor *in situ* soil salinity (Oster and Ingvalson, 1967). Acquarium airstones were installed at 40 and 80 cm depths to withdraw samples of soil air for CO_2 determinations. Each lysimeter was irrigated individually when a tensiometer at 60 cm depth reached 0.5 bar. The water was flooded on the surface in approximately 20 litre increments and in a total amount which would achieve the target LF. Approximately 3 to 5 days were required,

Table 1

COMPOSITIONS OF RIVER WATERS USED FOR IRRIGATION OF ALFALFA

River	EC 1/	Ca	Mg	Na	K	cations	HCO_3	SO_4	Cl	SAR 2/	pH_c^* 3/	Water type
	mmho/cm	meq/liter										
Feather	0.10	0.45	0.36	0.20	0.04	1.05	0.66	0.16	0.03	0.3	8.6	Ca,Mg-HCO_3
Grand	0.94	2.00	0.79	7.08	0.19	10.06	6.29	3.43	0.34	6.0	7.3	Na-HCO_3
Missouri	0.91	4.06	1.92	3.02	0.10	9.10	3.24	4.05	1.81	1.8	7.3	mixed
Salt	1.56	3.15	1.35	9.62	0.17	14.29	3.21	0.89	10.19	6.4	7.5	Na-Cl
Colorado	1.27	6.95	3.63	3.35	0.22	14.15	3.73	9.31	1.11	1.5	7.0	Ca-SO_4
Sevier	2.03	3.71	6.05	10.62	0.15	20.53	5.21	5.96	9.36	4.8	6.9	Na>Mg>Ca-Cl
Gila	3.14	7.22	5.88	18.55	0.09	31.74	3.17	8.48	20.09	7.3	7.1	Na-Cl
Pecos	3.26	16.98	9.07	11.38	0.08	37.51	3.11	22.39	12.01	3.2	6.8	Ca-SO_4

1/ Electrical conductivity.

2/ $SAR = Na+/[(Ca^{2+} + Mg^{2+})/2]^{\frac{1}{2}}$, where all concentrations are expressed in meq/l.

3/ $pH_c^* = (pK_2' - pK_c') + p(Ca + Mg) + pAlk$, where p(Ca + Mg) and pAlk are the negative logarithms of the molar concentration of Ca + Mg and of the equivalent concentration of titratable base (CO_3 + HCO_3, respectively) and pK_2' and pK_c' are the respective logarithms of the second dissociation constant of H_2CO_3 and the solubility constant of calcite, respectively, both corrected for ionic strength (Bower *et al.*, 1965).

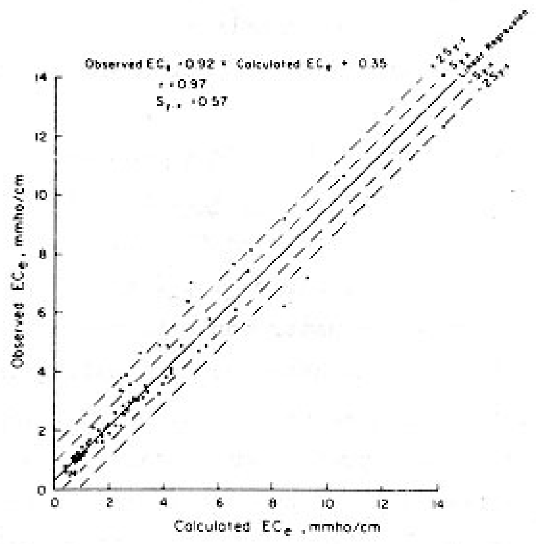
depending on the LF, to finish an irrigation. When it rained, the lysimeters were covered with sheet plastic. Upon completion of this experiment, soil samples were taken from the lysimeters at 30 cm intervals for analysis of soluble salts and exchangeable cations.

The water uptake pattern with depth was determined from the soil profile Cl distribution (Table 2; Ingvalson et al., in press). The LF achieved past each increment in the profile was calculated from the ratio Cl_{iw}/Cl_{sw}. Here Cl_{sw} was calculated from $Cl_e \times (\theta_e/\theta_{fc})$, where $_e$, $_{fc}$, and θ refer to saturation extract, field capacity and gravimetric water content, respectively. Cl_e and θ_e were obtained from the soil analyses; θ_{fc} was obtained by sampling the lysimeters for gravimetric water content by depth 2 days after irrigation was stopped. The fraction of water consumed at any depth in the profile was obtained from $(1 - LF_a)/(1 - LF\ total)$, where LF total represents the LF obtained at the bottom of the root zone or soil profile as determined by Cl_{iw}/Cl_{dw}. The fractional water uptake for each soil profile interval (f) was then obtained as the difference in water consumed by appropriate successive depths in the root zone.

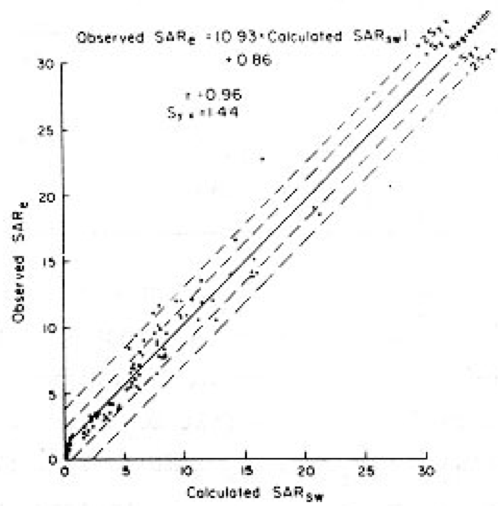
Table 2 DETERMINED LEACHING FRACTION, LF_a, AND CARBON DIOXIDE LEVELS BY FRACTIONAL ROOT ZONE IN ALFALFA LYSIMETER EXPERIMENT

Fractional depth of root zone	CO_2 %	LF_a for leaching fraction treatment		
		.1	.2	.3
1/4	3	.70	.74	.75
1/2	6	.49	.63	.70
3/4	9	.22	.37	.48
4/4	12	.13	.22	.32

The relation between the observed and predicted EC_e is given in Fig. 1 for each of four depth intervals in the 24 treatments (95 data points) with appropriate statistics. The corresponding relations for SAR are given in Fig. 2. The observed and predicted average profile EC_es are compared in Fig. 3. The observed relations between SAR_e and EC_e combinations obtained by water, leaching fraction and depth in the calcareous soil lysimeters are given in Fig. 4, while the predicted SAR_{sw} - EC_{sw} relations are presented in Fig. 5. The good correspondence obtained between observed and predicted EC and SAR values demonstrates the applicability of the chemical model for predicting the levels of soil "salinity" and "sodicity" throughout the root zone. As discussed later, this kind of prediction can be used as the basis for assessing salinity and sodicity hazards associated



<u>Fig. 1</u> RELATION BETWEEN OBSERVED AND PREDICTED EC_e



<u>Fig. 2</u> RELATION BETWEEN OBSERVED SAR_e and predicted SAR_{sw}

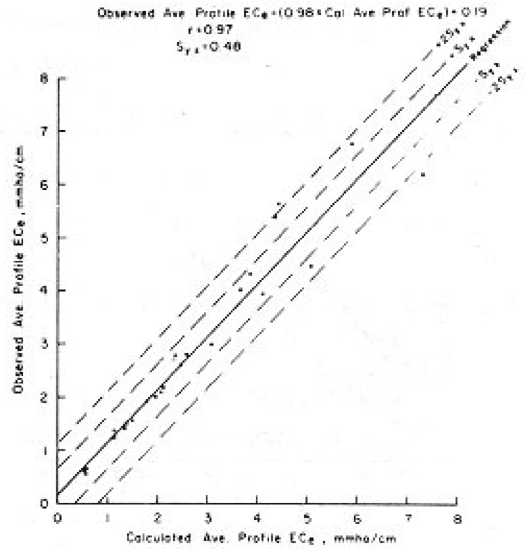


Fig. 3 RELATION BETWEEN OBSERVED AND PREDICTED AVERAGE PROFILE EC_e

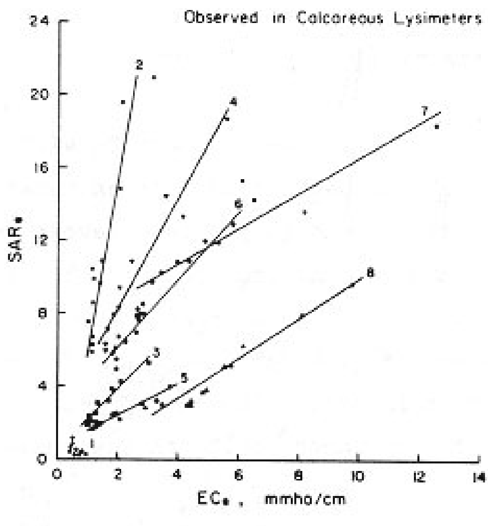


Fig. 4 OBSERVED RELATIONS BETWEEN EC_e AND SAR_e
IN THE LYSIMETER SOIL PROFILES

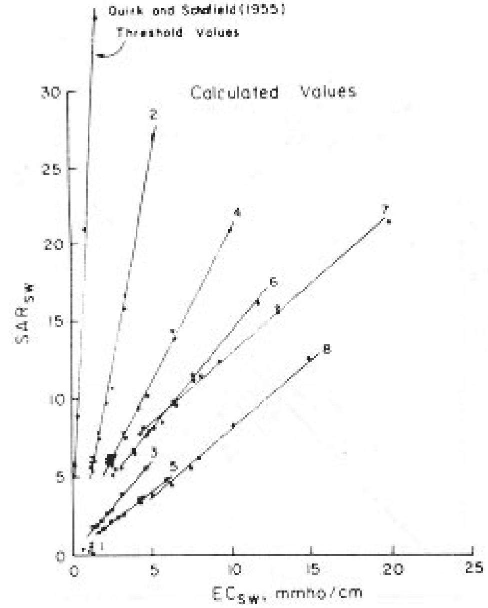


Fig. 5 PREDICTED RELATIONS BETWEEN EC_{sw} AND SAR_{sw} IN THE LYSIMETER SOIL PROFILES AND THRESHOLD VALUES ACCORDING TO QUIRK AND SCHOFIELD (1955). ANY COMBINATION OF SAR AND EC TO THE RIGHT OF THE "THRESHOLD" LINE WOULD NOT BE EXPECTED TO RESULT IN SIGNIFICANTLY REDUCED HYDRAULIC CONDUCTIVITIES FOR SOILS LIKE THAT USED BY QUIRK AND SCHOFIELD

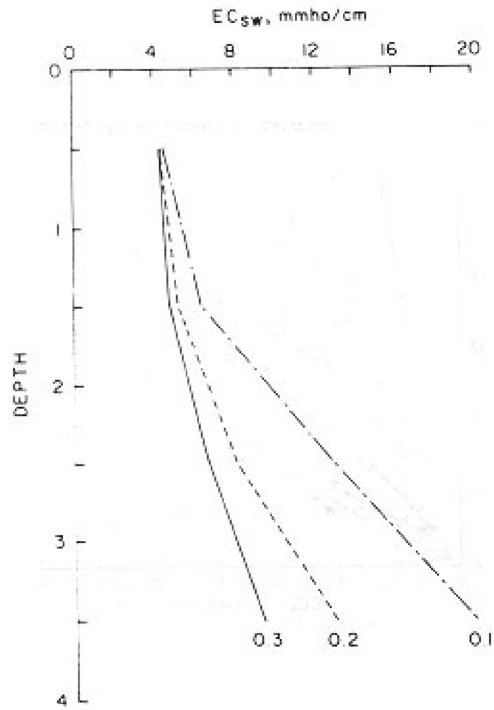


Fig. 6 EFFECT OF LF ON EC_{sw} DISTRIBUTION WITH DEPTH IN THE ROOT ZONE USING GILA RIVER WATER FOR IRRIGATION

with the use of the waters. From the EC distribution predicted by the model, the π distribution, and $\bar{\pi}$ as a function of LF can be estimated as previously discussed. This latter value is valuable in assessing the salinity hazard under conditions of low τ. It has less applicability for conditions of high τ.

3.2 Predicting the Matric and Total Stress of the Soil Water

The degree of water depletion between irrigations and the soil water retentivity characteristics are assumed to be the dominating factors affecting τ in irrigated soils. For this reason we developed a first approximation method of incorporating soil water retentivity effects on τ with π to aid in the assessment of water suitability.

The calculations pertain to a crop, assumed to be at a constant rate of evapotranspiration, and for which the leaching fraction and soil salinity profile averaged over the irrigation cycle are at steady values. The purpose, then, of the calculations is to calculate osmotic and matric stresses in the crop root zone. The assumptions are:

1) At the end of an irrigation cycle, the total water stress, $\emptyset_f$, is at the same level throughout the root zone. Under conditions where the crop is extracting water from soil storage against significant osmotic and matric stresses simultaneously, Wadleigh <u>et al</u>. (1947) and Rawlins <u>et al</u>. (unpublished data, U.S. Salinity Laboratory) found that the total stress at the end of the irrigation cycle tends to be equal throughout the root zone.
2) After an irrigation, the root zone is assumed to come to a "field capacity" water content, θ_{fc}, and vertical water flows are assumed to end for all practical purposes.
3) The salinity profile of the root zone at "field capacity" is, as a first approximation, taken as that calculated by the equilibrium soil chemistry model (discussed above) assuming uptake fractions of 0.4, 0.3, 0.2, 0.1 for the four quarters of the root zone in descending depths. The reader who wishes to improve this illustrative calculation scheme could well take the final osmotic pressure value π_{fc} calculated by the model, and using the simplified salt flow model of Bresler (1967) arrive at a better field capacity profile, π_s, (s denotes parameters at "field capacity", f denotes parameters at the end of the irrigation cycle).
4) The water retentivity characteristics of the soil are represented as by Gardner <u>et al</u>.(1970), i.e., $\tau = A\theta^{-\alpha}$.

By the use of assumption No. 1, and the simple formulae given below, one avoids specifying the uptake pattern at θ below the field capacity level, although when the calculations are completed, a new uptake pattern is given. The calculations proceed then as follows: the root zone is divided into 10 equal increments (we used a value of 10 cm for an increment, i, in our calculations). Next, one assumes a final total stress value, ϕ_f. The greater the value of ϕ_f [1] chosen, the longer will be the length of the irrigation cycle. This θ_f is, of course, equal to $\pi_{fi} + \tau_{fi}$, where $\phi_{si} = \tau_{f.c.} + \pi_{si}$ (f.c. denotes field capacity). The components of $\Delta\pi_i$ and $\Delta\tau_i$, along with $\Delta\phi_i$, are given by:

$$\Delta\phi_i = \phi_f - (\pi_{si} + \tau_{f.c.}) = \Delta\pi_i + \Delta\tau_i \qquad [4]$$

$$\Delta\tau_i = \tau_{fi} - \tau_{f.c.} = A\theta_{fi}^{-\alpha} - \tau_{f.c.} \qquad [5]$$

and

$$\Delta\pi_i = \pi_{fi} - \pi_{si} = F\,[EC_{si}\,\theta_{f.c.}/\theta_{fi}] - \pi_{si} \qquad [6]$$

where $0.98\ F = -0.0740 - 0.3470\ EC + 0.0023\ EC^2$ based on the data of Campbell et al. (1948). The only unknowns are θ_{fi}; they are obtained by iteration for each depth increment.

Once these calculations were made and values for each depth increment i obtained, several subsequent calculations and evaluations were made. These were as follows:

i. From the $\Delta\theta_i = \theta_{f.c.} - \theta_{fi}$ values, we estimated a time over which the crop is extracting water below $\theta_{f.c.}$ as

$$\Delta Tu = \Delta z \Sigma \Delta\theta_i / Et \qquad [7]$$

In our calculations, we used a value of 0.5 cm/day for the evapotranspiration, Et. Further, one can estimate the entire length of the irrigation cycle, $\Delta Tt + \Delta Tu + \Delta T_\pi$ by using an approximate value of ΔT_π, the time for irrigation water infiltration and redistribution to $\theta_{f.c.}$. We chose a value of 5 days for ΔT_π which we use for all irrigation waters and leaching fractions, based on experience with Pachappa f.s.l. soil ($A = 2.53$, $\alpha = 2.79$) and some calculations using Gardner et al. (1970) redistribution formulae.

ii. We prepared tables of times ΔTt for different chosen ϕ_f values and water qualities at leaching fractions of 0.1, 0.2 and 0.3. This data makes apparent the number of days when the total stress is above some arbitrarily "critical" level, at which crop growth may be assumed to have ceased. With this part of

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1/ If an ϕ_f value that is less than some of the π_{fi} values in the lower root zone is chosen, ϕ_{fi} values for points i where $\phi_f < (\pi_{si} - \tau_{f.c.})$ are used to calculate uptake so that the differences $(\phi_{fi} - \pi_{si})$ are in proportion to the distance from from the bottom of the root zone, with the last $(\phi_{fn} - \pi_{sn})$ at the bottom "mesh" of the root zone set at some arbitrarily small value. Of course, for points i where $\phi_f > (\pi_{si} + \tau_{f.c.})$, ϕ_f is used as the final, total potential, adhering to the basic, generating assumption of the model (assumption no. 1).

the model, the effect of duration of stress is taken into account in the assessment, by comparing "stress days" for irrigation intervals of equal lengths.

iii. We calculated an "uptake weighted osmotic potential", $\bar{\pi}$, from the π_{si} and the assumed uptake pattern at $\theta_{f.c.}$, as used in the soil chemistry model. This gives a volume integrated $\bar{\pi}$, which, as discussed above, strictly applies to a system of absolute "piston displacement" water flow with no molecular diffusion.

iv. A root uptake weighted matric pressure, $\bar{\tau}$, was calculated by

$$\bar{\tau} = \frac{\sum_i \int_{\theta_{f.c.}}^{\theta_{fi}} \tau_i \, d\theta}{\sum_i (\theta_{fi} - \theta_{f.c.})} \qquad [8]$$

where $\tau = A\theta^a$ 1/ thus

$$\bar{\tau} = \frac{\frac{A}{a+1} \sum_i \left[\theta_{fi}^{a+1} - \theta_{f.c.}^{a+1}\right]}{\sum_i \left[\theta_{fi} - \theta_{f.c.}\right]}$$

where the depth increments are of equal size.

4. INTERPRETATIONS AND USES OF WATER SUITABILITY CALCULATIONS

4.1 Sodicity Hazard Evaluation

There are two separate effects of sodium that must be considered in assessing water quality. The first is the effect of excessive sodium on soil permeability, infiltration and soil structure deterioration. The other is the direct effect of exchangeable sodium on plants specifically sensitive to sodium. The chemistry part of our water quality model can be used to evaluate both of these considerations.

The EC-SAR combinations predicted with the model for the eight irrigation waters, whose compositions are given in Table 1, for all combinations of profile depths and leaching fractions (0.1, 0.2 and 0.3) are given in Fig. 5. These data are summary forms of individual plots of EC and SAR like those of Figs. 6 and 7 for the Gila River. These EC-SAR combinations can be compared to determine if "threshold" values of SAR are exceeded either with respect to the soil hydraulic conductivity or ESP 2/ tolerance of the crop. An example of such critical values for

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1/ $a = -\alpha$ used by Gardner et al. (1970).

2/ ESP refers to exchangeable sodium percentage of the soils' cation exchange capacity. Since the SAR of the soil water is a good estimate of the ESP of soils, it can be used advantageously in place of ESP for diagnosing sodicity problems (USSL Staff, 1954).

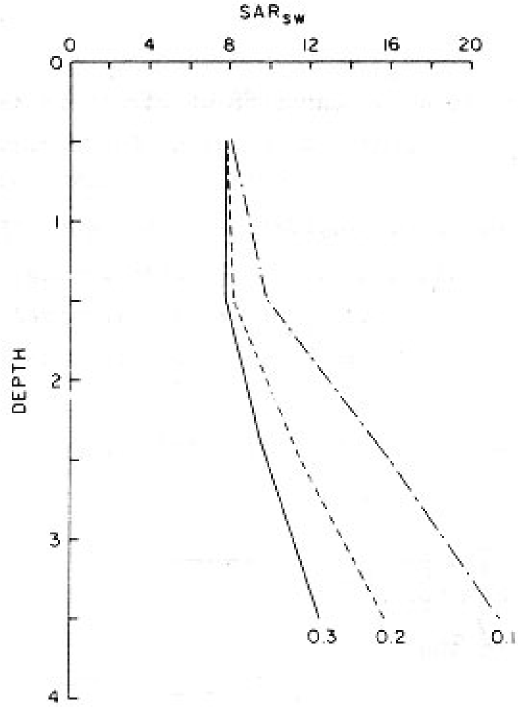

Fig. 7 EFFECT OF LF ON SAR_{SW} DISTRIBUTION WITH DEPTH IN THE ROOT ZONE USING GILA RIVER WATER FOR IRRIGATION

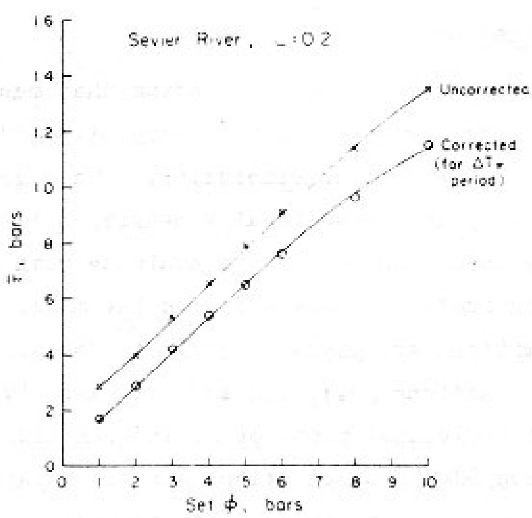

Fig. 8 RELATIONSHIP BETWEEN $\bar{\tau}$ AND SET ϕ_c VALUES CORRECTED AND UNCORRECTED FOR WATER UPTAKE DURING INFILTRATION AND DRAINAGE TO "FIELD CAPACITY", SEVIER RIVER, LF = 0.2

permeability is given in Fig. 5 according to the limits recommended by Quirk and Schofield (1955). In all instances, the EC-SAR values lie to the right of these limits indicating that no permeability problems would be expected with the use of these waters under these conditions of LF and soil type.

To complete the sodicity hazard evaluation, the question of effect of excessive exchangeable sodium, presuming the absence of poor structural problems, on crop yield, must also be considered. Tolerance of crops to sodicity under non-saline conditions varies widely (Pearson and Bernstein, 1958; Bernstein and Pearson, 1956; Pearson, 1960). The most sensitive crops (for example, beans) are affected at ESP levels of about 10. Most crops are moderately tolerant and are affected at ESPs of about 25. Highly tolerant crops, like tall wheatgrass, are not affected until ESPs reach or exceed 50. Tolerance reflects the species' ability to absorb nutritionally adequate levels of Ca and Mg and K from low concentrations of these elements in the soil solution.

Since the SAR distribution in the root zone, resulting from the use of a given water for irrigation and leaching fraction, can be predicted with the chemistry model (Fig. 7), it can be used to evaluate the likelihood of reduced crop yields because of excessive exchangeable sodium in the soil. Predicted ESP levels are compared with established crop tolerances to ESP for this evaluation. If exchangeable sodium is excessive for crop yield, possibly the ESP level associated with the use of any irrigation water can be reduced by increasing the LF. For such reasons, the concept of leaching requirement for exchangeable sodium control was introduced previously (Rhoades, 1968). The data of Fig. 7 illustrate the point. By increasing the LF from 0.1 to 0.3, the lower profile ESP level associated with the steady state use of Gila River water for irrigation can be reduced from 21 to 12. The surface ESP, however, is largely insensitive to LF, being only reduced from 8.1 to 7.7 for the same change in LF.

The chemistry model is of additional value in assessing the sodicity hazard because it can predict the concentrations and distributions of Ca and Mg as well as SAR (data not shown). This is important because whether a sodic soil condition upsets crop nutrition depends on the total salt concentration (Bernstein, 1974). As the total concentration increases into the saline range (> 4 mmho/cm EC_e), even high ESPs are associated with nutritionally adequate levels of Ca and Mg (> 2 meq/l), and the nutritional levels of high exchangeable sodium decrease or even disappear Lagerwerff and Holland, 1960). The question of how crops are affected by non-uniform distributions of ESP in the root zone is not known; such information is needed before the sodicity hazard can be properly assessed.

4.2 <u>Salinity Hazard Evaluation</u>

Representative summary results of $\bar{\tau}$, $\bar{\pi}$, $\bar{\phi}$, and $\Sigma\Delta\theta_i$ are given in Table 4 for the case of Pachappa f.s.l. soil. Input data for this evaluation as obtained from the chemistry model are given in Table 3. The effects of correcting $\bar{\tau}$ and $\bar{\phi}$ for the amount of water uptake before the soil comes to field capacity, i.e., $\bar{\tau}^*$ and $\bar{\phi}^*$, are illustrated in Figs. 8 and 9. Because the correction made only about a 9 percent difference in $\bar{\phi}$, we felt this correction was unnecessary, considering the other uncertainties in the model. For this reason the remaining data presented here are uncorrected.

The relations shown in the data of Table 4 are illustrated in Figs. 10 to 16. Briefly, these figures illustrate the following points:

i. The lower the EC of the irrigation water and the higher the LF used with the water, the lower is the resultant water uptake weighted osmotic pressure (Fig. 10) and total (Fig. 11) water stress. Such a lowering of $\bar{\pi}$ would expectedly increase crop yield in some cases.

ii. While $\bar{\tau}$ is not appreciably affected by LF, it does respond to EC_{iw} (Fig. 12) and to ϕ_f (Fig. 13). Thus, $\bar{\tau}$ increases with ϕ_f and at any given level of ϕ_f decreases with increasing EC_{iw}, as is expected. The drier the soil becomes between irrigations (i.e., the longer the irrigation interval and the greater ϕ_f), the greater will be the degree of water depletion (Fig. 14) and hence $\bar{\tau}$. Furthermore, the lower the EC_{iw}, the lower the osmotic pressure in the upper part of the root zone where most of the water is absorbed and hence the greater the extent of water depletion for any fixed level of ϕ_f (frequency) (Figs. 12, 13, 14). LF mainly affects the π level in the lower part of the root zone where there is water uptake, hence its minimal effect on $\bar{\tau}$.

iii. Leaching fraction affects the need for increased frequency of irrigation more than it does $\bar{\tau}$, for any given EC_{iw}, as shown in Figs. 15 and 16, because it decreases the availability of water more in the lower soil depths where π is high (Figs. 6 and 10) while having little effect on the upper root zone (Fig. 6) where most of the water uptake is absorbed; hence, $\bar{\tau}$ is not greatly affected, except under conditions of marked water depletion between irrigations, i.e., with very low frequency irrigation.

The values of $\bar{\tau}$, $\bar{\phi}$, and $\Sigma\Delta\theta_i$ obtained with the water quality model for Sevier River water and three soil types are given in Table 5. The effects of soil retentivity characteristics for a fixed level of osmotic pressure on $\bar{\tau}$, $\bar{\phi}$, and $\Sigma\Delta\theta_i$ are illustrated in Figs. 17, 18, 19 for the Sevier River water and LF = 0.1. These data clearly show the importance that retentivity characteristics of different soil types may have on $\bar{\phi}$ (Fig. 18) because of its effect on $\bar{\tau}$ (Fig. 17). Its effect is much less, however, on the extent of water depletion (Fig. 19), especially under conditions

Table 3 INPUT DATA FOR SALINITY HAZARD MODEL CALCULATIONS AS OBTAINED FROM CHEMISTRY MODEL SUBROUTINE

River	LF	Water uptake pattern[1]	EC_{iw}	EC_{sw} values[1]			
Missouri	.1	.40, .30, .20, .10	0.91	1.32,	1.76,	3.08,	4.69
	.2	↓	0.91	1.28,	1.55,	2.19,	3.17
	.3	↓	0.91	1.27,	1.47,	1.89,	2.49
Salt	.1	↓	1.56	2.35	3.26	6.43	10.00
	.2	↓	1.56	2.25	2.70	4.18	6.53
	.3	↓	1.56	2.23	2.51	3.42	4.80
Colorado	.1	↓	1.27	1.69	2.29	4.27	5.98
	.2	↓	1.27	1.63	1.95	2.89	4.35
	.3	↓	1.27	1.61	1.83	2.43	3.30
Sevier	.1	↓	2.03	2.79	3.88	7.67	11.85
	.2	↓	2.03	2.67	3.19	5.00	7.80
	.3	↓	2.03	2.64	3.20	4.06	5.76
Gila	.1	↓	3.14	4.56	6.40	12.94	20.02
	.2	↓	3.14	4.34	5.21	8.14	13.04
	.3	↓	3.14	4.28	4.73	6.64	9.35
Pecos	.1	↓	3.26	4.48	6.20	10.10	14.90
	.2	↓	3.26	4.26	5.06	7.49	10.16
	.3	↓	3.26	4.20	4.62	6.34	7.99

1/ For successively deeper quarter fractions of the root zone.

Table 4

PARTIAL SUMMARY RESULTS OF WATER QUALITY MODEL FOR SALINITY HAZARD ASSESSMENT, PACHAPPA SOIL

River	LF	set Ø	$\bar{\tau}$	$\bar{\pi}$	$\bar{Ø}$	$\Sigma \Delta\theta i$
		bars	bars	bars	bars	
Missouri	.1	1	0.34	0.54	0.88	0.32
		2	0.52		1.06	0.69
		3	0.68		1.22	0.92
		4	0.83		1.36	1.05
		5	0.97		1.50	1.16
		6	1.10		1.64	1.20
		8	1.33		1.87	1.29
		10	1.55		2.09	1.34
	.2	1	0.34	0.44	0.79	0.33
		2	0.54		0.99	0.77
		3	0.72		1.16	0.97
		4	0.86		1.31	1.09
		5	1.01		1.46	1.17
		6	1.15		1.59	1.22
		8	1.39		1.83	1.30
		10	1.61		2.05	1.36
	.3	1	0.35	0.41	0.76	0.34
		2	0.56		0.97	0.80
		3	0.73		1.14	0.99
		4	0.89		1.30	1.10
		5	1.03		1.44	1.18
		6	1.17		1.58	1.23
		8	1.41		1.82	1.31
		10	1.63		2.04	1.36
Salt	.1	1	0.29	1.11	1.40	0.17
		2	0.43		1.54	0.45
		3	0.57		1.68	0.64
		4	0.68		1.79	0.82
		5	0.79		1.90	0.96
		6	0.90		2.01	1.05
		8	1.11		2.22	1.18
		10	1.31		2.42	1.26
	.2	1	0.29	0.87	1.16	0.19
		2	0.44		1.31	0.50
		3	0.58		1.46	0.79
		4	0.72		1.59	0.95
		5	0.85		1.72	1.06
		6	0.98		1.85	1.14
		8	1.21		2.08	1.24
		10	1.42		2.29	1.31
	.3	1	0.29	0.79	1.08	0.20
		2	0.44		1.23	0.60
		3	0.60		1.39	0.84
		4	0.75		1.54	1.00
		5	0.89		1.67	1.10
		6	1.02		1.81	1.17
		8	1.25		2.04	1.26
		10	1.47		2.26	1.32

Table 4 (Cont'd)

River	LF	set Ø	$\bar{\tau}$	$\bar{\pi}$	$\bar{\phi}$	$\Sigma\Delta\theta i$
		bars	bars	bars	bars	
Sevier	.1	1	0.28	1.35	1.64	0.15
		2	0.39		1.75	0.38
		3	0.53		1.88	0.58
		4	0.65		2.00	0.72
		5	0.74		2.10	0.88
		6	0.84		2.19	0.99
		8	1.04		2.39	1.13
		10	1.24		2.59	1.22
	.2	1	0.29	1.07	1.35	0.17
		2	0.40		1.47	0.42
		3	0.54		1.61	0.69
		4	0.66		1,73	0.89
		5	0.79		1.86	1.01
		6	0.91		1.98	1.10
		8	1.14		2.21	1.21
		10	1.35		2.42	1.29
	.3	1	0.29	0.94	1.23	0.18
		2	0.41		1.35	0.48
		3	0.56		1.50	0.78
		4	0.70		1.64	0.95
		5	0.83		1.78	1.06
		6	0.95		1.89	1.13
		8	1.18		2.12	1.24
		10	1.40		2.34	1.30
Gila	.1	1	0.28	2.34	2.62	0.11
		2	0.32		2.66	0.21
		3	0.42		2.76	0.39
		4	0.52		2.86	0.53
		5	0.62		2.95	0.64
		6	0.71		3.05	0.73
		8	0.87		3.21	0.90
		10	1.01		3.35	1.04
	.2	1	0.28	1.80	2.08	0.14
		2	0.32		2.12	0.23
		3	0.42		2.23	0.44
		4	0.53		2.34	0.61
		5	0.63		2.43	0.78
		6	0.73		2.53	0.91
		8	0.92		2.72	1.08
		10	1.11		2.91	1.18
	.3	1	0.28	1.62	1.90	0.15
		2	0.32		1.94	0.25
		3	0.43		2.04	0.47
		4	0.54		2.15	0.71
		5	0.65		2.27	0.88
		6	0.76		2.38	0.99
		8	0.97		2.59	1.13
		10	1.17		2.79	1.22

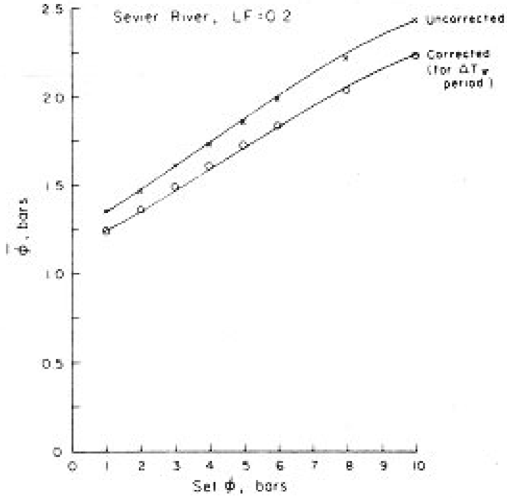

Fig. 9 RELATIONSHIP BETWEEN $\bar{\phi}$ AND SET ϕ_f VALUES CORRECTED AND UNCORRECTED FOR WATER UPTAKE DURING INFILTRATION AND DRAINAGE TO "FIELD CAPACITY", SEVIER RIVER (EC_{iw} = 3.14 mmho/cm), LF = 0.2

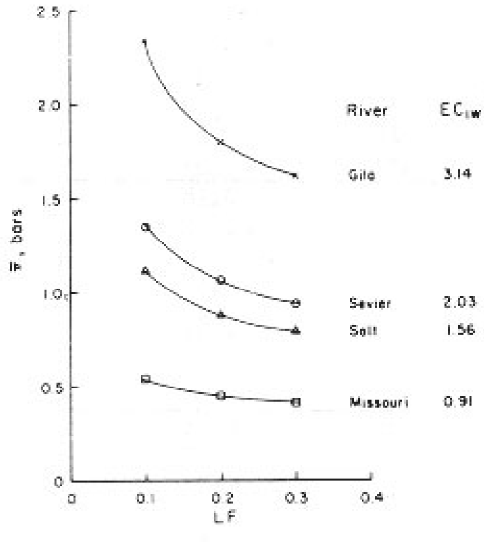

Fig. 10 EFFECTS OF EC_{iw} AND LF ON $\bar{\pi}$

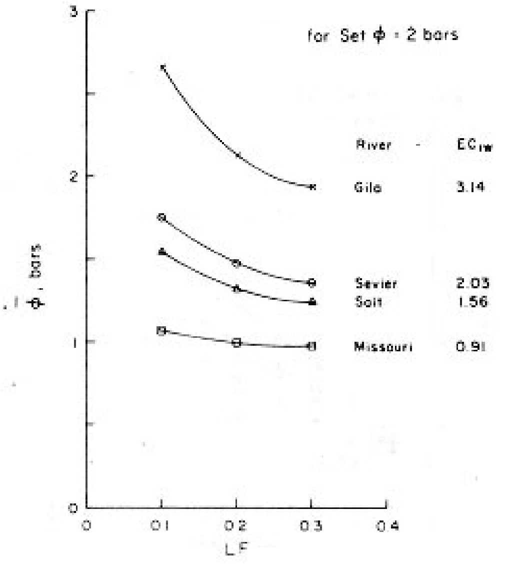

Fig. 11 EFFECTS OF EC_{iw} AND LF ON $\bar{\phi}$

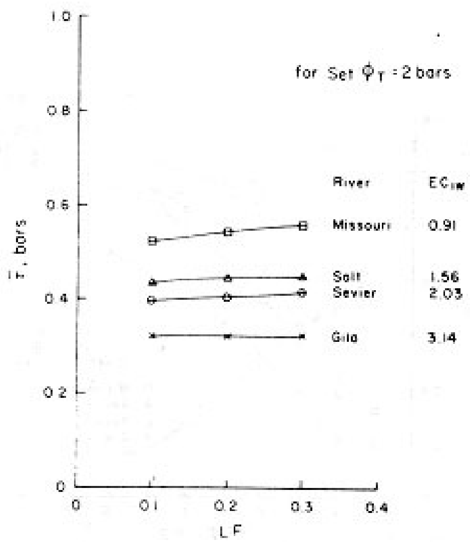

Fig. 12 EFFECTS OF EC_{iw} AND LF ON $\bar{\tau}$ FOR SET ϕ_f OF 2 BARS

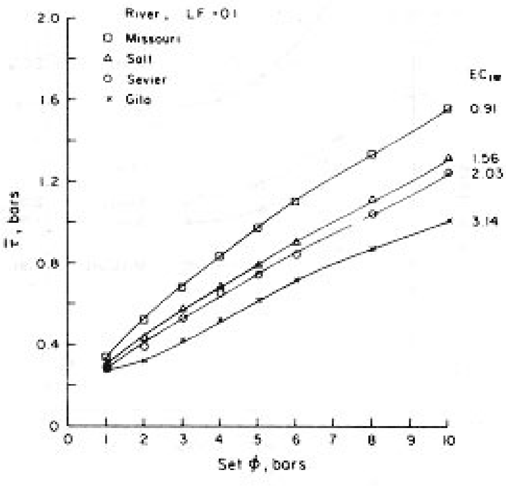

Fig. 13 EFFECTS OF EC_{iw} AND SET ϕ_f ON $\bar{\tau}$ FOR LF OF 0.1

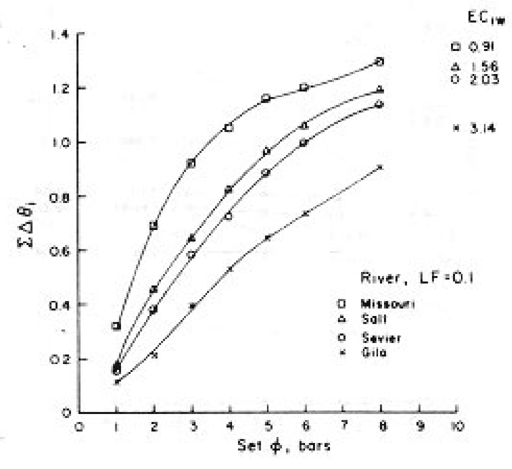

Fig. 14 EFFECTS OF EC_{iw} AND SET ϕ_f ON $\Sigma\Delta\theta_1$ FOR LF OF 0.1

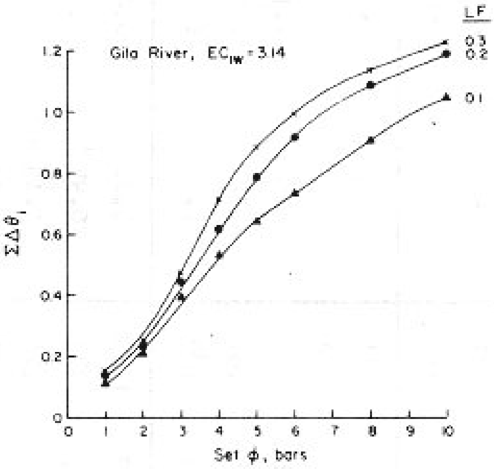

Fig. 15 EFFECTS OF LF AND SET ϕ_f ON $\Sigma\Delta\theta_i$ FOR GILA RIVER (EC_{iw} = 3.14 mmho/cm)

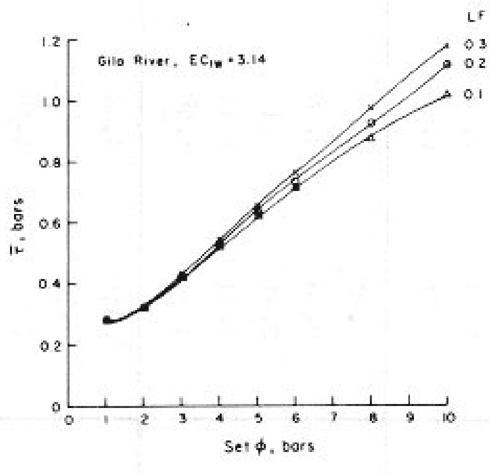

Fig. 16 EFFECTS OF LF AND SET ϕ_f on $\bar{\tau}$ FOR GILA RIVER (EC_{iw} = 3.14 mmho/cm)

Table 5 EFFECTS OF SOIL WATER CHARACTERISTICS ON $\bar{\tau}$, $\bar{\phi}$, AND $\Sigma\Delta\theta_i$, USING SEVIER RIVER WATER

LF	Set ϕ_f bars	$\bar{\tau}$, bars			$\bar{\phi}$, bars			$\Sigma\Delta\theta_i$		
		Pachappa 1/	Gilat 1/	Geary 1/	Pachappa	Gilat	Geary	Pachappa	Gilat	Geary
.1	2	0.39	0.43	0.46	1.75	1.78	1.80	0.38	0.40	0.39
	4	0.65	0.75	0.83	2.00	2.10	2.18	0.72	0.75	0.72
	6	0.84	1.02	1.15	2.19	2.37	2.50	0.99	1.03	0.98
	8	1.04	1.30	1.49	2.39	2.65	2.84	1.13	1.19	1.12
	10	1.24	1.56	1.81	2.59	2.91	3.16	1.22	1.29	1.22
.2	2	0.40	0.44	0.47	1.47	1.51	1.54	0.42	0.43	0.42
	4	0.66	0.78	0.87	1.73	1.85	1.94	0.89	0.91	0.86
	6	0.91	1.11	1.25	1.98	2.18	2.32	1.10	1.13	1.06
	8	1.14	1.41	1.60	2.21	2.48	2.67	1.21	1.25	1.17
	10	1.35	1.68	1.93	2.42	2.75	3.00	1.29	1.33	1.25
.3	2	0.41	0.44	0.46	1.35	1.42	1.50	0.48	0.46	0.41
	4	0.70	0.81	0.91	1.64	1.79	1.89	0.95	0.96	0.90
	6	0.95	1.15	1.30	1.89	2.13	2.28	1.13	1.16	1.08
	8	1.18	1.46	1.65	2.12	2.44	2.63	1.24	1.27	1.19
	10	1.40	1.73	1.97	2.34	2.71	2.94	1.30	1.35	1.26

1/ In the relation τ, cm $H_2O = A\theta^{-\alpha}$, the values of (A,α) are (0.108,6.645), (0.63,4.3), (2.53,2.79) for Geary (Hanks and Bowers, 1962), Gilat (Gardner et al., 1970), and Pachappa (Wesseling, 1974) soils, respectively.

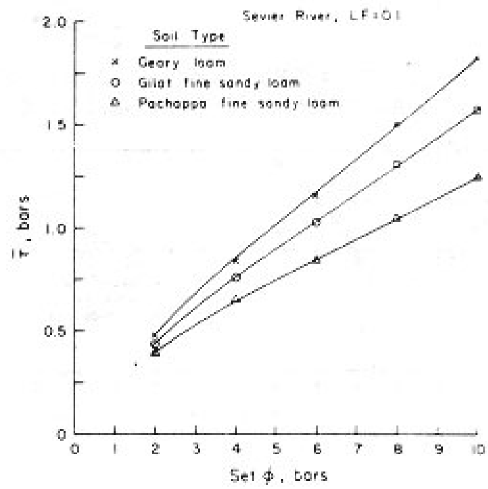

Fig. 17 EFFECTS OF SOIL PROPERTIES AND SET ϕ_f ON $\bar{\tau}$, SEVIER RIVER (EC_{iw} = 2.03 mmho/cm), LF = 0.1

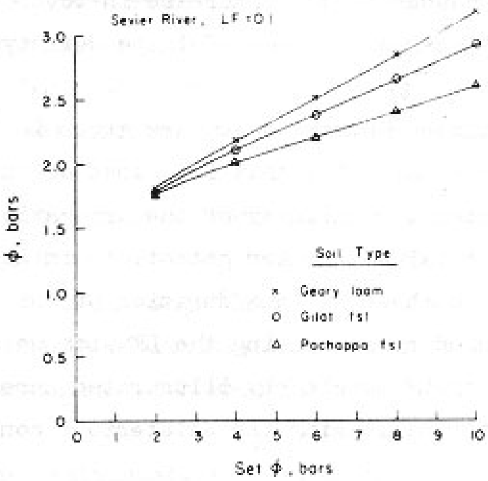

Fig. 18 EFFECTS OF SOIL PROPERTIES AND SET ϕ_f ON $\bar{\phi}$ SEVIER RIVER (EC_{iw} = 2.03 mmho/cm), LF = 0.1

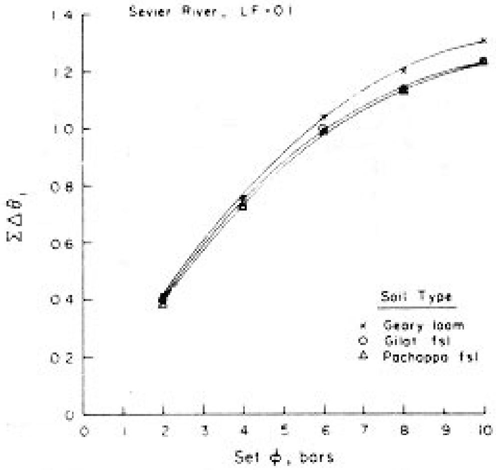

Fig. 19 EFFECTS OF SOIL PROPERTIES AND SET ϕ_c ON $\Sigma\Delta\theta_i$, SEVIER RIVER (EC_{iw} = 2.03 mmho/cm, LF = 0.1

of low set ϕ (in high frequency irrigation). This is so because with water uptake by the crop shortly after irrigation, a considerable decrease in water content causes only a minor increase in total water stress; however, later when a substantial fraction of the available moisture has been used, then the further additional loss of moisture from the soil causes a large increase in total water stress. Parameters for describing the moisture characteristics of these soil types are given in the footnote to Table 5.

Results of calculated "stress days" are given in Table 6 for four different irrigation waters. These data show that for cases of infrequent irrigation (like 33 days here), the greater the salinity of the irrigation water, the longer the period the crop is exposed to total soil water potentials in excess of some arbitrary critical value. The data also show that the duration of this exposure to excessive stress can be appreciably reduced by increasing the LF with which saline irrigation waters are used. The benefit of LF is clearly illustrated here. These results support the value of increased LF for minimizing the deleterious consequences of saline irrigation waters.

5. DISCUSSION

5.1 Sodicity Hazard Evaluation

Examination of the soil permeability data now established in the literature shows that soils with similar texture and CEC may vary considerably in their

Table 6 ILLUSTRATIVE CALCULATIONS: DAYS AT TOTAL SOIL WATER STRESS GREATER THAN ARBITRARY "CRITICAL" LEVELS

River Water	Leaching Fraction	Days for which $\phi > \phi_c = 10$ bars	Days for which $\phi > \phi_c = 8$ bars
Missouri	0.1	1.12	2.28
$EC_{iw} = 0.91$	0.2	0.82	1.90
	0.3	0.72	1.77
Salt	0.1	2.75	4.37
$EC_{iw} = 1.56$	0.2	1.80	3.16
	0.3	1.49	2.76
Sevier	0.1	3.49	5.32
$EC_{iw} = 2.03$	0.2	2.27	3.77
	0.3	1.90	3.28
Gila	0.1	7.09	9.92
$EC_{iw} = 3.14$	0.2	4.38	6.28
	0.3	3.50	5.35

Assumptions of calculations: 33-day irrigation cycle, assuming 5 days to reach $\tau_{f.c.} = 0.25$ bar. Pachappa soil ($\tau = A\theta^{-\alpha}$, $A = 2.53$, $\alpha = 2.79$ for τ in cm H_2O). E_t assumed constant at 0.5 cm/day.

susceptibility to the deleterious effects of exchangeable sodium and electrolyte concentration (Yaron and Shainberg, 1974; McNeal and Coleman, 1966a and b; Rhoades and Ingvalson, 1969). These findings demonstrate the inadequacy of using "average types of soils" for the basis of irrigation water suitability evaluations and the need of making such assessments with specific knowledge about the properties of the soil in question.

To illustrate the individuality of soils with regard to their stability of permeability to exchangeable sodium and electrolyte concentration, a brief review of pertinent studies follows. Quirk and Schofield (1955) found that the permeability of a Rothamsted Experimental Station soil, whose mineralogy was estimated to be 40% illite, 40% kaolin, and 20% vermiculite, was maintained (did not decrease more than 10 to 15%) as along as the electrolyte concentration, in meq/l of the infiltrating water exceeded the exchangeable sodium percentage (ESP) of the soil by a factor of two over the concentration range 0 to 20 meq/1 and ESP range 0 to 40. On the basis of this study, the authors proposed the use of a graph (these data are shown in Fig. 5) to determine the suitability of waters for irrigation with respect to soil permeability problems. Doneen (1961) has similarly proposed a scheme for classifying waters into various "permeability classes" based on montomorillonitic Yolo soil whose permeability was reduced 25% when the electrolyte concentrations were less than 3.5, 6.5 and 10.0 at ESP values of 0.6, 3.4 and 8.0, respectively. McNeal and Coleman (1966a) presented detailed information on the effect of ESP and electrolyte concentration on the hydraulic conductivities (HC) of seven well characterized soils. In addition, studies of the swelling properties of these same soils have been made (McNeal and Coleman, 1966b). Five of the soils had exchange complexes which were predominantly montmorillonitic in nature, while one was kaolinitic and one was a mixture of montmorillonite and hydrobiotite. Four of the montmorillonitic soils and the montmorillonite-hydrobiotite soil demonstrated pronounced decreases in HC at ESP values of 25 but over a concentration range of 9 to 40 meq/1. Swelling properties of three of the montmorillonitic soils and of the montmorillonite-hydrobiotite soil were well correlated with their relative hydraulic conductivities. One montmorillonitic soil which underwent HC decreases apparently did not swell. Another of the montmorillonitic soils was stable (no decrease in HC) until ESP values over 50 were reached. This soil failed to swell appreciably. The HC of the kaolinitic soil was essentially independent of exchangeable sodium and electrolyte concentration.

Yaron and Thomas (1968) have reported on the effect of sodic waters on the HC properties of four Texas soils. At an electrolyte concentration of 11.3 meq/1 reductions in HC were appreciable when ESP values exceeded approximately 7 to 8, 15 and 20 for soils whose mineralogy was predominantly montmorillonite, montmorillonite-illite, and illite-kaolin, respectively. At a higher electrolyte concentration of 34.5 meq/1 analogous "threshold" ESP values were 8 to 10 (montmorillonite), 22 (illite kaolin) and 27 (montmorillonite-illite). Rhoades and Ingvalson (1969) investigated the relationship between hydraulic conductivity, ESP, and electrolyte concentration for vermiculite dominant soils and found that HC did not decrease at ESP values lower than 50 in the absence of mechanical and chemical disaggregation. After disaggregation, HC decreases in the ESP range of 10 to 40 at electrolyte concentrations of 5 to 10 meq/1. The apparent insensitivity of such soils to ESP were concluded to be related to the fact that most of the exchangeable sodium was sorbed on relatively large (silt-sized), semi-expanding vermiculite particles. Hence, swelling and dispersion processes are limited compared with montmorillonitic-type soils.

McNeal (1968) has proposed a procedure for predicting the relative HC of soils to mixed salt solutions using calculated swelling values of montmorillonite as a frame of reference. The procedure was tested with a group of soils of nearly constant clay mineralogy (42% montmorillonite, 29% mica, 16% quartz and feldspar, and 13% other) but varying in clay content from 5 to 49%. Yaron and Thomas (1968) have also proposed a semi-empirical method of predicting HC decreases expected from the use of sodic waters on the basis of their studies on four soils. Both of these procedures have given encouraging results. We do not yet know, however, how generally applicable these methods or those of Quirk and Schofield (1955) and Doneen (1961) will prove to be due to the limited number of soils so far studied. These attempts do, however, suggest the usefulness and potential application of such knowledge for evaluating the suitability of waters (with regards to soil permeability problems) for irrigation purposes.

With the above background, apparently our ability to evaluate the sodium hazard of waters will improve as our ability to predict the effect of exchangeable sodium and electrolyte concentration on the structural stability and permeability of soils improves. In the interim, however, we recommend that appropriate EC-SAR "threshold" relations for the particular soils in question be empirically determined under field conditions for this assessment. If field data are unavailable, we recommend that saturated hydraulic conductivity or swelling and dispersion sensitivities of the soils to anticipated EC-SAR levels be evaluated to guide in assessing the potential sodicity hazard of the water.

5.2 Salinity Hazard Evaluation

Before we can take advantage of the utility of any water quality model for evaluating the salinity hazard, it is necessary to know how crops respond to time and space varying π and τ and critical values of π or ϕ. At present, such information is not known and, for this reason, any salinity hazard assessment of water quality is only an approximation at best. If crops respond to "stress days" of time and space integrated total water stress in excess of certain critical values, then such values must be established for important crop types and complicated dynamic types of models will be required to evaluate the suitabilities of waters for irrigation taking all of the crop, soil, water, atmosphere, irrigation management and time variables into account. Comprehensive models built upon those of the type described by Nimah and Hanks (1973), Bresler (1967), and Dutt et al. (1972) will be needed for such evaluations. At present, more information on how crops respond to salinity and more tests are needed to verify the abilities of comprehensive models to predict such crop responses.

If the concept of Bernstein and Francois (1975) that crop response is related to water uptake, weighted salinity can be shown to apply in general, and not just to high frequency irrigation, and if the concept of the additivity of osmotic and matric stresses of Wadleigh and Ayers (1945) is verified by a broader range of experimentation, then simpler models could be developed for assessing the salinity hazards of irrigation waters. Specifically one based on the evaluation of water uptake weighted total water stress as introduced herein. This would have great appeal because the time factor is eliminated. Needed information is not available to either prove or disprove the appropriateness of this concept. For this purpose and that described in the preceding paragraph, we recommend that experiments of the kind described by Ingvalson _et al._ (in press) be carried out for many different crop species only with modification to include frequency of irrigation and determination of time and depth integrated τ in addition to π. Comparisons of correlations of yield with $\bar{\pi}$, $\bar{\phi}$, and analogous time and space integrated values would demonstrate whether or not, and under what conditions, if any, the time aspect of crop response to salinity and matric stresses can be eliminated by weighting these parameters in proportion to water uptake.

If it is found that crop response is suitably relatable to $\bar{\phi}$ and that the effects of $\bar{\pi}$ and $\bar{\tau}$ are additive, then appropriate critical values for salinity hazard assessment could be established in one of four ways. Data on crop response to water stress could be used. Richards and Wadleigh (1952) have reviewed and summarized much of the early work and Slatyer (1969) some of the more recent work. Data on crop response to osmotic pressure in water or sand culture studies could be used, like that of Eaton (1942). Appropriate data could be collected using presently available matric and osmotic sensors. The fourth way would be to estimate the $\bar{\pi}$ incurred for the experiments under which the great majority of presently available salt tolerance data were collected. This latter way would be the simplest and quickest. Most of the salt tolerance data were determined under conditions of relatively uniform soil salinity levels obtained by irrigating with highly saline waters and a leaching fraction of about 50 percent (the range of salinity within the root zone was about $\pm$ 10 percent of the mean) (Bernstein, 1964). The EC_{iw} values used to establish the salinity levels in these studies, if known, could be used along with knowledge that the LF was ~ 0.5 to calculate $\bar{C}$ using Eq [1] and hence $\bar{\pi}$. These values could then be related to corresponding determined crop yields to establish the required crop response relations, since under these experimental conditions, $\bar{\tau}$ should have been relatively insignificant. The $\bar{\pi}$ values could then be used as estimates of $\bar{\phi}$. Such values could also be used to establish appropriate set point ϕ values for guiding irrigation frequency and determining appropriate LF values (i.e., establishing the leaching requirement) to minimize crop-yield reductions (van Schilfgaarde _ét al._, 1974).

Since the present salt tolerance lists are summarized in terms of EC_e and corresponding yield decrements, it would be useful if this information could be directly used for purposes of establishing $\bar{\pi}$ and $\bar{\phi}$-crop response relations. This can be estimated, given the above-mentioned assumptions, as follows: select the

EC_e value (Ayers and Branson, 1975, have assembled a convenient list) corresponding to no yield reduction, EC_e', (or some higher EC_e value if some yield reduction can be tolerated). Multiply this value by 2 to obtain the approximate soil water EC_{sw} ($EC_e \sim \frac{1}{2} EC_{sw}$ at near field capacity) and divide by 1.5 to obtain the corresponding EC_{iw} which would have produced this EC_{sw} (for LF = 0.5, average root zone EC_{sw} should be between EC_{iw} and 2 EC_{iw}, hence $EC_{sw} \sim 1.5\ EC_{iw}$). This value is then multiplied by 0.36 to convert EC values to bars, i.e., $\pi_{iw} = (0.36)\left(\frac{1}{1.5}\right)\ EC_e' \simeq 0.5\ EC_e'$, then calculate maximum allowable values of $\bar{\pi}$ (or $\sim \bar{\phi}$) $\bar{\pi}'$ (or ϕ') for use without yield reduction for given crops from,

$$\bar{\pi}' = \frac{0.5\ EC_e'}{1 - 0.5}\ \ell n\left(\frac{1}{0.5}\right) = 0.69\ EC_e' \qquad [10]$$

If our assumptions are valid, results of Eq [10] show that the range of $\bar{\pi}$ (or $\bar{\phi}$) for most crops is 0.7–5 bars. Such values seem to agree with experience and research findings.

Speculation aside, our present state of knowledge does not allow us to adopt with any conclusive justification time integrated, stress day durations, or water uptake weighted indices for assessing the salinity hazards of irrigation waters. Each of the above, also assumes that crop response is only related to a water availability stress and ignores the consequences of nutritional or toxicity factors of salt damage. Yet a need exists now for some reasonable method for evaluating the salinity hazards of irrigation waters and, therefore, some approach must be adopted based on best available information and logic. For this reason, we considered the results obtained with our illustrative model along with experimental observations discussed later to aid us to come to some decision as to what can we now recommend for this purpose.

In our example evaluations, we found the following: the EC_{iw} and LF combination establish the osmotic stress distribution in the root zone and $\bar{\pi}$; they also affect $\bar{\phi}$. Leaching fraction has little effect on $\bar{\tau}$, but irrigation frequency, extent of water depletion between irrigations and soil water retentivity characteristics do. The duration of "stress days" is affected by irrigation water salinity, LF, frequency of irrigation and soil water retentivity characteristics. The importance of these effects on crop response will vary with crop tolerance and climatic stress conditions. On the basis of this, where saline waters are used for irrigation, LF should be increased to lower π and $\bar{\pi}$ and frequency of irrigation be increased to lower τ and $\bar{\tau}$, the two combining to minimize ϕ and $\bar{\phi}$ and duration of "stress days". We conclude on the basis of our results, especially Table 6, that space averaged salinity should be a reasonably good index of crop response to soil-water salinity in cases where matric stress is significant, such as with infrequent irrigation, because of the marked dependence of duration of stress days on LF. LF primarily affects the level of salinity in the lower depths of the root zone; therefore, a parameter of salinity related to the space distribution of salinity, and especially lower root zone salinity, for infrequent irrigation, should be related to crop response. The data given in Table 7 support this conclusion. In each of these studies, irrigations were given when tensiometers at about the 60 cm depth reached 0.5 bar suctions. Under the outdoor atmospheric conditions, this resulted in an irrigation interval of about several weeks. Under these conditions crop response was well related to average root zone EC_e and EC_{dw} values and poorly related to EC_{iw} values. Duration of stress is increased and less opportunity is allowed for growth "catch-up" as the irrigation interval is extended. The increased osmotic pressure associated with lower LFs and use of more saline irrigation waters becomes especially disadvantageous then, because the "critical stress" level of $\emptyset$ will be reached quicker for a given amount of water use if the initial level of π present at the start of water depletion is high, than if it is low. Under conditions of more frequent irrigation, based on our model findings, we conclude that crop response would become more responsive to EC_{iw} and $\bar{\pi}$ than to LF and irrigation interval.

Table 7 CORRELATION OF CROP RESPONSE WITH VARIOUS INDICES OF SALINITY UNDER CONDITIONS OF NON-UNIFORM ROOT ZONE SALINITY AND CONVENTIONAL IRRIGATION FREQUENCIES

Crop	Reference	Correlation coefficients				
		EC_{iw}	$\bar{\pi}$ 1/	EC_{dw}	Ave. EC_e	$\bar{\pi}$ 2/
Sudan grass	Bower et al. (1970)	0.19	0.57	0.88	0.84	-
Tall fescue	"	0.50	0.85	0.81	0.99	-
Alfalfa	" (1969)	0.31	0.84	0.89	0.98	-
Alfalfa	Ingvalson et al. (in press)	0.53	0.71	0.80	0.78	0.89

1/ as calculated with Eq [2]

2/ from time and space integrated in situ soil water salinity values.

6. RECOMMENDATIONS

6.1 Sodicity Hazard Evaluations

6.1.1 With computer facilities

We conclude that the soil-water chemistry information required to assess the sodicity hazard of any arbitrary irrigation water can be closely estimated with the "Oster" chemistry model, i.e., the EC and SAR levels in the soil-water by fractional depth throughout the root zone, and recommend its adoption for this purpose. With appropriate information on certain properties of the soil to be irrigated, like its critical limits of EC-SAR for maintaining hydraulic conductivity or preventing excessive swelling or dispersion or degradation of aggregate stability, etc., the suitability of a water for irrigation can then be assessed with respect to this soil related sodicity hazard. Similarly, the suitability of the water with reference to the crop related sodicity hazard can be assessed from the predicted SAR distribution in the profile, established ESP-SAR relations, and tables of crop tolerance to ESP. While data were not presented herein, the chemistry model also predicts the concentration of calcium and magnesium so that the likelihood of nutritional imbalance can be evaluated. This is important because, according to Bernstein (1974, in press), the deleterious effects of high ESP on crop response is moderated or eliminated for some crops at sufficiently high levels of calcium and magnesium ($> \sim 2$-3 meq/l).

6.1.2 Without computer facilities

For rough assessments of sodicity hazard, when computer facilities are unavailable, it is recommended that upper (u) and lower (ℓ) root zone values of SAR be estimated as

$$SAR_u = SAR_{iw} \left[1 + (8.4 - pH_c^*)\right] \qquad [11]$$

and

$$SAR_\ell = k \, SAR_u \qquad [12]$$

respectively, after Rhoades (1972), where pH_c^* is as defined in the footnote of Table 1 and k is a factor dependent on LF and soil properties. For many soils this factor has been found to be 2.06, 1.36 and 1.03 for LFs of 0.1, 0.2 and 0.3, respectively. Several studies have demonstrated the utility of the above adjusted SAR procedure; these studies have been previously reviewed (Rhoades, 1972). More recently, Oster and Rhoades (1975) obtained results for a wide range of water types also supportive of this semiquantitative calculation procedure.

For soil related sodicity considerations, EC_{iw} and SAR_u are recommended for use to assess the likelihood of significant permeability reductions for a soil of given EC-ESP (or SAR) tolerances as discussed in the proceeding section; SAR_u and SAR_ℓ are recommended to predict the minimum, maximum and average root zone ESP values for comparison with crop tolerance - ESP tables to assess the likelihood of sodium toxicity problem of a given crop. Convenient ESP-tolerance lists are given in Bernstein (1974).

6.2 Salinity Hazard Evaluations

6.2.1 With computer facilities

For the reasons discussed in Section 5, in the interim, until more information is available on how crops respond to time and space varying osmotic pressures and matric stresses as a function of irrigation management, soil water retentivity characteristics and atmospheric stresses, the following procedures are recommended for evaluating the salinity hazards of irrigation waters. The assumption is made that good irrigation management practices are followed, including uniform application of water. For irrigation regime in which significant matric stresses are achieved, during the irrigation cycle, we recommend that the average root zone EC_e be estimated for any give water and LF with the chemical predictive model presented herein and that this value then be used to assess the likelihood of yield reduction of any given crop by comparison with EC_e' values given in standard tables of crop tolerance to salinity (like those of Bernstein, 1974 or Ayers and Branson, 1975).

For conditions where significant matric stresses are avoided, like high frequency irrigation, and osmotic pressure is the dominant factor affecting crop response to saline irrigation waters, we also advise the use of the chemistry model for assessing the salinity hazard. In this case, however, we recommend that $\bar{\pi}$ be calculated by Eq [2], and that the expected crop response evaluation be made by comparison of such values with critical $\bar{\pi}'$ values obtained with Eq [10] and appropriate values of EC_e' (such as those given in Ayers and Branson (1975) tables).

6.2.2 Without computer facilities

For rough assessments of salinity hazard, when computer facilities are unavailable and for irrigation regimes where significant matric stresses are achieved during the irrigation cycle, we recommend that the maximum acceptable level of EC in the irrigation water, EC_{iw}', for a crop of given salt tolerance and for a given LF be estimated with

$$EC'_{iw} = 5 \text{ ave } EC'_e/(1 + \frac{1}{LF}) \quad [13]$$

Equation [13] is obtained by substitution of $EC_{dw} = (\frac{1}{LF}) EC_{iw}$ into Eq [14].

$$EC'_{dw} = 5 \text{ ave } EC'_e - EC_{iw} \quad [14]$$

where EC'_{dw} is the estimated maximum allowable EC_{dw} without crop yield reduction recommended for use in establishing leaching requirements ($LF = EC_{iw}/EC'_{dw}$) after Rhoades (1974). The derivations and logic of Eqs. [13] and [14] are given in this latter reference. The major assumption in these equations is that crops respond to average root zone EC. EC'_{iw} values obtained with Eq [13] are higher and lower than those recommended by Ayers and Branson (1975) depending on LF.

For irrigation regimes where significant matric stresses are avoided with appropriate management procedures, such as high frequency irrigation (like drip irrigation), we recommend that $\bar{\pi}$ values be estimated with Eq [1] as $0.36\ \bar{c}/10$. Such values then being compared with $\bar{\pi}'$ values obtained with Eq [10] and appropriate EC'_e values as previously discussed to assess the likelihood of crop yield reductions with use of that water for that crop. This approach is the same as that recommended previously for such irrigation regimes with use of computer facilities except in this case corrections for salt precipitation and mineral weathering are ignored.

6.2.3 Research needs

We recommend that i) quantitative models be developed to predict the composition, the osmotic and matric potentials of the soil water, and the corresponding exchangeable-cation composition of the soil, both in time and space, that would result from the use of any arbitrary irrigation water under any given soil-crop-water management system and climatic conditions; ii) such models be verified by field testing, and iii) studies be carried out to determine how crops respond (rooting patterns, vegetative growth and yield) to time and space varying salinity and sodicity, as affected by LF, irrigation frequency, climatic stress and irrigation water composition, so that results of quantitative water suitability assessment models can be properly interpreted.

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c. SOIL MANAGEMENT AND AGRONOMIC PRACTICES

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1. INTRODUCTION

The present need for more food and fibre entails reclamation and development of new land resources besides an increase in the agricultural inputs necessary for greater production. Irrigated agriculture plays, and will continue to play, a major role in increasing the food supply especially in arid and semi-arid regions. The contribution of irrigation to a substantial increase in quantity and quality of agricultural production, over that of rainfed farming, is an established fact in regions such as the Near East where 70% of the total crop production comes from irrigated lands. Consequently, heavy investments are being made in land reclamation and development of irrigated farming in countries such as Iraq, Iran, Syria, Egypt and Pakistan. In most of these development projects the quality of either the soil or the water, or sometimes both, is not good enough to yield an economic return without the addition of reclamation measures or special management practices. Salinity and alkalinity are amongst those unfavourable land characteristics responsible for this requirement. Moreover, the deterioration of agricultural production on previously productive lands in the arid and semi-arid regions can be directly attributed to the development of salinity and alkalinity. The decline of ancient civilizations in the Mesopotamian Plain was due to the spread of salinity over the agricultural lands.

The lack of awareness of the problems of salt affected soils where conditions permit their formation, and of necessary reclamation measures is one of the main factors for the failure of irrigated projects, while the early prediction of these hazards helps the timely setting up of land protection programmes. Although too much attention is being given to the study of diagnostic and improvement techniques, little is being paid to the study of prognosis of salt affected soils. Successful prognostic techniques should be based on knowledge of the factors involved in the formation and development of salt affected soils and the adoption of a sound methodology.

The factors that should be considered for prognosis could be broadly grouped under (a) natural and (b) man-made. This paper outlines some of the latter group related to soil management and cropping practices. It is not meant to be a detailed study, but rather to raise questions and to stimulate discussion as to how these factors or parameters will be considered in working out a methodology or guidelines for prognosis.

2. SOIL MANAGEMENT AND CROPPING PRACTICES

The main characteristics of these man-made factors are that:

a. they are dependent, by definition, on man's role where he can change their effects according to his management, to improve or worsen the situation;

b. they do not have the same importance or magnitude and consequently, should have different weighted values;

c. they are functionally interrelated and, therefore, should not be evaluated separately but in an integrated approach.

However, for the purpose of the present study those factors related to soil management and cropping practices are going to be presented as individual ones.

3. LAND LEVELLING

This is an important operation, especially in newly developed irrigated lands, for efficient water distribution by surface methods and for the control of runoff. If land levelling is not done properly, or executed under certain conditions, the following may be expected:

a. creation of a micro-relief;

b. variation in depth and homogeneity of the soil profile;

c. pulverization of the fine soil material and changes in the soil structure.

Each of the above physical alterations may contribute to the formation of salt affected soils. Changes in the micro-relief in the order of less than 30 cm result in increasing salt content on the raised spots and better leaching in the dips, which explains the spotted nature of salinity observed in poorly levelled but otherwise normal fields. Early detection of variations in micro-relief either during irrigation or from the crop performance helps to give warning of future degradation. Fortunately, by repeated land shaping before cropping and as the development of the land proceeds, the micro-relief variations disappear and their effect becomes less obvious.

The changes in depth and homogeneity of the soil profile as a result of land levelling depend on topography, original soil depth and nature of stratification and size of earth moving. Where shallow profiles are found or relatively less permeable layers are exposed close to the surface, the chances for development of salt affected soils become much greater than in the case of deep and homogeneous soils. Unlike the micro-relief, variations in soil depth are not easy to correct. Therefore, improper land levelling operations associated with shallow profile formation should be given more consideration in prognostic investigations than those with micro-relief.

Heavy land levelling machinery affects the texture and structure of certain soils, such as the calcareous ones and those high in silt content. Pulverizations of the soil material, breaking of aggregates and compaction alter the pore size distribution and decrease the soil permeability. Such alterations would slow down water movement, reduce leaching of salts, encourage waterlogging and, consequently, the build up of salinity. Costly ameliorative measures have to be taken to correct these undesirable effects if improvement of aggregation and permeability can not be achieved by normal cropping practices.

Generally speaking, land levelling as a requirement for land reclamation and preparation of fields for surface irrigation is executed by technicians who may not be aware of the consequences of improper levelling on soils and crops. Under these circumstances not only technical training but also creation of awareness are needed in order to avoid land degradation. Since levelling is one of the earliest reclamation operations in newly irrigated farming projects it should be carefully evaluated at an early stage as a possible cause of secondary salinization.

TILLAGE

This is another mechanical operation that is usually carried out for numerous reasons including seed bed preparation and improvement of soil permeability. The relation between tillage and salinity depends on the following factors:

a. vertical distribution of salts;

b. depth of tillage and soil stratification;

c. soil moisture at time of ploughing;

d. tillage machinery and implements;

e. timing of tillage.

It is known that salts tend to accumulate closer to the soil surface in unirrigated dry lands and to move downward with reclamation and irrigation. So, tillage would speed up desalinization and dealkalization by mixing the easily soluble salts deeper in the soil, loosening the dense subsoil and mixing amendments, such as gypsum when applied to alkali soils. At an advanced stage of soil reclamation and under good management practices, where the salts are being pushed below the active root zone, care should be taken in order not to turn the soil by ploughing.

Within the normal depth of seed bed preparation, which does not exceed 35 cm for most crops, a relatively less pervious layer might be formed as a result of repeated ploughing to the same depth, especially in heavy textured soils and at above adequate moisture content. This plough layer may cause temporary waterlogging followed by salinization that both affect seedling growth and crop stand.

Variations in depth of ploughing, subsoiling, growing of crops with different rooting depth and growth habits, and thermal fallowing decrease the effect of this layer. For prognostic purposes, the depth and reversibility of the plough layer should be investigated.

Soil compaction induced by the use of heavy tillage machinery, especially at an unfavourable degree of wetness, increases the soil bulk density and decreases its infiltration rate and, consequently, promotes secondary salinization. Therefore, the degree of soil compaction should not be overlooked in the prognostic investigations.

Soil ploughing can be done by various implements that not only affect differently the soil bulk density and aggregate stability but also the distribution and mixing of salts. A chisel plough will cause less disturbance than a mould-board and, therefore, the former is preferable to the latter where turning over of the soil is to be avoided. So, the use of implements that enhance salt leaching, such as chisel and mould-board, has to be weighted differently from others, such as a disc harrow, in evaluating the role of tillage in salinization.

Tillage is mostly practised before sowing of each crop and if it is perfectly executed and followed by irrigation or heavy rainfall an effective leaching of salts can be achieved. Tillage after harvest may not be so effective, especially if the soil is tilted, dry or a long period lapses before sowing the next crop. In the latter case, salts may accumulate and affect seedling germination and growth. Therefore, the timing of tillage operations must be observed carefully as a factor in secondary salinization.

PLANTING

Planting techniques and positions vary with the type of crop and can be modified to overcome unfavourable conditions for germination and seedling growth. For saline soils and furrow row crops, in decreasing order, the effects of salinity on crop stand, due to planting position, are as follows:

a. planting on top of a single-row bed;

b. planting near edges of a double-row bed;

c. planting on side of a sloping bed;

d. planting in irrigation furrow, where crusting is not a problem.

Broadcasting or drilling of seeds on flat fields followed by heavy irrigation is also practised to overcome salinity effects on germination. However, where crusting is a problem, measures have to be taken to loosen the soil surface or break the crust to help seedling emergence. Under alkali conditions, characterized by low permeability and susceptibility to waterlogging, row crops are usually planted on high beds to reduce the harmful effects of waterlogging.

The amount of seed required for planting a given crop on a salt affected soil is higher than on a normal one. Similarly, a decrease in the percentage of emerging seedlings and a delay in emergence are to be expected.

For prognostic purposes, observation of the above relations would help in the identification of the progress of salinity and alkalinity problems. In this regard, keeping records of the amount of seeds, percentage of emerging seedlings and time of emergence is a recommended practice.

6. MULCHING

Among the various objectives of this practice, the reduction of water losses by evaporation is closely related to the movement of salts. Disruption of capillary continuity hinders upward water movement to the soil surface and its loss as vapour, and consequently reduces salinity build up at the surface. Surface tillage, maintenance or surface application of crop residues and placement of gravel layers on the soil surface or slightly beneath it are among the various practices that are worth mentioning. Generally speaking the effectiveness of mulching depends on the depth to water table, pore size distribution, climatic conditions and crop cover.

Under a given circumstance, for surface tillage to be of value it must be done at an early stage while the evaporation rate is high and not after there has been considerable surface drying by evaporation which reduces the beneficial effects of mulching. The effectiveness of maintaining or spreading crop residues on the soil surface depends on the rate and method of application of mixing with the soil. Regarding the placement of a gravel layer for mulching, it is best suited for trees requiring minimum disturbance around the trunks, since the gravel layer creates a problem when cultivating the soil.

The practice of minimum or zero tillage as a measure for conserving water and controlling erosion should be carefully applied where the threat of salinization exists.

Considering the role of proper mulching in checking surface salinization and the various factors affecting it, evaluation of mulching should take into account these factors and the timing of this operation.

7. FALLOWING

Under conditions where water is a limiting factor for crop production the land may be left fallow for some time to increase the soil water reservoir to benefit subsequent crops as in dry farming, or until an adequate water supply is available in irrigated farming. Measures are usually taken during fallowing to reduce evaporation and, consequently, salinization. Mulching, as discussed before, weed control and shading of the soil surface are practised with fallowing to reduce salinity and increase subsequent crop production.

The effectiveness of fallowing in this regard depends on other factors including depth to water table, quality of groundwater, soil properties, climatic conditions, and length and frequency of fallowing. Soil salinity reductions attributed to fallowing are greater under deeper water table regimes and fresh circulating groundwater, compared to more shallow water table and groundwater of higher salt content. Theoretically speaking, evaporation from a dry surface of a fine sandy loam soil would proceed at a rate of about 8, 3 and 1 mm/day if the water table is kept at 90, 120 and 180 cm respectively. This indicates the importance of the water table depth factor and the danger of fallowing where a shallow water table exists.

Where the soil has favourable water transmitting properties and there is a high atmospheric evaporative demand, summer fallowing should be avoided or otherwise irrigated and fallow areas should be grouped and arranged in such a way to reduce unnecessary circulation and rise of groundwater. Temporary fallowing between cropping may not require special practices as would a longer one and more frequent ones.

Fallowing as a factor in salinity prognosis should be considered not only as a process for reducing water losses by evaporation and reducing salinity but also as a possible reverse process. In this respect, depth to and quality of groundwater are the most important parameters.

3. APPLICATION OF MANURES, FERTILIZERS AND AMENDMENTS

Manures and fertilizers are frequently added to the soil to improve its productivity, while amendments are applied in the first place to correct undesirable physical and chemical properties.

Manuring, beside its nutritional value, improves the physical condition of the soil, and therefore enhances leaching of salts and drainage of wet soils. In certain cases, the application of manures high in salt content may add to an existing problem and green manuring would be advantageous. Under arid conditions, manures do not have such a long lasting effect as in temperate or humid climates and frequent applications would be needed. Since the amount of manure normally applied is much higher than when using inorganic fertilizers, care should be taken in the preparation of the former to reduce its salt content. Evaluation of manuring with regard to salinity development should include the salt content, amount added and the effect of manures on the soil physical properties.

Fertilization is an important and essential input in present agricultural production. There is already much information on the characteristics, availability, methods of application, crop response to fertilizers and their effect on the environment. With regard to prognosis of salinity, consideration should be given to the chemical composition, solubility, rate of release and methods of placement, especially in the early stages of plant growth.

The application of amendments is an ameliorative measure that has a positive effect on desalinization and dealkalization. Consequently, favourable consideration should be given to that practice in prognostic investigations. Other ameliorative techniques such as subsoiling, moling and sanding should be treated similarly.

9. CROP ROTATIONS

The selection of a given crop rotation is governed by the availability and adequacy of soil and water resources, suitability of crops to the prevailing climatic conditions and assurance of an economic return. While the latter factor may not be important in a reclamation rotation, the suitability of the crop to the soil and water qualities will be. Under conditions that encourage salinization crops should be selected on the basis of their salt tolerance and their effects on the salt balance. For alkali conditions, they are selected on the basis of their tolerance to the specific effects of the sodium ion and to the adverse physical conditions. Lists are available for the relative tolerance of crops to salinity and alkalinity.

Since plants not only differ in their tolerance to salts but also in their water needs in terms of quantity and frequency, it is to be expected that the salinity of the soil will be affected differently under various crop rotations. For example, the salinity will be higher after a rotation of cotton-cotton than after berseem-cotton-beans or cotton-berseem-rice. Crops with a long duration of evapotranspiration will cause, in the absence of proper leaching practices, accumulation of salts in the root zone, while crops such as berseem, rice and others requiring frequent irrigation reduce salinity effectively especially where there is adequate drainage.

For prognosis of salinity and alkalinity, an advance knowledge of the salt balance under various crop rotations is very important. Continuous monitoring of salinity and alkalinity after each crop or at least a rotation, not only creates awareness of a potential problem but also helps to re-evaluate the management practices associated with the cropping system. Crop performance and yield are good indices of the improvement or deterioration of the production inputs including soil conditions.

10. CONCLUDING REMARKS

The effects of the soil management and cropping practices on salinization and alkalization are closely related to water management, quality and use, and to climatic and other natural factors. For prognosis of salinity and alkalinity, factors having a long duration effect are land levelling, fallowing and crop rotations. The other factors, although important, generally have less effect and are less significant than the above ones and could be corrected with less difficulty. Parameters such as depth of soil, depth to water table, quality of groundwater, atmospheric evaporative demand and tolerance of crops to salinity and alkalinity are important for prognostic investigations.

C. Methods of Prognosis and Monitoring

Paper 8

SOIL AND HYDROLOGIC SURVEYS FOR THE PROGNOSIS AND MONITORING OF SALINITY AND ALKALINITY

by

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1. INTRODUCTION

The main cause of the formation and occurrence of salt affected soils is the accumulation of Na^+ ions in the solid and/or liquid phases of the soil, i.e. the presence of dissolved sodium salts in the soil solution and/or exchangeable Na^+ ions in the soil absorption complex. These two phenomena are directly or indirectly responsible for the low fertility of salt affected soils. The high salt concentration of the soil solution is directly toxic to plants in several cases, it limits their water and nutrient uptake, metabolism and results in physiological deteriorations. The high sodium saturation of the soil causes increased hydration, dispersion and peptization of soil colloids, structural destruction, aggregate failure and consequently results in unfavourable physical and hydrophysical properties (low available moisture range, high wilting percentage, swelling, low infiltration rate, low saturated and unsaturated hydraulic conductivity, etc.). All these factors limit the agricultural potential of salt affected areas and determine both the possibilities for their rational land use (including cropping pattern, agrotechnics, irrigation, etc.) and the necessity and optimum combination(s) of ameliorative measures (leaching, drainage, chemical amendments, etc.).

The final aim of any research and survey on salt affected soils is to establish the exact scientific basis for efficient salinity and alkalinity control including:

- amelioration of salt affected soils;
- regulation of actual salinity and alkalinity;
- prevention of salinization and alkalization processes, limiting their further development.

For this purpose it is necessary:

- to describe the salinization and alkalization and reverse processes exactly;
- to characterize the influencing factors and to analyse their mechanisms and relationships quantitatively;
- to elaborate a comprehensive prognosis system for the prediction of these processes;
- to establish a regular monitoring system for the continuous registration of salinity and alkalinity changes due to natural factors or human activity.

On this basis, the possibilities of establishing a satisfactory salinity and alkalinity control can be revealed, and from these possibilities the optimum (most effective, efficient and economic) variants can be selected according to the local natural and farming conditions, and precise technology can be elaborated for these optimum combinations.

2. GENERAL CONSIDERATIONS ON PROGNOSIS AND MONITORING

For the description and prediction of salinization and alkalization processes the following factors have to be considered.

i. The main actual and potential sources of water soluble salts (especially sodium salts) have to be identified and quantitatively characterized (groundwaters; deep subsurface waters; irrigation waters; seepage waters from higher lands, irrigated areas, canals, reservoirs; inundation and runoff waters; salt water intrusion; deeper soil horizons, geological layers; products of local weathering; airborne salts; etc.).

ii. The main features of the salt regime have to be characterized (salt balances: spatial distribution, both vertical and horizontal, and seasonal dynamics of water soluble salts and mobile sodium compounds; solute movement in saturated and unsaturated soil layers; diffusion; solubility changes; interactions between the soil's solid, liquid and gaseous phases; etc.).

iii. The whole range of environmental factors influencing the role and importance of various salt sources and the components of the salt regime summarized above have to be analysed(meteorological, geographical, geological, geochemical, geomorphological, hydrogeological and hydrological conditions; topography; soil conditions: physical, hydrophysical, physico-chemical, chemical, biological soil properties and their spatial distribution, and seasonal dynamics, etc.).

iv. The impact of human activity (land use, agrotechnics, amelioration, irrigation, drainage, leaching, erosion control, water and soil pollution, etc.) has to be studied and accurately determined.

For comprehensive salinity and alkalinity prognosis, data are required from survey on the following disciplines: soil, hydrology, meteorology, geology and geomorphology, and agricultural development plans must also be taken into consideration. This integrated analysis necessitates at least two steps:

- preliminary (small or medium scale) reconnaissance survey and mapping;
- detailed (large scale) survey and mapping.

The survey must be supplemented with a monitoring system for the continuous registration of changes in the salinity and alkalinity status and in the accompanying soil and water characteristics.

SMALL OR MEDIUM SCALE RECONNAISSANCE SOIL AND HYDROLOGICAL SURVEYS AND MAPPING

The aim of these surveys is to give a general outline of the actual salinity and alkalinity status in soils of a given area and of the potential possibilities of salinization and alkalinization and reverse processes. The reconnaissance type of low intensity surveys (scale 1:100 000, 1:200 000, 1:500 000 or similar) should not be limited to the project area but must be extended to the whole geographical unit (water catchment area, hydrological region, irrigation system, etc.). For these surveys all kinds of descriptive, numerical, cartographical and other materials (air photos, etc.) of meteorological observations, geomorphological, geological, hydrological and soil surveys can be used which give information on the factors summarized in the general considerations. The soil and hydrological surveys should cover the following factors:

A. <u>Soil characteristics</u>

i. general characteristics of the soil cover (associations of great soil groups and parent materials);

ii. general information on the dominant soil processes with an evaluation of the actual and potential soil forming factors;

iii. salinity and alkalinity status of soils (horizontal and vertical distribution, characteristic ion composition of soluble salts and their dynamics: general salt balances, soil reaction, exchangeable Na^+ status) and potential factors of salinization and alkalization processes (hydrological conditions, salinity and alkalinity status of deeper soil horizons or geological layers, factorial salt balances).

B. <u>Hydrological characteristics</u>

i. groundwater conditions (depth and fluctuation of the water table, height of the water table above a reference level, horizontal flow of groundwater, sources of groundwater supply, concentration and chemical composition of the groundwater, evaluation of groundwater as a potential irrigation water, etc.);

ii. surface water conditions (concentration and chemical composition of surface water and its evaluation as potential irrigation water or as leaching water, hazards of waterlogging and flooding, hazard of seepage and salt water intrusion, etc.).

Based on this information salt or sodium balances can be established and properly used for a preliminary prognosis of salinity and alkalinity:

$$\Delta S = S_2 - S_1 \qquad (1)$$

Where:

ΔS = Salt or sodium balance: change of storage in the soil, t/ha

S_2= Quantity of salts or mobile sodium at the end of the reference period, t/ha

S_1= Quantity of salts or mobile sodium at the beginning of the reference period, t/ha

The types of balance and the length of the balance period have to be chosen according to the type of problem to be investigated. Salt balances can be calculated:

a. for the total salt content, or for various ions (when studying specific ion effects and chemical changes in the soil solution during filtration, etc.);

b. for the whole soil profile from the soil surface to the water table, or for various layers, horizons (when studying salt profile redistribution, hazard of resalinization, leaching efficiency, etc.) or for the root zone;

c. for soils, mapping units or territories (having a sufficiently homogeneous hydrological character);

d. for vegetation periods, irrigation seasons, seasons, years or longer periods of time (having a sufficiently homogeneous hydrological character).

Beside the general salt balance, detailed or factorial salt balances (for certain substances, ions, etc.) have to be established too, reflecting not only the integrated changes but also revealing the causes of the changes and quantitatively characterizing the partial contribution of various factors in these changes. In this way the potential possibilities of a proper salinity-alkalinity control (man-controlled salt balance regulation: the prevention, moderation or halting of processes increasing the salt reserve; the promotion, or introduction of processes reducing the salt reserve) can be determined; a prognosis can be given for the natural salinization and alkalization processes and the probable effect of various human interventions, e.g. land use, agrotechnics, amelioration, irrigation, leaching, drainage, control of flooding, seepage and runoff, etc., can be predicted to a certain extent, as well. On this basis the necessity, effectivity and efficiency of a given measure can be evaluated, the most favourable variant(s) can be selected and realized and proper technology can be elaborated for this purpose.

The general equation of detailed (factorial) salt balances can be written, as follows:

$$\Delta S = [P + I + R + G + W + F] - [1_p + 1_i + r + g + n] \qquad (2)$$

Where:

ΔS = Salt balance

P = Quantity of salts derived from the atmosphere (airborne salts, rainfall, wind action, etc.)

I = Quantity of salts added with the irrigation water

R = Horizontal inflow of salts transported by surface waters (runoff, flood, waterlogging)

G = Horizontal inflow of salts transported by subsurface water (groundwaters, deep subsurface waters, etc.)

W = Quantity of salts derived from local weathering processes

F = Quantity of salts added with fertilizers and chemical amendments

1_p = Quantity of salts leached out by atmospheric precipitation

1_i = Quantity of salts leached out by irrigation (leaching) water

r = Horizontal outflow of salts (discharge) transported by surface waters

g = Horizontal outflow of salts transported by subsurface waters (drainage)

n = Quantity of salts taken up by plants and transported from the area with the yield

All factors can be given in the dimension t/ha.

P, I, F and n can be measured and predicted easily; R and r can be estimated on the basis of topographical surveys, meteorological observations, surface water investigations and infiltration studies; G and g can be calculated from groundwater characteristics, taking into account the hydrophysical properties of the soil layers between the soil surface and the water table; 1_p and 1_i can be estimated on the basis of data on these hydrophysical properties, on the flow rate of downward filtration and on the chemical composition of the filtrating solutes, or they can be determined experimentally in leaching studies; W can be estimated by evaluation of factors influencing local weathering, the transport and transformation of weathering products.

The probability and accuracy of such salinity and alkalinity prognosis depend on the homogeneity (from the viewpoint of hydrological and soil conditons) of the area surveyed and the reference period studied and on the quantity, quality, probability, accuracy, processability and interpretability of the available data and information concerning the soil and hydrological characteristics summarized. Consequently, all the available information has to be collected, processed, analysed and interpreted during the preliminary soil and hydrological surveys which should be extensive enough to provide adequate data and information on the factors already listed, according to the scale of the preliminary survey and the aim of study.

An example is given in the map, Fig. 1, prepared for the eastern part of the Hungarian Plain. This area is the bottomland of the geologically, geomorphologically, hydrologically and hydrogeologically closed Carpathian Basin; there, in a semi-humid climate, with a considerable deficit in the water balance during summer, the main reasons for the occurrence of extensive salt affected areas and for the potential hazard of salinization and alkalization processes are the geological and hydrological conditions (closed character of the basin, thick, salty Tertiary and Quaternary layers in the geological profile) and the main salt sources are the stagnant, salty groundwaters with a high (rising easily, markedly and rapidly) water table with very slow horizontal flow (low slope and very low hydraulic conductivity). The situation is aggravated by the predominance of sodium carbonates and bicarbonates (high sodium saturation) and by the heavy-textured parent material with high swelling clay content (more or less irreversible alkalization processes).

The map was constructed at scale 1:100 000 and indicates the general possibilities for efficient salinity and alkalinity control, the prevention of secondary salinization and alkalization processes, and the preconditions for effective irrigation from the viewpoint of soil conditions. For the construction of this synthesised map a series of maps were prepared or adapted with the same scale:

- soil map, i.e. soil type,
- map of the average depth of the water table,
- map of the minimum depth of the water table,
- map of the average salt concentration in the groundwater,
- map of the chemical composition of the groundwater.

The following information was used as well:

- map of the absolute height of the water table,
- map of the hydrophysical properties of soils,
- geological maps,
- data of long-term groundwater table observations (more than 500 wells were observed for over ten years).

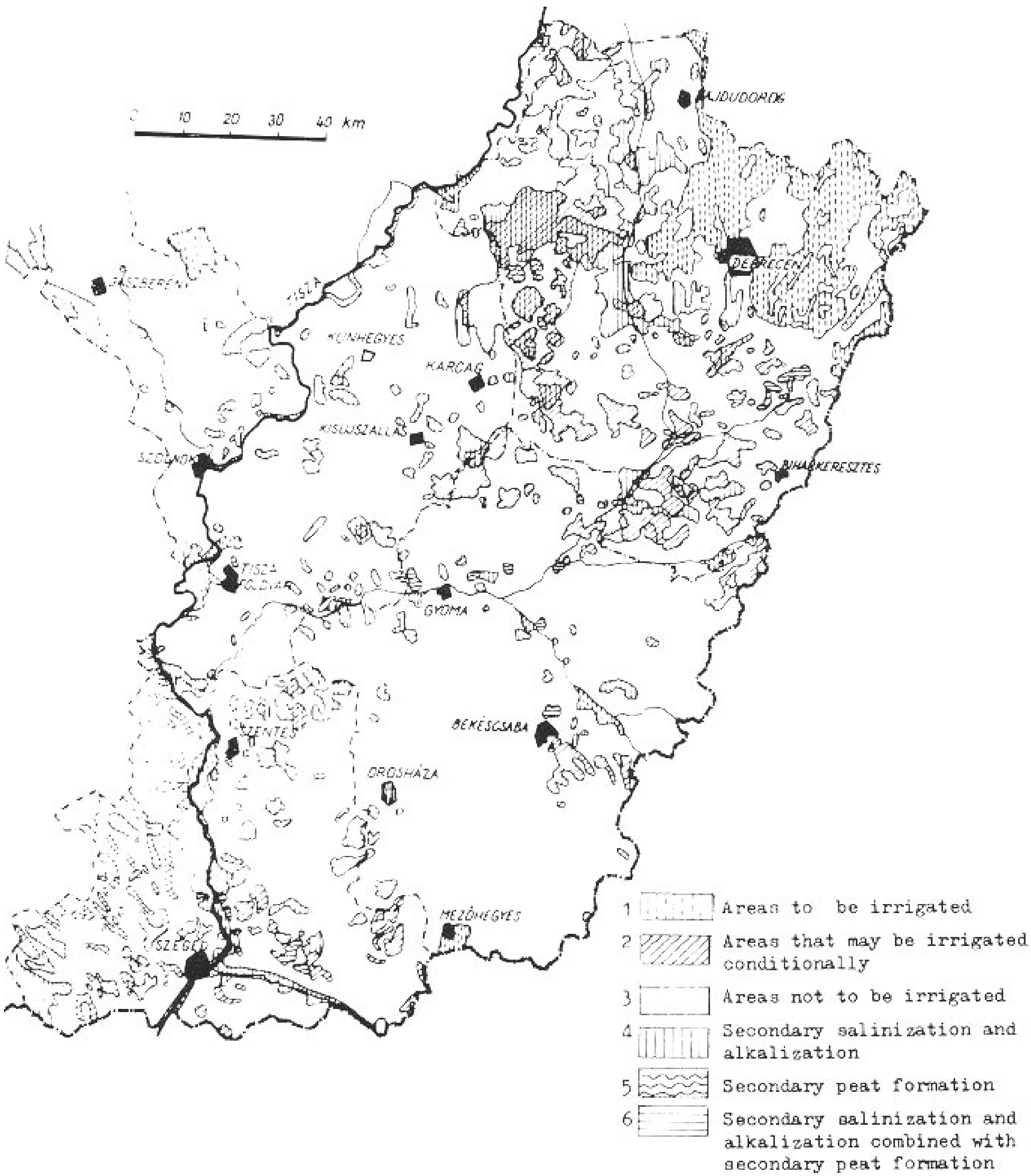

Fig. 1 GENERAL POSSIBILITIES FOR EFFECTIVE IRRIGATION FROM THE VIEWPOINT OF SOIL CONDITIONS AND THE EXISTING UNDESIRABLE SOIL PROCESSES DUE TO IRRIGATION IN THE EASTERN PART OF THE HUNGARIAN PLAIN

4. DETAILED SOIL AND HYDROLOGICAL SURVEYS AND MAPPING

With a general knowledge of factors and processes influencing the present and future salinity and alkalinity status of soils in a large area (water catchment area, ecological region, irrigation network, etc.), more precise soil and hydrological surveys are necessary for the detailed description and prediction of salinization and alkalization and reverse processes, in order to be able to make a more exact and accurate analysis of factors influencing them and the possibilities of controlling them. The elements and subjects of the detailed surveys are the same or similar to those of the preliminary surveys. But, on account of the larger scale, a wide variety of sub-factors must be surveyed, measured, monitored and analysed thoroughly:

A. Soil characteristics

i. characteristics of the soil cover: soil types, subtypes, variants and their associations; structure of soil cover; heterogeneity; evaluation of the existing and potential soil processes, etc.;

ii. characteristics of the parent material: evaluation of parent material as a potential salt source and as the main influencing factor of the vertical and horizontal flow of subsurface waters;

iii. physical characteristics of the soil: texture; structure: rate and stability of aggregation, porosity, pore-size distribution; moisture characteristics of the soil: pF curves, water retention, water holding capacity, wilting percentage, available moisture range; saturated flow; flow of solutes in unsaturated soil layers; time and spatial variation of suction and/or moisture profiles;

These factors must be interpreted first of all for the description and prediction of water and salt movement in layered soil profiles: the possibilities and preconditions of leaching on the one hand and those of salt accumulation from the groundwater on the other hand.

iv. salt regime characteristics of the soil and of the area: spatial, vertical and horizontal, and time variations of the quantity and quality of water soluble salts: general and factorial salt balances;

v. other chemical characteristics of the soil: soil reaction; carbonate status; CEC; exchangeable cations especially the mobile sodium balance; etc. In this respect special attention must be paid to the reversibility of salinization and alkalization processes, because reversible processes can be controlled and balanced relatively easily, while salinity and alkalinity control is far more difficult in the case of irreversible (or nearly irreversible) processes, i.e. salinization and alkalization of heavy-textured swelling clays under the effect of sodium salts capable of alkaline hydrolysis: Na_2CO_3, $NaHCO_3$.

B. Hydrological characteristics

i. groundwater hydrology: depth and fluctuation of the water table, horizontal flow of the groundwater as a function of hydraulic gradient and hydraulic conductivity, main factors of groundwater supply, etc.;

ii. chemical characteristics of the groundwater: concentration and ion-composition of groundwater, changes in these factors during upward capillary flow, etc.;

Factors B.i. and ii. supply information for the estimation of the possibilities of salt accumulation processes from the groundwater (reality of the hazard of secondary salinization and alkalization due to a rise in the water table under the effect of changing environmental factors or human activity) and for the evaluation of subsurface waters as potential irrigation waters.

iii. surface water characteristics (listed in the preliminary survey). These factors need to be evaluated as a potential source of salt and of water for irrigation and leaching.

Adequate data on these soil and hydrological characteristics can be obtained from reports on geographical, geomorphological, hydrological, hydrogeological and ecological surveys (descriptions, data, maps, cartograms, various air photos, photo-mosaics, and recently satellite spectral photographs, etc.); it can be collected from the regular climatological, groundwater and piezometric observations and available soil moisture records; it can be measured directly during the detailed soil and hydrologic surveys, and it can be calculated and/or estimated from available data or from measured values.

It is suggested that all these parameters be indicated on a series of maps (cartograms) at scale 1:10 000 or 1:25 000 or similar. The optimum or, more exactly, the rational scale of the surveys, laboratory analyses and data processing depends on the hydrological and soil heterogeneity of the project area, on the aim of the study, on the sources of data available, and on the main concepts of the agricultural development programme, including time and financial possibilities.

On the basis of these data, exact and quantitative general and factorial salt balances can be calculated for sufficiently homogeneous reference periods and territorial units. Using predicted values instead of measured ones from meteorological, hydrological and geohydrological prognosis, irrigation, drainage and amelioration plans, etc., predicted salt balances can be established and prognosis can be made of the probable future changes in the salinity and alkalinity status of soils due to the influence of environmental factors and/or human activity. For this purpose not only adequate data are necessary but also a detailed (exact and quantitative) knowledge of the influencing factors, their mechanisms and relationships based on the integrated analysis of these phenomena with the application of multifactorial mathematical models, simulation techniques, computer approaches, etc. Research must guarantee this scientific background for practical salinity and alkalinity surveys.

As an example, during the detailed hydrological and soil surveys, the 1: 100 000 scale general map of the eastern part of the Hungarian Plain, shown in Fig. 1 was supplemented with a series of maps at a scale of 1:25 000:

- soil map (soil type, subtype and parent material),
- map of soil texture and water properties (water holding capacity, available moisture range, permeability),
- map of salinity and alkalinity status (average salt content of soils, maximum salt content in the soil profile, depth of this salt maximum, soil reaction),
- map of groundwater conditions (depth of the water table, average salt concentration and Na^+ percentage of the groundwater).

In the Hungarian Plain the main salt sources are the subsurface waters and the dominating process in the formation of salt affected soils is sodium accumulation from the groundwater due to the potential gradient inducing a vertical, upward capillary flow of solutes. In this respect the depth of the water table has special significance: if the actual water table is above a certain critical depth salinization and alkalization processes develop; on the contrary, if the actual water table is below this critical depth leaching is predominant and the salt balance of the soil profile is negative. Based on composite hydrophysical and physico-chemical studies, Szabolcs, Darab and Varallyay elaborated various approaches to the exact determination of this critical depth or, more exactly, the "critical" groundwater regime, taking into consideration numerous soil and hydrological factors (actual salinity of soils; harmful salinity limit; depth and fluctuation of the water table; concentration and ion composition of the groundwater; infiltration rate, saturated hydraulic conductivity, unsaturated capillary conductivity as a function of suction; moisture dynamism; water holding capacity, available moisture range; pH; etc.). With the application of these calculations, on the basis of data indicated on the maps mentioned previously, two more maps were constructed at the same 1:25 000 scale:

- map of the "critical" depth of the water table,
- map of practical recommendations for efficient salinity and alkalinity control, for the prevention of harmful salinization and alkalization processes and for the preconditions of effective irrigation.

This prognosis system was successfully used for the planning and operating of Tisza irrigation systems and it afforded the practical possibility of preventing soil deterioration due to salinity and alkalinity in the Hungarian Plain.

The general approach to salinity and alkalinity prognosis is similar in any region but, of course, the influencing factors and especially the limiting values are different and should be studied and determined according to the local conditions.

5. MONITORING

For efficient salinity and alkalinity control continuous information is necessary on the soil and hydrological factors characterizing or influencing actual and potential salinization and alkalization processes. The monitoring of these factors provides possibilities for the elaboration of preventive and ameliorative measures and for their effective realization.

The Monitoring includes observation of the following factors:

i. moisture regime: time and territorial distribution of moisture or suction profiles, or both;

ii. salt regime: time and territorial distribution of salt profiles, concentration and ion composition of the soil's liquid phase;

iii. interactions between the solid and liquid phases: time and territorial distribution of mobile sodium profiles, pH and characteristics of the soil absorption complex; solubility changes during drying, etc.;

iv. changes in hydrophysical properties: pF, saturated and unsaturated hydraulic conductivity, etc.;

v. depth of the water table;

vi. horizontal flow of the groundwater;

vii. concentration and ion composition of the groundwater;

viii. concentration and ion composition of surface waters;

ix. concentration and ion composition of irrigation and drainage waters; quantity of irrigation and leaching waters; and quantity of drainage water drained out from the soil profile.

Monitoring can be realized by periodical observations of iii, iv, vii, viii and ix, or by automatic registration using moisture meters and tensiographs for i; salinity sensors for ii; automatically observed test-wells and piezometer installations for v and vi; automatically registered water quality tests for vii, viii and ix; etc. Automatic monitoring of these factors can be combined with automatic processing of data and their computerized evaluation and interpretation for salinity and alkalinity control; for instance, what kind of factors can and have to be artificially modified or regulated; what kind of practical measures bring about these modifications or regulations. Remote sensing systems have an ever-growing significance in this respect.

SOILS AND HYDROLOGIC SURVEYS

by

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INTRODUCTION

Soil surveys are an important tool for improving salt affected soils and for preventing salt damage to soils that are to be irrigated. Salt and alkalinity problems are most common in irrigated areas, and soil surveys are most valuable as a tool for planning irrigation projects so that salinity problems in the project area can be controlled and damage to water resources can be minimized. This paper will, therefore, emphasize the use of soil surveys in planning and managing irrigation projects, but salinity problems of non-irrigated soils will be discussed briefly.

We contend that a soil survey can be planned and executed in such a way that it provides all the needed information on the soil resource of an irrigation project.

Irrigation suitability ratings and irrigation guides can be developed from such a soil survey and there is no need for an additional land classification survey by field techniques if the soil survey meets the following criteria:

a. the soil survey is an integral part of the planning process. It takes full advantage of hydrologic, geologic, economic and other resource analyses that have been developed for the area and, in turn, other resource analyses are planned in such a way as to supplement the soil survey;

b. its objectives are carefully defined and the survey is designed to meet these objectives;

c. it is of high quality in terms of the accuracy of the delineations of mapping units and the descriptions and interpretations developed for these mapping units;

d. it contains relevant interpretations and meaningful management recommendations for each of the identified mapping units.

In the modern soil survey the scale of the base map, the detail of the mapping, the kinds of mapping units used and the kinds of supplementary research needed for developing interpretations must be carefully tailored to the foreseeable needs in the survey area. The soil survey should, however, be a basic inventory of the soil resource that is not tailored to current needs and land use so closely that it cannot be reinterpreted for new objectives or new management requirements in a changing technological or economic environment. It should be flexible enough so that the interpretations of mapping units can be modified if the pattern of farming changes or if new technology becomes available. An effort should be made to consider alternative uses of the land and changes in technology in the design of the survey.

The kind of survey needed depends on the kind of farming that is to be conducted in an area, the technological possibilities and constraints, sociological factors, environmental constraints and, to some extent, the resources available to conduct the survey. Farming systems, the kinds of crops to be grown and the size of farms are of obvious importance in deciding on the limits and on the allowable variability within mapping units. A soil survey for an area that will be used primarily for pasture and livestock will be quite different from one for an area where intensive cash crop farming will be practised. Even the kinds of crops that are to be grown can make a difference in designing mapping units. Technological constraints have to be considered. If flood or furrow irrigation is to be used, very narrow slope classes have to be defined within the range of slopes suitable for these kinds of systems. In addition, certain critical permeability and infiltration characteristics that influence run lengths have to be considered. If, on the other hand, conventional sprinkler irrigation or centre pivot sprinklers are an economically viable alternative, a greater latitude in slope, in infiltration characteristics and in salinity characteristics can be allowed within one mapping unit. But, more slope phases have to be delineated on steeper slopes than would have been outside the area suitable for flood or furrow irrigation. A related constraint is of a sociological nature. If highly sophisticated management systems are expected in the area, more detailed mapping may be desirable in areas of marginal soils that would not lend themselves to simple farming and irrigation practices. Finally, environmental constraints are becoming more and more important. We have to consider the quality of the excess irrigation and drainage water and we have to consider the potential movement of silt and plant nutrients. We may have to design mapping units that would identify areas that may be critical in this respect.

As has been pointed out before, soil surveys have to be designed in such a way that they meet the immediate needs and still retain maximum usefulness if there is a drastic change in the pattern of farming or in technology. The more comprehensive the soil survey, the more detailed the mapping, and the more thorough the identification of soil properties, the more likely it is that the usefulness of the survey can be extended over a longer period of time. Such comprehensive surveys require more manpower, more skilled manpower, than simple surveys that address themselves primarily to immediate needs.

Soil surveys in presently or potentially salt affected areas do not differ greatly from good soil surveys elsewhere. Except for extremes, soil salinity in irrigated agriculture is primarily a problem of regional hydrology, design and soil management and not of the original salt content of the soil. The factors that influence irrigation management and the movement of water through the soil are important, not salinity _per se_. Surveys of the salinity status of the soils of a farm or of a whole irrigation project may be needed to appraise the effectiveness of current practices to control salinity. Such surveys have a function similar to that of soil tests for soil fertility assessment. They are not soil surveys. They are best conducted as a single-purpose survey and not as part of a comprehensive soil survey.

A comprehensive soil survey may be divided into three phases: exploratory studies which include an assessment of the geology and hydrology of the area, the detailed soil mapping, and supplementary studies to develop design and management criteria for individual kinds of soils.

2. EXPLORATORY STUDIES

Exploratory studies are an important phase in all soil surveys. They are particularly important in soil surveys of potential reclamation projects. In such areas the soil survey must not only delineate soils as they are now but must include predictions as to how the soil will be changed upon drainage, irrigation and the consequent removal or addition of salts. The degree of change will, in part, depend on the quality and the quantity of irrigation water and the extent to which reclamation practices are related to specific combinations of soil and water quality. This situation contrasts quite sharply with soil surveys in areas where a great deal of practical experience on the response of individual kinds of soils to certain management practices is available. In such areas the soil scientist's job consists primarily of assembling and formalizing this information and relating it to the kinds of soils he identifies. In areas that will be changed drastically, such information is usually not available and must be developed through formal research before and during the progress of the soil survey.

Exploratory studies may be divided into the following steps:

i. assembling background information,

ii. making exploratory field studies,

iii. determining critical soil parameters,

iv. developing the initial mapping legend and mapping techniques.

2.1 Assembling Background Information

This includes assembling information that has been developed by specialists in other disciplines and cooperating with those specialists in developing additional data needed. The amount, reliability and quality of water are, of course, basic considerations in evaluating the feasibility of an irrigation project. In addition, this information is needed for making management recommendations and for evaluating the suitability of individual kinds of soil for irrigation. The amount of water needed is determined by the kind of crop and the consumptive use of water by the crop, the permeability of the soil, and the leaching requirement - which in turn depends on the soil, the quality of the water and the kind of irrigation system used. Water quality is determined largely by the salt content of the water, the composition of the water in terms of cations, anions and toxic substances. The salinity of the water determines, in part, the kinds of crops that can be grown and the amount of leaching that has to be achieved to remove excess salts. Relatively poor water can be used on a permeable soil where excess salt can be leached readily, but it may not be used for a sensitive crop in a slowly permeable soil.

As in any soil survey, studies of the geology and geomorphology are needed to predict the distribution and properties of kinds of soils. If salinity is expected to be a problem information on underlying formations and the regional hydrology are needed for predicting the movement of groundwater and for evaluating the feasibility of installing a drainage system. If underlying formations contain saline or toxic materials, especially careful provisions have to be made to protect the area from salinization by rising groundwater and to protect adjacent areas from salinization. Excessive saline return flow can be avoided by installing a drainage system that intercepts drainage water above the saline sediment and by using irrigation systems that minimize return flow. These requirements, again, may influence the evaluation of the relative suitability of various kinds of soils.

The need for climatic information is obvious. The need for economic information has been mentioned before.

2.2 Exploratory Field Studies

In exploratory fields studies, the soil scientist crisscrosses the survey area and studies the major landforms and soils on them. He describes the soils in as many places as possible and classifies them in an appropriate general taxonomic system. He makes highly detailed studies of typical areas of each landform to determine the patterns of soil variability. If he has had experience in similar areas with similar soils and similar requirements, he may tentatively apply criteria that have been successful elsewhere.

The soil scientist usually prepares a general soil map, using soil associations, of the area. If the exploratory field studies indicate a predominance of grossly unsuitable soils the project may be terminated. If the mapping base has not yet been established, the preliminary studies may be used to develop criteria for the base map for the detailed mapping period. One may, for example, establish the best time for aerial photography and the resolution that is desirable for efficient mapping.

2.3 Determining Critical Soil Properties

As the next step, the soil scientist will establish specific criteria for defining soil mapping units and will relate these criteria to soil properties that can be identified in mapping. In defining these properties, he has to consider the criteria that will be used for the technical classification, e.g. irrigation suitability groupings and management guides of the soils in the project area. In most cases soil characteristics relating to water and salinity are most important. These characteristics include available water-holding capacity, infiltration capacity, hydraulic conductivity and leaching requirements. At the present state of our knowledge, we may not be able to infer these properties with certainty from field observation or laboratory measurements alone. Hence, field experiments to determine field capacity over a range of soil conditions, trial plots to measure infiltration rates and hydraulic conductivity, and leaching experiments may be needed. These experiments should encompass the range of morphological characteristics, soil salinity and SAR (Sodium-Adsorption-Ratio) encountered in the project area. Specific criteria then have to be related to properties that can be measured relatively easily in the laboratory and to properties that can be determined in the field and checked by laboratory measurements. Available water-holding capacity, for example, is a useful concept for practical application in spite of its theoretical shortcomings. It can be determined only in field experiments, but for soils that lack strongly contrasting layers, available water-holding capacity can be related to laboratory measurements of the difference between water retentivity at low and high tensions. The influence of contrasting soil horizons and the influence of small differences in soil structure cannot be predicted from laboratory measurements. Especially in coarse-textured soils, microstratification that is not readily visible in the field and that cannot be evaluated under equilibrium conditions in the laboratory can be extremely important. Likewise, the presence of small amounts of volcanic ash can dramatically increase the available water-holding capacity. If one disregards these factors, some coarse-textured soils are unnecessarily penalized. In the USA we have some striking examples where soils, declared unsuitable for irrigation on the basis of laboratory measurements, were later used successfully by farmers who were unaware of these findings.

Nevertheless, with the help of careful field and laboratory studies, soils with similar available water-holding capacity can be identified by using soil texture, soil structure and the kind and contrast of horizons as clues in the field.

A knowledge of hydraulic conductivity is important for evaluating the feasibility and for developing design criteria for drainage systems. Again, the performance of such systems depends highly on the sequence of soil horizons and in many places on the microstructure of the soil materials. There may be drastic differences between horizontal and vertical hydraulic conductivity; soil characteristics that cause these differences must be recognized as critical properties in the soil survey. Ranges allowed in mapping units in turn have to be related to depths that are critical for drainage systems and for land levelling. Inasmuch as the hydraulic conductivity of soils is strongly influenced by the exchangeable sodium content, field experiments have to establish the changes in hydraulic conductivity that can be expected after the soil has been leached with the kind of irrigation water that will be used. In such experiments the effect of amendments such as gypsum has to be considered. From these studies, it is possible to establish criteria in terms of electrical conductivity, sodium adsorption ratio and, if applicable, the gypsum and calcium carbonate distribution in the soils in relation to the physical properties of the soil. The composition of salts in the soil, by the way, is important for engineering consideration. Sulphates corrode concrete so that special kinds of cements have to be used in canal linings and other concrete structures. Sodium sulphates can cause salt heaving that may damage lightweight structures.

Other soil characteristics that may detract or enhance the capability of the soil to perform under irrigation have to be considered. In extremely dry areas, the initial irrigation may cause subsidence that has to be considered in the design of irrigation and drainage systems. Thus, means have to be found to identify soils that will subside and to estimate the amount of subsidence. Such subsidence may be several metres. Smaller subsidence in mineral soils may be caused by dissolution of gypsum. Although the total amount of subsidence due to solution of gypsum may not be large, it may nevertheless require frequent land levelling and may cause damage to irrigation and drainage systems. Hence, critical values as to the amount and distribution of gypsum may have to be considered in the definition of soil mapping units.

Finally, the presence and effect of toxic substances such as boron have to be established and means have to be found to detect such substances and predict their distribution.

Mapping Legends and Techniques

After critical soil parameters have been established, a preliminary descriptive soil legend can be developed. This has to be done in close cooperation between the soil scientist and the potential users of the soil survey. The soil scientist should propose mapping units and have irrigation engineers, drainage engineers, agronomists and others evaluate their usefulness. Usually sample surveys should be made in major landscape units of the survey area to help the users of the survey in evaluating various alternatives. In addition, the soil scientists who will do the mapping have to be provided with the proper tools to enable them to make the observations they are asked to make. As far as possible, the mapping criteria should be recognizable in the field by visual or tactile observations of soil depth, texture, structure and other soil properties whose significance has been established. In addition, simple field tests may be useful. High SAR can be deduced from pH measured with colour indicators or with relatively simple field potentiometers and high salt content can be deduced from the electrical conductivity of the saturated paste. These simple tests can, however, be misleading if their validity has not been established for the specific soils under consideration. In addition, simple devices for measuring carbonate content are available. SAR, the EC of the saturation extract and the gypsum content can be determined in somewhat more complex field tests.[1/] Usually, such complex tests are too time consuming to be made at each site where the soil is being investigated and every effort should be made to develop simpler criteria.

Vegetation also can provide clues. The validity of these and other field clues, however, have to be carefully tested, especially in survey areas with complex and contrasting soils. In any case, clues and field tests that allow the soil scientist to make decisions on the spot are preferable to sending samples to the laboratory, even if the results of the tests are returned to the soil scientist promptly. The ability to classify soils on the spot, to draw delineations in the field and to decide on the next test site on the basis of these observations are important considerations for an efficient and accurate soil survey. The soil scientist, on the other hand, should not be burdened with making separations simply because they can be made with relative ease. Although soil salinity, for example, can be estimated with a high degree of precision from the conductivity of the saturated paste, soil salinity is so easily altered by water management that only areas with extreme amounts should be delineated unless salinity can be used as a clue to other soil properties. Similarly, only those slope classes should be set up that are meaningful for foreseeable uses of the land.

1/ A field laboratory is available from Hach Chemical Company, P.O. Box 907, Ames, Iowa 50010, U.S.A. (Trade names are used solely to provide specific information. Mention of a trade name does not constitute a guarantee of the product by the U.S. Department of Agriculture nor does it imply an endorsement by the Department over comparable products that are not named.)

Finally, one has to explore mapping techniques. If the distribution of kinds of soils can be related to recognizable landforms, efficient mapping techniques that project soil boundaries from field observations, air photo interpretations and more advanced remote-sensing techniques can be used. Some former lake basins or very flat areas near the toes of coalescent fans may provide few clues to the distribution of soils. Such areas may have to be mapped in systematic transects or through observations at the nodes of a systematic grid. Even then the mesh size of the grid has to be related to the objectives of the survey, the size of projected management units, the contrast between soils and the complexity of the soil pattern.

3. DETAILED SOIL MAPPING

If the exploratory studies have been comprehensive and pertinent, the detailed mapping phase of the soil survey should not be particularly difficult. To some extent, mapping techniques depend on the kinds of base maps available. High-altitude air photography of high quality, taken at the right time of the year, is an important prerequisite for efficient mapping. Orthophotography has the advantage of providing a highly corrected map base that can be related directly to engineering surveys. Stereoorthophotography may be worth the extra cost because it combines the advantages of a highly corrected base map with the possibilities of stereoscopic air-photo interpretation.

As in any other soil survey, constant communication between soil scientists and constant review and updating of the mapping legend are important. Notes must be kept by all soil scientists and must be incorporated in a soil handbook that provides the basis of the final decision on the composition and naming of the mapping units of the area.

4. SUPPLEMENTARY STUDIES

During the progress of the soil survey, supplementary studies arrive at background information for irrigation and other management guides for the individual mapping units. Such studies usually emphasize soil behaviour and continue and expand the exploratory studies described before. They include leaching studies, fertility experiments and trial irrigation to establish run lengths, irrigation schedules, permissible slopes and allowable distances between drains, etc. The studies should be conducted on a selected number of soils that encompass the major soil conditions so that recommendations for kinds of soils with intermediate properties may be interpolated.

5. SALT AND ALKALI PROBLEMS IN OTHER THAN IRRIGATED AREAS

So far this paper has dealt with problems related to salinity and alkalinity in irrigation farming. Changes in the hydrology of an area that may cause salinity problems may be induced by man without irrigation. Sometimes they may be caused by changes in climate or other natural factors.

Saline seeps, for example, are an increasingly serious problem under dry-land farming in semi-arid parts of the USA. They are saline areas that form locally in lower parts of slopes. Research results available so far indicate that the seeps are induced by the introduction of summer fallow in areas that had been under native prairie vegetation or under annual cropping before. Under these conditions, less water evaporates than before and more water moves through the soil profile. If the soils are underlain by impermeable sediments, water moves laterally at the top of such sediments and seeps out where the sediments are bisected by the modern land surface. Any evaluation of the problem requires the cooperation of the soil scientist and the geologist. The likely place of occurrence of salt seeps can only be predicted from comprehensive surveys of hydrology, geology and soils.

6. CONCLUSIONS

Soil surveys can be an important tool in the reclamation and management of salt affected soils. The behavior of salt affected soils in intensive farming, usually under irrigation, is however more affected by their ability to retain and transmit water than on their initial salt content. Mapping units used in the soil survey, therefore, must be defined in terms of criteria that are critical relative to the quality of water and the kind of irrigation and drainage system, as well as to environmental, economic and sociological constraints.

Such a survey can be used with confidence to rank soils on their relative suitability for irrigation, to develop engineering design criteria, to predict soil behavior and to develop management guides for sustained production.

Paper 10

USE OF SATELLITE IMAGERY FOR SALINITY APPRAISAL IN THE INDUS PLAIN

by

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1. INTRODUCTION

The imagery provided by the Earth Resources Technology Satellite (ERTS) is being increasingly used for the assessment of natural resources of the world. In the field of agriculture it is used for preparing crop inventories to estimate individual crop acreage, to predict crop yields and to locate areas of plant disease. It is also being used to develop scientific land use on a regional or country level. Generalized soil maps can also be prepared from this data.

Soil is an important variable in the agriculture of any country. Soil problems such as salinity and alkalinity, drainage, erosion, etc., affect crop production directly. In Pakistan the Soil Survey of Pakistan has collected information about the soils and soil problems of the Indus Plain which comprises the agriculturally important area of the country. This information has been collected through reconnaissance soil survey.

The present study is designed to test the feasibility of using ERTS imagery for assessment of the soil salinity problem. Through field studies made during the soil surveys, five different types of salt affected soils have been recognized. These are:

i. saline soils having slight surface salinity and/or alkalinity - a minor problem;
ii. strongly saline soils with a saline-alkali surface;
iii. porous saline-alkali soils;
iv. dense saline-alkali soils;
v. saline soils containing gypsum.

The first type of salt affected soils can be corrected easily. The porous saline-alkali soils and saline soils containing gypsum can be reclaimed in a few years and their reclamation is economic. The dense saline-alkali soils are, however, very difficult and uneconomic to reclaim.

It is with this background knowledge that the study is being undertaken and three representative areas of the Indus Plain have been selected. An effort is being made to interpret ERTS imagery in the light of the available soil survey information with a view to finding out the criteria that can be used for demarcating areas affected by salinity.

2. LOCATION AND GENERAL NATURE OF THE STUDY AREAS

The three areas selected for this study are Sheikhupura, Multan and Muzaffargarh. The Sheikhupura area is located in the northern part of the Indus Plain and has a semi-arid, subtropical, continental climate with mean annual rainfall of 250 to 400 mm. The remaining two areas occupy the central part of the Indus Plain and fall in the arid, subtropical, continental climatic zone, with mean annual rainfall of 140 to 180 mm. About two-thirds of the rainfall occurs as monsoons during the period from mid June to mid September. The summers are usually hot but winters are mild. Agriculture depends mainly on irrigation provided chiefly by canals, and in addition by tubewells and Persian wells. In narrow belts along the rivers only winter crops are grown with the moisture provided by summer floods.

3. METHODS OF STUDY

For the purpose of this study, ERTS imagery of bands 4, 5 and 7 (scale 1: 1 000 000) were used. This imagery was taken in the month of January 1973, the part of the year when the appearance of salinity is most pronounced. In the absence of proper facilities, the study was made simply by superimposing the available soil maps of the area over the respective imagery of bands 5 and 7, and delineating different types of salinity on them. These delineations were then correlated with the different photo tones of the imagery through visual observations. In addition, a colour composite which was available for one area (Sheikhupura) was also studied. Salinity patches picked up on this composite closely matched these delineations on the imagery. Vegetative cover also provides a clue to the recognition of different types of salinity. Three broad delineations have been made. They are shown in Fig. 1 and discussed below:

i. areas having white and grey tones cover about 50 percent each. The white tone represents saline patches having no vegetation and the grey patches are those of vegetation. This delineation correlates with porous saline-alkali soils;

ii. areas having a white tone representing salinity and alkalinity cover about 75 percent, whereas the area of grey tone is only about 25 percent; the grey areas represent vegetation or buildings. This delineation represents dense saline-alkali soils;

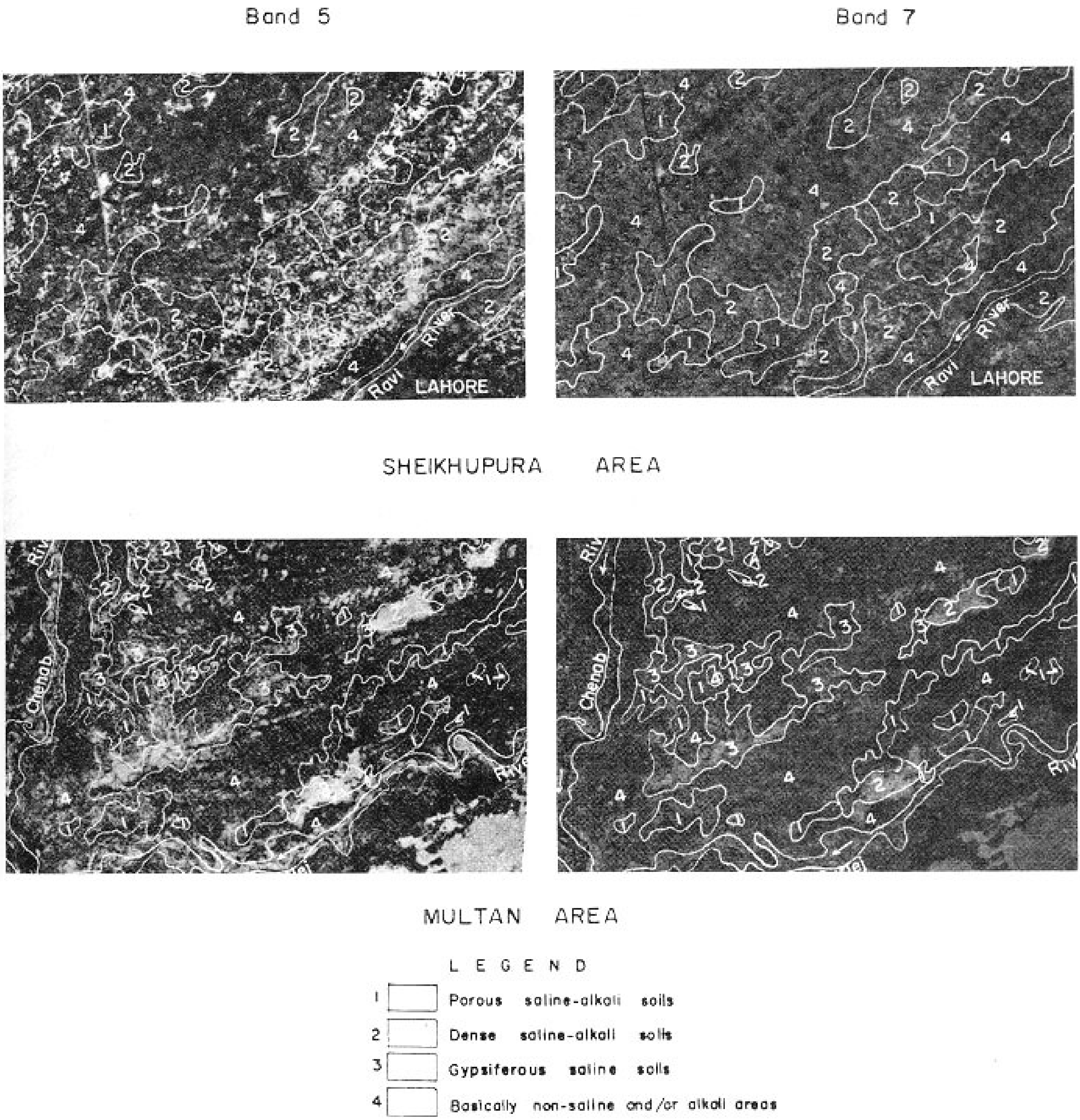
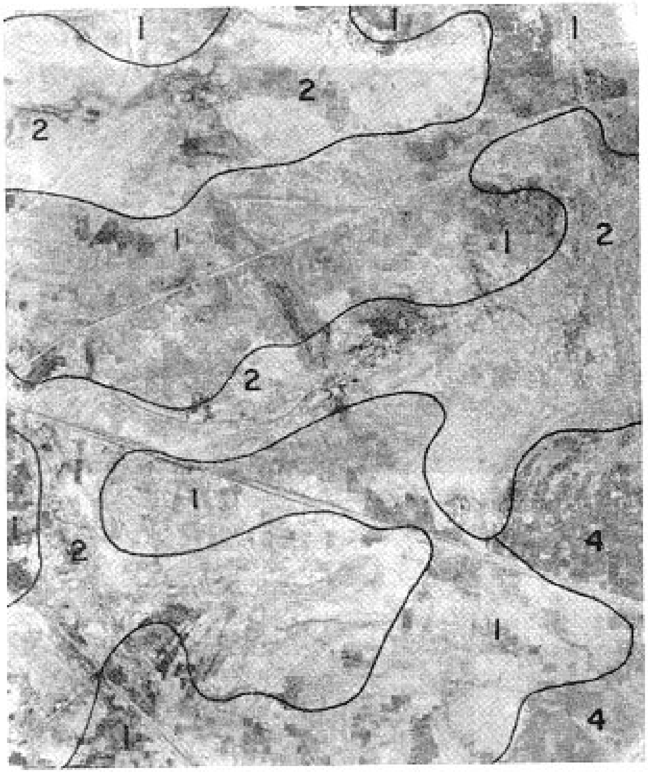


Fig. 1 ERTS IMAGERY, BANDS 4, 5 & 7 OF SHEIKHUPURA AND MULTAN AREAS



SHEIKHUPURA AREA

MULTAN AREA

LEGEND

1 Porous saline-alkali soils
2 Dense saline-alkali soils
3 Gypsiferous saline soils
4 Basically non-saline and/or alkali areas

Fig. 2 AERIAL PHOTOGRAPHS

iii. areas covered almost completely by a white tone with occasional grey spots are either vegetation mounds having some shrubs, or occasional salt bush growing in the saline soils. This delineation represents very strong salinity containing gypsum. This type of salinity is encountered only in the arid zone and therefore occurs in the Multan and Muzaffargarh areas but not in the Sheikhupura area. Scattered white patches in the undelineated parts of the imagery may represent either saline or sandy areas.

4. DISCUSSION

Areas of three kinds of salt affected soils have been delineated on ERTS imagery. The soils are predominantly clayey or fine-silty. If we compare the saline areas on ERTS imagery with those on the corresponding aerial photographs taken in 1953-54 (Fig. 2), which were used as base maps for the reconnaissance surveys, we find that the extent of saline areas is less on the ERTS imagery. This could be attributed to the reclamation of parts of saline soils during the period between 1953-54 and 1973. The change is mostly in the case of porous saline-alkali and saline soils containing gypsum. This is because it is easy and economic to reclaim them. The dense saline-alkali soils are very difficult to reclaim, so there is little change in their area. Cultivated patches within areas of these soils may be those of good soils. Also, in the dense saline-alkali areas of Sheikhupura many factories and housing colonies have sprung up and the grey spots may partially be attributed to these buildings. Changes from reclamation are more pronounced in the Sheikhupura and Multan areas than in that of Muzaffargarh.

5. SUMMARY AND CONCLUSIONS

A study was made on the feasibility of using ERTS imagery for salinity appraisal in irrigated areas of Pakistan. For this purpose, three areas representing semi-arid and arid parts of the Indus Plan were selected. Information about the salinity in these areas was already available from reconnaissance soil surveys. The study was made by superimposing the soil maps of these areas on the ERTS imagery of bands 5 and 7, and delineating saline areas. These delineations were then correlated with tone patterns of the imagery and fairly close correlation was found between some of the latter and the information provided by the soil maps of the respective areas. The ERTS colour composite of the Sheikhupura area was also studied and correlated with patches delineated on the imagery. Comparison of the extent of salt affected areas shown by ERTS imagery was made with that shown by aerial photographs taken in 1953-54 and these were used as base maps for the reconnaissance soil surveys.

It was noticed that the extent of saline areas was less on the ERTS imagery than on the aerial photographs of 1953-54, indicating that parts of the saline areas have either been reclaimed and put under cultivation or built over with factories and houses.

This study indicates that ERTS imagery could be used for salinity appraisal in cultivated zones if some information on saline areas is available for use as a check. The capability of the ERTS to produce imagery of the same spot at intervals could help to indicate any changes taking place in the salt affected areas. The ERTS imagery would be especially useful for making studies of soil problems on a regional basis, as one single frame covers very large areas. However, knowledge of the area of study for use as a check is necessary. Some additional ground checks may also be required.

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2. Laboratory and Field Characterization

Paper 11

a. LABORATORY ANALYSES OF SOILS RELATED TO THE PROGNOSIS AND MONITORING OF SALINITY AND ALKALINITY

by

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The purpose of laboratory analyses of soil samples collected from fields to be irrigated is to obtain data for the evaluation of the possible influence of irrigation and drainage. The analyses necessary for a complete survey are as follows:

i. Determination of physical and hydrophysical characteristics of soils
Most of these determinations have to be carried out in the field. The laboratory analyses add further data to the field analyses. The determination of soil structure, soil texture and pore space distribution are the most frequent laboratory analyses in this group.

ii. Analyses for the chemical characterization of soils
Soil reaction, cation-exchange characteristics and salinity status are the most important soil chemical properties which have to be determined from the point of view of irrigation and drainage.

iii. Analyses for the determination of soil fertility
This is the determination of mobile and/or total contents of plant nutrients in soil samples.

A general scheme of laboratory analyses for the survey of soils to be irrigated does not exist. The number of samples to be analysed, the type and methods of analyses to be carried out always depend on the planned irrigation development, and on the requirements, intensity of soil survey, etc. Furthermore, they depend on the properties of the soils to be irrigated and on the environmental factors determining soil forming processes under natural and irrigated conditions. Not only does the method of survey have to be different under different conditions but so also does the system of laboratory analyses; for instance: if the hazard of waterlogging has to be avoided, or if secondary salinization and/or alkalization is to be prognosticated, or if the amelioration of saline and alkali soils is the aim of the project.

The methods of analyses and the limit values are by no means uniform. They vary in different countries, regions, or even in the various laboratories of the same country.

Variations in methods and limit values may be accepted: under diverse climatic conditions, if soils with different properties and origins are being examined and when the aims of soil investigations are different. Laboratory facilities may also play a decisive role when the most suitable methods for analytical work are being selected.

All methods of soil analyses are standardized; they are based on theoretical considerations, as well as practical experience, and any deviation from these methods may cause differences in the analytical results. Even using the proper methods, it is necessary to know the systematic and random errors of the analyses for a proper evaluation of the determined soil properties. In order to compare and evaluate data determined by various methods, we must know the causes and the magnitudes of the deviations brought about by the differences in the analytical methods. The accuracy of the soil analyses is influenced not only by the error of analyses, but by several factors as well, which are independent from the selected analyses methods. These factors include the error of sampling and the error of the preparation of soil samples for analyses (drying, grinding, storage of samples, etc.).

1. DETERMINATION OF PHYSICAL AND HYDROPHYSICAL CHARACTERISTICS OF SOILS

During the determination procedure of some soil physical properties, the analyses are carried out with undisturbed soil samples (the determination of bulk density, water retention of soils under controlled conditions, hydraulic conductivity, unsaturated conductivity). In this case the reliability of data largely depends on the method of sampling. Cores appearing to be undisturbed can be distorted to a high degree. The degree of possible distortion is influenced first of all by the core's size. The larger the sample core is, the better the sample characterizes the structure of soil units. The diameter of sample core should be at least 7.5 cm and preferable 10 cm. In the case of swelling soils, the moisture content of the sampled soil plays an important role in the collection of undisturbed core samples. The best sampling can be carried out when the soil moisture content is close to the field capacity and is in equilibrium with the bulk of soil. From the undisturbed soil cores the following determinations are necessary:

- bulk density;
- water retention at one-tenth atmosphere, pF 2.0;
- water retention at one-third atmosphere, pF 2.5;
- water retention at fifteen atmospheres, pF 4.0;
- hydraulic conductivity;
- unsaturated conductivity.

The values of bulk density vary between 1 and 1.5 and they are influenced by the texture of the soil, e.g.

Texture	Bulk Density
Sandy soil	1.4-1.7
Sandy loam	1.35-1.5
Loam	1.2-1.40
Clay	1.3-1.6

High bulk density should be measured in the deeper layers or subsoil where adverse drainage conditions are encountered. Water retention at one-tenth atm, pF 2, gives the tension at the field capacity in sandy soils; at one-third atm, pF 2.5 corresponds to the field capacity of medium and heavy textured soils; and at fifteen atm, pF 4 is a measure of the wilting point of soils.

From the values of the bulk density and the moisture at pF 2.0, 2.5 and 4 the total porosity, non-capillary porosity and capillary porosity can be calculated.

To assure the reliability of data, the determination of bulk density and water suction values must be carried out in four or five parallels to avoid any errors due to soil structure heterogeneity.

1.1 Particle Size Analyses

Soil particles are the discrete units of the soil's solid phase. The distribution of inorganic particles and their sizes is one of the basic characteristics of soil: it effects the soil water retention, cation-exchange characteristic, etc.

Particle size analysis includes several pretreatments. For instance:

- drying and grinding of the collected samples;
- dry sieving of ground samples;
- removal of organic substances, free carbonates, gypsum, soluble salts, amorphic substances;
- the dispersion of particles.

In the technical literature there are diverse opinions regarding the necessary pretreatments. Some textbooks do not advise the removal of organic compounds and carbonates before the analyses of particle size distribution because "the texture as modified by the organic matter and lime is a more reliable criterion of irrigability than an analysis with these removed". In other cases they suggest not removing organic matter and lime because "more reliable results are obtained by putting soils through the normal pre-treatment procedures before dispersion". Bouyoucos involves no pretreatments to remove organic matter or calcium-carbonate; Kachinski removes only carbonates; Day proposes the removal of organic matter, soluble salts, gypsum, but not the dissolving of carbonates: Loveday uses chemical and mechanical treatments depending on the soil chemical properties.

NaOH, Na_2CO_3, $Na_2C_2O_4$, $Na_4P_2O_7$, or various mixtures of these salts are used as dispersion agents in dilute concentrations. The analytical data determined after different pretreatments in suspensions prepared with various solutions as dispersing agents are hardly comparable. We effect more controversy applying the same classes of particle size ranges to evaluate the data obtained by different methods.

The texture is a rather unchanging property of soil and it makes it possible to determine the particle size distribution only from samples collected in the representative soil profiles. In this case it is advisable to use a complete pretreatment. From other samples collected during the detailed survey, the proportion of particles 20 μ can be determined without pretreatment with the Bouyoucos method: in this case the limits to the characterization of soil texture can be applied as follows:

Texture of soil	Proportion of particles < 20 μ (%)
Coarse sand	<10
Sand	11–25
Sandy loam	26–30
Loam	31–60
Clay loam	61–70
Clay	71–80
Heavy clay	80<

2. ANALYSES FOR THE CHEMICAL CHARACTERIZATION OF SOILS

2.1 Determination of Soil Reaction

The reaction of the soil solution is one of the most variable properties of the soil. Its value is influenced by the soil moisture content, the total concentration and ionic composition of the soil solution, by the temperature of the soil layer, and by several other factors. A soil sample taken with a given moisture content brought to the laboratory, dried, ground and rewetted with water or salt solution has a reaction which correlates with the soil reaction, but without doubt it will not be the same as could be measured in the field.

The fact that we determine the reactions of samples under completely different conditions to those in nature, is a source of disagreement over the optimal methods and evaluation of soil pH. Measured pH values are different if we determine them in the soil suspension or in extracts, because they are influenced by soil:water ratio applied for the preparation of the soil suspension or extract. The differences of pH values measured in soil-water suspension and in water extracts with different ratios of soil:water, can surpass not only the error of analyses, but the differences in soil pH due to the soil heterogeneity.

To overcome these difficulties, the use of the N KCl solution was proposed instead of water for the preparation of the soil suspension. The pH values determined in N KCl solution are lower but more stable than those measured in water. They decrease the error due to the junction potential. The disadvantage of this method is that the KCl solution decreases with an unpredictable value the reaction of the soil suspension. Furthermore, the pH value also depends on the soil:solution ratio. More recently Schofield and Taylor have proposed a method for the determination of pH in 0.01 M $CaCl_2$ solution. The method has the advantage of eliminating the junction potential and in the case of non-saline soils the pH is independent of dilution.

Regarding saline soils, the pH values will depend, even in a diluted calcium-chloride solution, on the initial amount of salts. In the case of soda-saline and alkaline soils, the use of the $CaCl_2$ solution involves such reactions as: precipitation of carbonates, sodium-calcium ion exchanges and changes in the solubility of salts causing unpredictable changes in pH values. It is true that, in a suspension or extracts prepared with water, the chemical properties are not the same as in the natural soil solution, but data can be obtained with good reproducibility if the same standardized method is used. Sensibility of the pH in water suspension to salt accumulation and leaching can be more advantageous than disadvantageous. The pH value measured in a soil-water suspension reflects the chemical properties of soils well, the unsaturation of the absorption complex, the presence of free alkali earth carbonates, alkali carbonates and the degree of sodium saturation.

2.2 Methods for the Characterization of Soil Salinity

One of the most important results of a soil survey before irrigation is the characterization of the salinity status of the soil. These soil salinity data serve as the basis upon which:

i. to establish the salt balance of soils to be irrigated;
ii. to prognosticate secondary salinization and/or alkalization;
iii. to decide the necessity, method and measure of soil amelioration;
iv. to develop a monitoring system for the irrigated land.

To fulfil these necessities salinity analyses must give data on:

a. the total soluble salt reserves in the soil layer effected by irrigation and amelioration;
b. the horizontal and vertical distribution of salts soluble in water;
c. the ionic composition of water soluble salts.

The soluble salt content of soils is usually low and the salts accumulate in the reverse sequence of their solubility because the poorly soluble salts (i.e. Ca and Mg bicarbonate, etc.) dominate in the soil solution in non-salt affected soils. Salt accumulation develops if the leaching of salts becomes restricted, or the layer is connected with mineralized groundwater, or saline water is used for irrigation. As the salt accumulation prevails over the leaching the absolute and relative quantities of salts with better solubility increase. It means that the vertical distribution of soluble salts and the changes in the ionic composition of salts, within a soil profile, reflect the dominant process (leaching or accumulation) in the soil.

The horizontal distribution of soluble salts is the cause of the changes in the effect of factors influencing the salt regime and salt balance in soils. The accumulation of salts effects the plant's water and nutrient uptake and the water's effect on the physical properties of the soil.

The degree of salinity is usually characterized either by the total salt content of soils, expressed in weight percentage, or by the concentration of the soil water extract expressed in the specific conductance of the extract. The determination of the ionic composition of the accumulated salts is always carried out from extracts prepared at different soil:water ratios.

In every case the soil samples are brought to the laboratory dried, ground and rewetted. The soil:water ratios during the preparation of the extract vary between 4:1 and 1:5, but they are always larger than the soil:water ratio in natural wet soils. The increase of the soil:water ratio not only dilutes the salt concentration in the li uid phase, but changes the solubility of salts, the ratio of alkali and alkali earth cations, the equilibrium between the exchangeable and dissolved cations, and it causes the hydrolysis of exchangeable sodium. Due to this reaction, it is very difficult to judge the concentration and composition of the soil solution on the basis of soil extract analyses.

From some points of view, it would be ideal to analyse the real soil solution. We have in fact methods to separate the liquid phase of natural soils and many data have been published on the chemical composition of the soil solution.

Salts with high solubility prevail in the soil solution. The concentration and ionic composition of the soil solution depends on the short term regime of the moisture and easily soluble salts. The great variability in the soil solution concentration and ionic composition makes it questionable to include the soil solution analyses in the soil survey methods without any further consideration of the evaluation of data.

For the analyses of soluble salts in soils, in praxis two methods are most frequently applied. They are: the method of saturation extract and that of 1:5 aqueous extract. In the case of the saturation extract, the soil:water ratio depends on the texture and swelling of soil samples. The total salt concentration is expressed by the electrical conductivity of the extract and the concentration of ions is given in meq/l. In the case of the 1:5 aqueous extract, the soil:water ratio is fixed and the total salt and ion content are given for 100 g of soil.

For the evaluation of salinity measured in saturation extracts, the limit values are based on electrical conductivity and measurement of the osmotic pressure and total ionic concentration. In the 1:5 aqueous extracts, the limit values are based on the total salt content, taking into account the ionic composition of soluble salts accumulated in soils. In some cases even the electrical conductivity and chloride concentration are used to establish limit values in the 1:5 aqueous extract.

If we express the total salt content determined in the saturation extract and in the same dimension in a 1:5 aqueous extract, the differences are not very high in saline soils, but they differ a lot in the case of soda-solonchak and solonetz soils. The differences can surpass not only the confidence limit of analytical analyses, but the deviations due to the heterogeneity of salt distribution in the soil.

The determination of the total salt content can be carried out by measuring the electrical conductivity of the saturated soil paste. The total salt content is expressed in g/100 g soil. The calibration takes into account the texture of soils and the ionic composition of soluble salts. The method is a semi-quantitative one, because:

- the cation composition of soluble salts is not taken into account,
- the ratio of anions varies with the changes of total soluble salt content,
- the exchangeable sodium is partly measured as soluble salt.

This method is simple and rapid and can be included in the monitoring system, if we have data of soil texture and ionic composition. The ionic composition in the extract varies with the soil:water ratio. The chlorides having high solubility are usually completely dissolved even in the extracts prepared with a close soil: water ratio. With an increase of the soil:water ratio, the concentration of chloride decreases, but the quantity of the total dissolved salts remains the same. In saline soils, $NaCl$ and $MgCl_2$ are the most common and widespread components.

In the case of chloride salinization both the saturation extract and the 1:5 aqueous extract give reliable data. The solubility of sulphates associated with different cations varies greatly. $MgSO_4$ and Na_2SO_4 have high solubility; they very often accumulate in the soils together with other easily soluble salts. Due to their high solubility, they are dissolved in an extract prepared with a narrow soil:water ratio. With the increase of the soil:water ratio, their concentration decreases within the extract, but the total quantity of dissolved salts remains the same. The solubility of $CaSO_4$ is relatively low and it accumulates together with chlorides and other sulphates. The $CaSO_4$ content of soils only partly dissolves in the saturation extract and in the 1:5 aqueous extract as well. The dissolution of $CaSO_4$ in saline soils changes with an increase in the soil:water ratio. The changes in $CaSO_4$ dissolution depend on the total ionic concentration and ionic composition of the extract.

In the case of sulphate and chloride-sulphate salinization either a saturation or 1:5 aqueous extract analyses will give satisfactory results, if the soil is strongly salinized or solonchak and it has a light texture. If the soil is slightly or medium saline the saturation extract is preferable. In every case the total $CaSO_4$ content has to be analysed separately.

Among the carbonates commonly appearing in soils, only sodium-carbonate has good solubility. The sodium-carbonate dissolves with alkaline hydrolysis and equilibrates with the carbon-dioxide dissolved in water, forming carbonate and bicarbonate ions. Due to the alkaline hydrolysis a solution containing sodium-carbonate is always alkaline. The pH value and the ratio of carbonate and bicarbonate ion concentrations depend on the conditions of the preparation of the soil extract. The other soil carbonates, such as calcium-carbonate and magnesium-carbonate have low solubility. Their dissolution depends on the total concentration and ionic composition of salts in the solution. In case of carbonate-salinization, the sodium ions dominate in the solution up to 90-95%. The prevalence of sodium ions in the solution and the sodium saturation of the soil depend on the concentration of the solution. With an increase in the sodium-carbonate concentration, the sodium saturation can be as high as 80-90%. In the case of soda-salinization, the saturation extract analyses give better results than the extracts with a high water:soil ratio, because the hydrolysis of exchangeable sodium increases with an increase in the water:soil ratio. The determination of Ca and Mg ion concentrations is usually not necessary in the saturation extract and if we do determine them, we have to take into account the high error possibility of the analyses.

2.3 Cation Exchange Characteristics of Soils

The cation exchange characteristics of the soil are determined by the cation exchange capacity (CEC) and the ratio of different exchangeable cations. The CEC is always related to the texture, organic matter contents and clay mineral composition of soils. CEC values refer to the water and cation retention. The exchange complex is saturated or may have a low value of exchange acidity. If the exchange acidity is high, the soil needs a lime dressing. The increased values of sodium saturation refer to the alkalinity (sodicity) of soils.

The determination of CEC is carried out in two steps: first, the soil is saturated with the selected cation, and in the second step, the amount of saturating cations is determined. The measured values of cation exchange capacities depend on:

- the completeness of saturation,
- the pH values of the saturating solution,
- the method of determination of the saturating cation.

A wide range of cations is used for saturation; among them the most usual are: NH_4^+, Na^+, Ba^{2+} and Ca^{2+} ions. The suggested concentration and pH values of saturating solutions and the ratio of soil: solution varies as well. The most common way to determine the saturating cation is to displace it with other selected cations. Potassium, ammonium and calcium ions are used most frequently for replacements. The following table gives a synthesis of the saturating and displacing ions and the characteristics of the solutions.

Process	Ion	Salt	Concentration of solution	pH of solution
Saturation	NH_4^+	NH_4- acetate	N	7.0
Displacement	K^+	KCl	10%	2.5
Saturation	Na^+	Na- acetate	N	8.2
Displacement	NH_4^+	NH_4- acetate	N	7.0
Saturation	Ba^{2+}	$BaCl_2$	0.2 N	6.5
Displacement	H^+	HCl	N	
Saturation	Ba^{2+}	$BaCl_2$	0.5 N	8.0
Displacement	NH_4^+	NH_4Cl	N	8.0
Saturation	Ba^{2+}	$BaCl_2$	0.1 N	8.1
Displacement	Ca^{2+}	$CaCl_2$	0.1 N	7.0

Recently, the determination of the saturation cation without replacement has been proposed by isotope-dilution, ion activity analyses, etc. These methods have the advantage of avoiding another chemical treatment after the saturation.

The determination of exchangeable cations is usually carried out by their displacement with cations not common in soils; ammonium and barium ions are the most frequently proposed replacements. The extract prepared during the saturation in CEC analyses contains the exchangeable cations. If we use a saturation solution with cations which are not common in soils, the extract is suitable for analyses of exchangeable cations.

The determination of exchangeable calcium and sodium can be carried out by the isotope-dilution method as well, which differs in principle from the "alien cation" method as it avoids the replacement of the exchangeable cations by the "alien cation" and is based on the isotope-dilution analyses in an equilibrium soil: water suspension.

All the methods for analyses of cation exchange characteristics are standardized. Only the data determined by the same method can be compared which means that during survey and monitoring the same laboratory methods must be used. A different method can be applied only after testing the comparability of the methods and if the differences between the values determined by different methods are less than the integrated error of the sampling procedure and analyses.

The accuracy of the determination of exchangeable cations and CEC depend on the soil properties as well.

a. The measured CEC values are too low if:

   i. the saturating ion does not replace the exchangeable cation completely. In calcareous soils for example, saturation with ammonium-ions at neutral pH of saturating solution is usually not complete;

   ii. the saturating ion tends to become fixed; this can occur in soils containing vermiculite with ammonium or potassium saturation;

   iii. the replacing ion does not displace the saturating ion, which can occur if the valency of the replacing cation is lower than the saturating ion.

b. The measured CEC values are too high, if:

   i. the saturating ion is absorbed in the form of metal hydroxide cations;

   ii. the saturating cation is held in exchangeable form by the solid carbonates of soils.

The determination of exchangeable cations is disturbed by the presence of calcium-carbonate, gypsum and soluble salts. Extracts prepared by the saturation of soil samples with salt solution contain the exchangeable cations and cations dissolved by the salt solution. In the case of sodium ions, the exchangeable and soluble sodium are determined together in the extract; for calcium ions, we determine the exchangeable calcium and the dissolved part of calcium-carbonate and gypsum, and for magnesium ions, the measured magnesium concentration is composed from exchangeable magnesium and from the dissolution of dolomite and magnesium-sulphate.

We do not have a proper method to separate the different forms of mobile cations into exchangeable and soluble forms. In special cases, we can decrease the dissolution of poorly soluble salts by increasing the pH of the saturating solution which, for example, avoids the dissolution of calcium-carbonate in calcareous soils. We can correct the data in the case of easily soluble salts by the subtraction of values determined in the saturation extract. For example: with sodium ions, the difference between mobile and soluble sodium is regarded as a value of exchangeable sodium. This is however, only an approximate value of the exchangeable sodium influenced by several "inexactnesses" in the preparation of the saturation extract and the determination of sodium from the saturation and salt solution extracts. The measured quantity of exchangeable sodium can be too low if exchangeable sodium hydrolysis occurs during the preparation of the saturation extract. This phenomena plays an important role in the case of sodic soils with a low degree of salinization. The measured amount of exchangeable sodium is erroneous if the soil is strongly saline and the ratio between the soluble and exchangeable sodium is too large.

Under different conditions, the following methods can be suitable for the determination of exchangeable cations and CEC:

1) 0.1 mol $BaCl_2$ solution at 8.1 pH for the determination of exchangeable cations of:
   - non-calcareous, non-saline soils,
   - calcareous-non-saline soils,
   - saline soils by subtraction of soluble cations.

   The method cannot be applied for gypsiferous soils.

   After Ba-saturation, the CEC can be determined by calcium replacement in all soils except the gypsiferous.

2) Normal ammonium-acetate solution at pH 7, for the determination of exchangeable cations of:
   - non-calcareous, non-saline soils,
   - non-calcareous, non-gypsiferous saline soils, by subtraction of soluble cations.

   After sodium saturation, at pH 8.5, the ammonium-acetate solution can be used for CEC determination in calcareous, gypsiferous and/or saline soils.

3) Isotope dilution method: in all cases it can be used to determine the CEC, exchangeable sodium and calcium.

The cation exchange properties and salinization of the soil must be determined in such density as is suitable for the evaluation of horizontal and vertical distribution of mobile compounds in the surveyed area.

3. ANALYSES FOR THE DETERMINATION OF SOIL FERTILITY

The treatment of soil fertility analyses is not included within the scope of this paper because, although very important for the planning of irrigation schemes and soil utilization, this group of analyses is only of indirect and secondary significance in relation to the prognosis and monitoring of soil salinity, alkalinity and waterlogging.

Paper 12

b. MEASURING, MAPPING AND MONITORING FIELD SALINITY AND WATER TABLE DEPTHS WITH SOIL RESISTANCE MEASUREMENTS[1/]

by

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1. INTRODUCTION

The proper management and treatment of saline soils requires knowledge of the concentration and distribution of soluble salts in the soil. The proper management of irrigation projects, furthermore, requires information on the time trends in soil salinity status and water table depths. Salt balance evaluations of irrigation regions have been (and are being) employed to ascertain the adequacy of leaching to avoid adverse salinity buildup (Bower et al., 1969; Smith, 1966; Wilcox and Resch, 1963). For both theoretical and practical reasons, salt balance evaluations are inadequate for their intended purpose. Such an evaluation is not a suitable criterion upon which to base the adequacy of leaching and salinity control of large irrigation basins, much less of individual fields or parts of them (Rhoades, 1974; Kaddah and Rhoades, in prep.). To date, the only reliable diagnosis of salinity has required the analysis of soil samples brought into the laboratory, although less precise measurements may be made in the field with portable field kits (Bower, 1963; USSL Staff, 1954). In either case the many samples required demand much time and effort (Sayegh et al., 1958). Furthermore, to evaluate the effects of farm management practices and assess time trends, soil salinity levels must be monitored periodically. The extensive time and labour requirements for sampling adequately with conventional procedures tend to reach the point of impracticality. Besides salinity, water table trends should be monitored in irrigation projects.

The four electrode soil conductivity technique can be used to great advantage for these needs in diagnosing and monitoring (Rhoades and Ingvalson, 1971; Rhoades, 1974; Kaddah and Rhoades, in prep.). The method measures soil salinity and depth to water table without requiring soil sampling, laboratory analysis, or numerous expensive in situ devices. It is rapid, simple, inexpensive and practical.

1/ Contribution from the Agricultural Research Service, USDA, U.S. Salinity Laboratory, Riverside, California.

The basic concept and principles of this method have been previously described (Rhoades and Ingvalson, 1971). Since then, the method has been used for detecting the encroachment of saline water bodies into soils (Halvorson and Rhoades, 1974), for mapping saline soils and subsurface materials (Halvorson and Rhoades, in prep.), for monitoring reclamation of saline soils (Kaddah, personal communication), and for monitoring salinity in irrigation projects (work in progress). In addition, new techniques have been developed for obtaining the necessary calibrations (Rhoades et al., in prep. (a); Rhoades and van Schilfgaarde, in prep.). A new version of the equipment to determine precisely the distribution with depth of soil electrical conductivity, EC_x, (Rhoades and van Schilfgaarde, in prep.), and the theory is developed and verified explaining the effects of soil water salt concentration, water content and soil properties on soil electrical conductivity (Rhoades et al., in prep. (b)).

This paper discusses the principles and application of the technique for measuring, mapping and monitoring soil salinity and sodicity, detecting a shallow water table, and estimating the leaching fraction.

2. PRINCIPLES: EFFECTS OF VARIATIONS IN SALT CONCENTRATION, WATER CONTENT AND SOIL PROPERTIES ON SOIL ELECTRICAL CONDUCTIVITY

Electrical conduction in saline soils is primarily electrolytic. Most soil minerals are insulators and conduction, therefore, is primarily through the interstitial water which contains dissolved electrolytes. In addition, soils may conduct current via the exchangeable cations that reside on the surfaces of charged soil minerals, which are electrically mobile to various extents (Cremers and Laudelout, 1966; Shainberg and Kemper, 1966; van Olphen, 1957). The contribution of exchangeable cations to electrical conduction is relatively small in saline soils because of the greater abundance and mobility of soluble electrolytes than exchangeable cations (Rhoades et al., in prep. (b); Shea and Luthin, 1961). However, in sodic soils (high in exchangeable sodium and low in electrolyte concentration) the relative magnitude of surface conduction will increase. Hence, the electrical conductivity of a saline soil (EC_a) will depend primarily on the electrical conductivity of the liquid (EC_w), on the volumetric water content θ, on the tortuosity (T), and on the extent of surface conductance (EC_s) (Rhoades et al., in prep. (b)), i.e., for a given temperature,

$$EC_a = f(EC_w, \theta, T, EC_s) \qquad [1]$$

The effects of tortuosity and surface conductance are related to soil type. Hence for a given soil type

$$EC_a = f(EC_w, \theta)_{T,\ EC_s} \qquad [2]$$

and if EC_a determinations are made at reference or calibration water contents

$$EC_a = f(EC_w)_{\theta, T, EC_s}. \qquad [3]$$

Since for any given soil, the electrical conductivity of a saturation extract (EC_e) is related to EC_w,

$$EC_a = f(EC_e)_{\theta, T, EC_s}. \qquad [4]$$

Based on Eq [4], Rhoades and Ingvalson (1971) recommended, in irrigated lands, making four-electrode conductivity measurements just after an irrigation. At this time the water content (field capacity) is reasonably reproducible (Wilcox, 1965). Under dryland conditions, early spring measurements take advantage of relatively uniform conditions when the soil is near field capacity (Halvorson and Rhoades, 1974). Normal variations in water content under these conditions will not interfere with salinity diagnosis. Calibrations between EC_a and EC_e have been determined for many soils under conditions of "field capacity" water content and used to diagnose soil salinity. Figure 1 is an example of such a calibration.

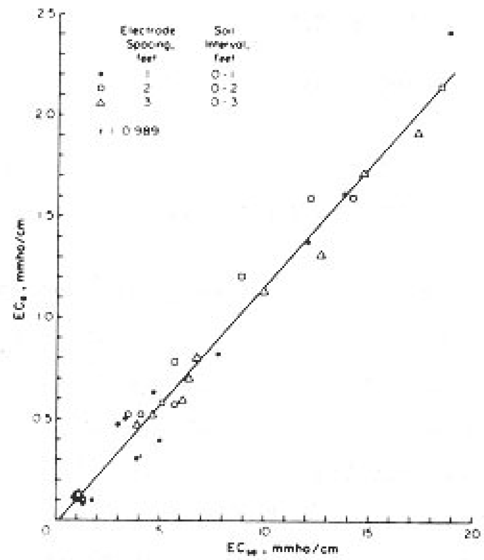
While the above technique of taking soil resistance measurements under conditions of reference water content is the simplest and most practical for general diagnosis, mapping and monitoring purposes, soil salinity may be assessed under conditions of any arbitrary water content if the water content is known and certain soil parameters have been established. Equation [5] describes the interplay of salt concentration, water content and soil properties on soil electrical conductivity (Rhoades *et al*., in prep. (b)):

$$EC_a = (EC_w \theta)[T] + EC_s \qquad [5]$$

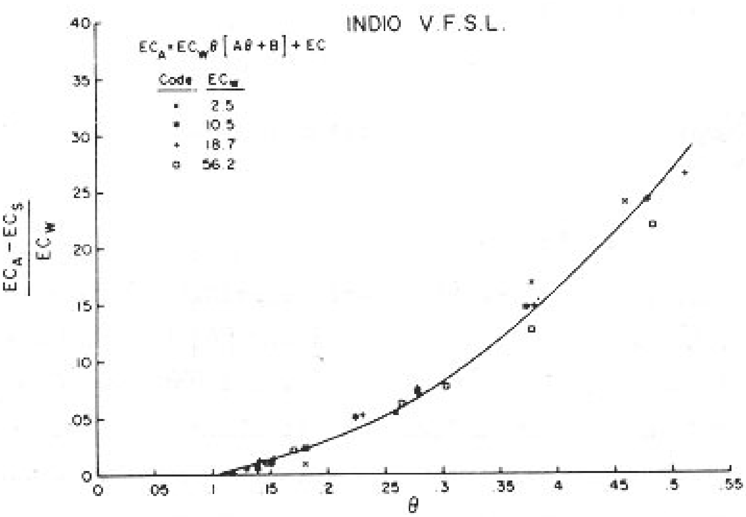
where [T] is an empirically determined "transmission" coefficient dependent on θ as

$$T = a\theta + b \qquad [6]$$

with constants a and b determined by linear regression. Figure 2 shows $EC_a - EC_w$, θ, T, and EC_s relations calculated with Eqs [5] and [6] (solid line) and experimentally determined values (data points) for Indio v.f.s.l. soil where EC_w ranged from 2.5 to 56.2 mmho/cm at 25°C and θ ranged from 0.12 to about 0.5. Table 1 shows values of a, b and EC_s for four soils ranging in texture from f.s.l. to c.l. These values are related to texture and sufficiently accurate estimates for these soil parameters may be estimated on the basis of texture. Given such values and where θ is known or measured, actual *in situ* soil water electrical conductivity, EC_w, can be determined from four-electrode soil conductivity measurements using Eq [5]. Thus, not only soil salinity but also *in situ* soil water EC_w can be determined from EC_a measurements at arbitrary water contents.



<u>Fig. 1</u> RELATIONSHIP BETWEEN SOIL CONDUCTIVITY AS DETERMINED WITH INTER-ELECTRODE SPACING OF 30, 60 and 90 cm AND SOIL SALINITY EXPRESSED AS EC_e FOR DEPTH INTERVALS 0 TO 30, 0 TO 60, AND 0 TO 90 cm, RESPECTIVELY (AFTER RHOADES AND INGVALSON, 1971)



<u>Fig. 2</u> RELATIONSHIP BETWEEN EC_a AND EC_w, θ, T AND EC_s FOR INDIO SOIL (AFTER RHOADES <u>et</u> <u>al</u>., IN PREP. (b))

Table 1 SURFACE CONDUCTIVITIES, TRANSMISSION COEFFICIENT PARAMETERS AND THRESHOLD WATER CONTENTS OF SOILS 1/

Soil type	EC_s 2/	A 3/	B 3/	θ_t 4/	r 5/
	mmho/cm				
Pachappa f.s.l.	.18	1.382	-0.093	.07	0.96
Indio v.f.s.l.	.25	1.287	-0.116	.09	0.98
Waukena l.	.40	1.403	-0.064	.05	0.97
Domino c.l.	.45	2.134	-0.245	.12	0.92

1/ Rhoades *et al.* (in prep. (b))

2/ EC_s = surface conductivity

3/ Transmission coefficient = [$A\theta + B$]; A = slope, B = intercept of $A\theta + B = G(\theta)$ plots

4/ θ_t = threshold water content = $-\frac{B}{A}$

5/ Linear correlation coefficient between the transmission coefficient and θ

Equation [5] shows that EC_a is a measure of the product of EC_w and θ, i.e., total solute per unit volume of soil, as modified by soil tortuosity and viscosity effects, plus a small contribution from surface conductance. Upon cessation of drainage after irrigation, θ is decreased by crop water uptake, but most of the salts are left behind in the soil solution. Except for the effects of salt precipitation, the product $(EC_w)_i(\theta)_i$, where i is the initial condition (after irrigation), would be unchanged at some later time, f, i.e., $(EC_w)_i(\theta)_i = (EC_w)_f(\theta)_f$. For the first few days after the cessation of drainage, $(EC_w)(\theta)$ should be reasonably constant, i.e., little salt should precipitate. Hence, changes in EC_a over this time should be primarily related to $T = f(\Delta\theta)$. From the data given in Table 1, for the case of Indio v.f.s.l., a 5% variation in θ from the reference "field capacity" water content will produce about a 6% change in EC_a. Thus, since the increase in salt concentration compensates for the decrease in water content, normally expected small variations in "field capacity" water content that would be encountered at different times of measurement (during the year) will not cause serious errors in salinity assessment.

Effects of textural stratification in the soil profile and temperature on EC_a interpretations are discussed later.

3. FOUR-ELECTRODE EQUIPMENT

The basic equipment needs for four-electrode soil conductivity determinations are but few. A combination electric current source and resistance meter, four metal electrodes, connecting wires, a measuring tape and a thermometer are all that is needed. Figure 3 shows typical basic equipment. For detailed or extensive survey studies, other pieces of equipment may be used to make the work more convenient, like a device for storing and retrieving the wire, a tripod and stand so that the meter and wire storage and retrieval system can be used at near waist height, a "fixed-array" rig in which the electrodes are fixed at a constant inter-electrode spacing for rapid traverse work or mapping, a pocket-sized portable calculator (especially convenient are the small, portable programmable calculators), and suitable graph paper.

Several suppliers produce combination current source-resistance meters suitable for soil salinity appraisal of either hand-cranked generator or battery-operated types which range in cost from about $300 to $1200 depending on accuracy and convenience features. The unit should have a range from 0.01 to 100 ohms, although for some uses it is helpful to be able to read resistance of less than 0.01 ohms.

Electrodes may be made of stainless steel, copper, brass, or almost any noncorrosive conductive metal. Electrode size is not critical, except that it must be small enough to support its weight and maintain firm contact with the soil when inserted to a 4 cm depth or less. Electrodes with dimensions of 1 to 1.3 x 45 cm are convenient for most purposes, although for very shallow readings, smaller electrodes are preferred.

Any flexible, well insulated, multistranded wire is suitable. A good size for general salinity appraisal is 1 to 2 mm wire.

For detailed determinations of soil electrical conductivity by depth or within soil depth intervals, it is convenient to have the four electrodes mounted on a single probe that can be inserted into the soil to different depths. A device developed for this purpose and associated auxiliary equipment are illustrated in Fig. 4. Figure 5 demonstrates the makeup of the soil "EC-probe". Four annular rings are placed between insulators to form a probe which is slightly tapered so that it can be inserted into the hole made by an Oakfield soil sampler. After the hole is made, the EC-probe is inserted to the depth(s) of interest. Wires from the four annular electrodes are led through the centre of the probe shaft and connected to the electrical meter. The manner of use of this equipment is discussed in Section 5.3. A more refined version of the EC-probe is now commercially available.

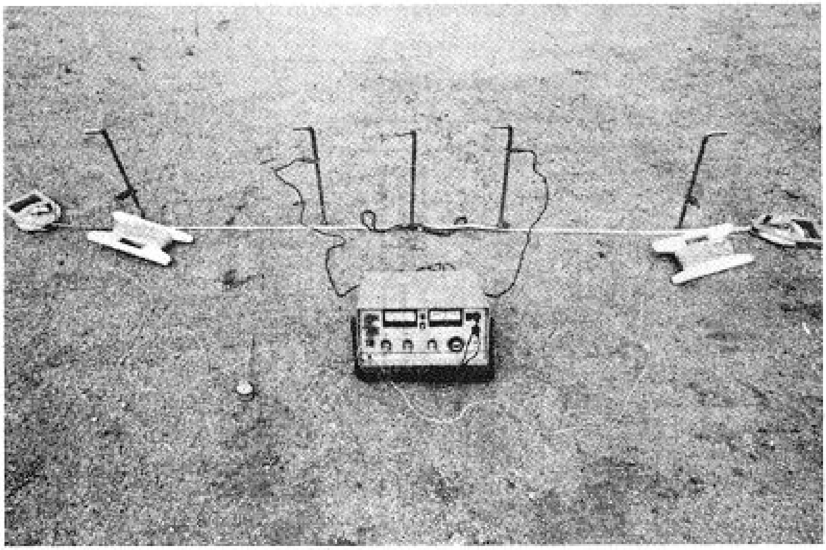


Fig. 3 FOUR-ELECTRODE EQUIPMENT SET UP IN THE WENNER ARRAY

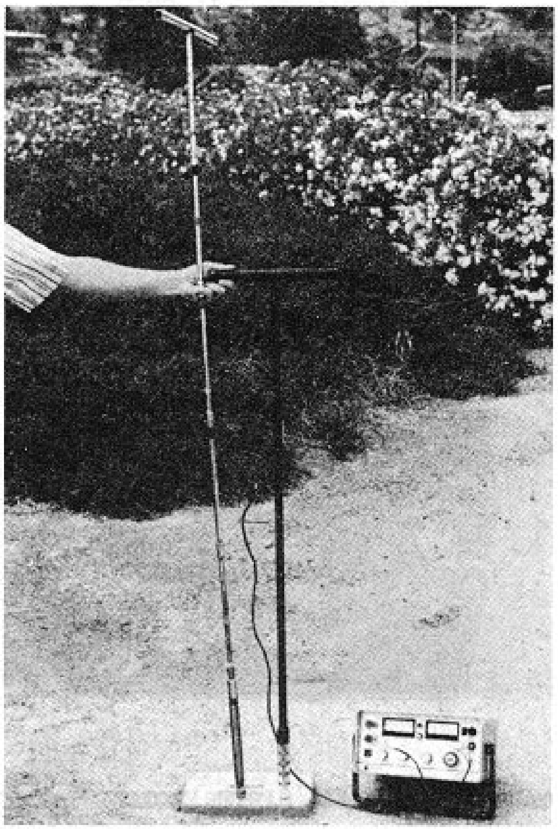


Fig. 4 SOIL EC_a-PROBE, OAKFIELD SOIL SAMPLER, AND RESISTIVITY METER

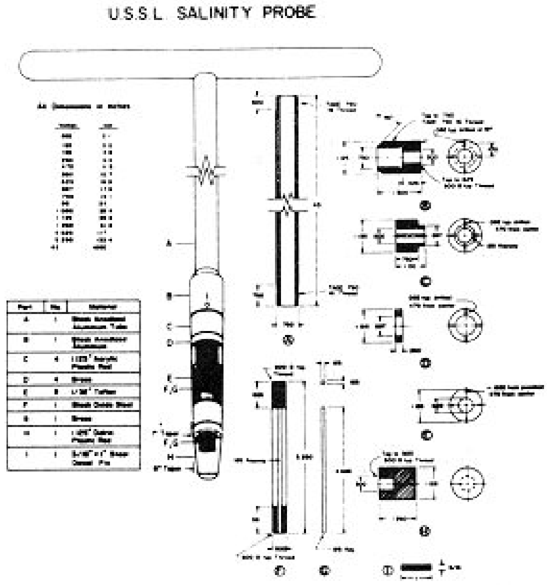


Fig. 5 SCHEMATIC OF SOIL EC_a-PROBE (AFTER RHOADES AND VAN SCHILFGAARDE, IN PREP.)

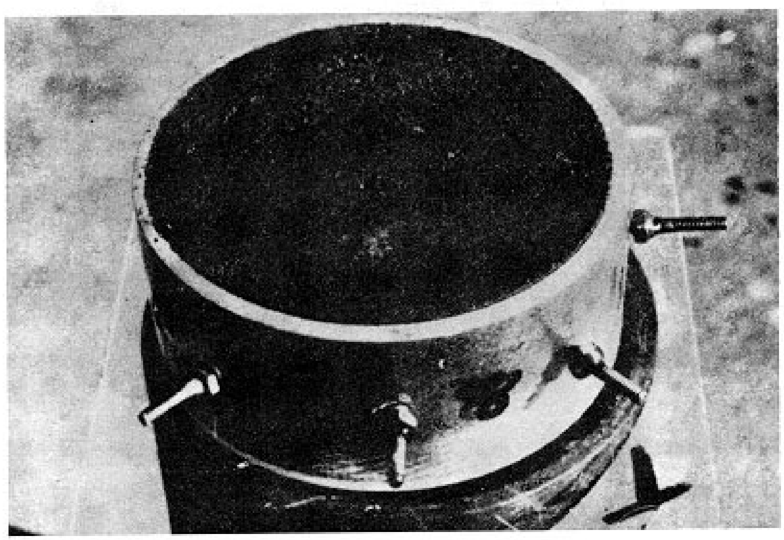


Fig. 6 FOUR-ELECTRODE CELL (AFTER RHOADES et al., IN PREP.(a))

Special "four-electrode cells" can be used advantageously for purposes of calibration and certain laboratory studies. Such cells are illustrated in Fig. 6. This equipment and its use is discussed in Section 5.

4. METHODOLOGY

In the conventional determination of four-electrode soil conductivity, four electrodes are placed in a straight line with equal distances (a) between them. This array of electrodes is called the Wenner configuration. The electrical resistance across the inner pair is measured while a constant current is passed between the outer pair (Fig. 7). The apparent bulk soil conductivity is calculated from Eq [7]:

$$EC_a = \frac{1000}{2\pi a} \frac{f_t}{R_t}, \qquad [7]$$

When R_t is measured resistance (in ohms) for an interelectrode spacing of "a" (in cm) at temperature t, and f_t is a factor to adjust the reading to a reference temperature of 25°C (for such factors, see Table 2 after USSL Staff, 1954); EC_a is given in mmho/cm at 25°C.

Information about EC within discrete soil depth intervals can be obtained by either of two different methods. Four-probe soil electrical conductivities of discrete soil depth intervals, EC_x, can be calculated from EC_a values obtained with successively increasing interelectrode spacings using Eq [8] after Halvorson and Rhoades (1974):

$$EC_{(a_i - a_{i-1})} = [(EC_{a_i} \cdot a_i) - (EC_{a_{i-1}} \cdot a_{i-1})]/(a_i - a_{i-1}) \qquad [8]$$

where a_i represents the depth of sampling and a_{i-1} represents the earlier depth of sampling. This equation is based on the assumptions that the depth to which conductivity is measured is equal to the interelectrode spacing and the stack of soil electrical resistances of a sequence of soil layers is assumed to behave like resistors in parallel (Fig. 8) (Barnes, 1954).

Where more precise information on the depth distribution of soil salinity is required, the soil electrical conductivity probe developed by Rhoades and van Schilfgaarde (in prep.) should be used. The soil resistance is measured in a manner analogous to that used for the conventional Wenner array; however, EC_x is now calculated as

$$EC_x = \frac{k f_t}{R_t} \qquad [9]$$

where k is an empirically determined geometry constant for the probe. This probe has dimensions so that when centred at 15, 45, 75, 105 cm, etc., EC_x is obtained within the 0 to 30, 30 to 60, 60 to 90, 90 to 120 cm, etc., soil intervals.

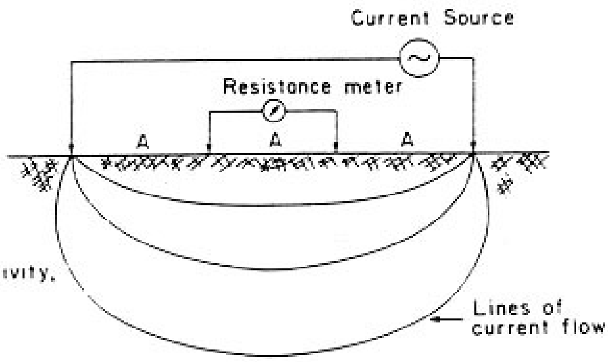


Fig. 7 SCHEMATIC OF FOUR-ELECTRODE SET UP IN WENNER ARRAY AND LINES OF CURRENT FLOW

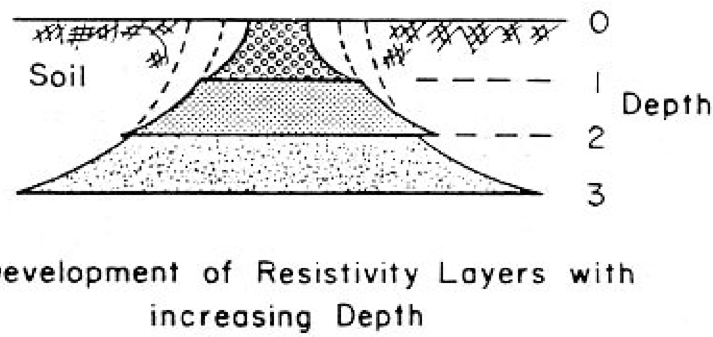


Fig. 8 MODEL OF THE SUCCESSION OF LAYERS DEVELOPED WITH INCREASING A SPACING AND CALCULATED AS EC_x WITH Eq [8]

Table 2 TEMPERATURE FACTORS (f_t) FOR CORRECTING RESISTANCE AND CONDUCTIVITY DATA TO THE STANDARD TEMPERATURE OF 25° C 1/

C°	F°	f_t
4.0	39.2	1.660
6.0	42.8	1.569
8.0	46.4	1.488
10.0	50.0	1.411
12.0	53.6	1.341
14.0	57.2	1.277
16.0	60.8	1.218
18.0	64.4	1.163
20.0	68.0	1.112
22.0	71.6	1.064
24.0	75.2	1.020
26.0	78.8	.979
28.0	82.4	.943
30.0	86.0	.907
32.0	89.6	.873
34.0	93.2	.843
36.0	96.8	.815
38.0	100.2	.788
40.0	104.0	.763

1/ After Table 15, p. 90, U.S. Salinity Laboratory Staff, 1954.

5. APPLICATIONS

5.1 Measuring Bulk Soil Salinity

To relate an EC_a reading to salinity, it must be calibrated under conditions of reference water content and soil temperature (25°C). A typical relationship is illustrated in Fig. 1 for a f.s.l. soil type. Once such calibrations have been obtained, soil salinity can readily be determined for such soils without the further need of soil sampling. As Fig. 1 shows, EC_a and EC_e are highly, linearly correlated so that results are quite reliable. The volume of soil measured in a single EC_a determination is about πa^3. This attribute is very valuable where representative values of salinity of typically heterogeneous soil are needed without excessive effort and expenditure of time and money. Another valuable attribute of the four-electrode method is that to make a single soil resistance measurement with this technique and equipment requires only a few tens of seconds.

It is often desirable to make resistance measurements within deeper bodies of soil. This can be accomplished by varying the interelectrode spacings. Figure 9 illustrates how expanding the interelectrode spacing increases the depth (and volume) of measurement. The effective depth of measurement of soil EC_a is approximately equal to the interelectrode spacing. The plots in Fig. 1 of EC_a (a = 30 cm) - average EC_e (0 to 30 cm), EC_a (a = 60 cm) - average EC_e (0 to 60 cm), and EC_a (a = 90 cm) - average EC_e (0 to 90 cm) data points all fall on essentially the same line. Thus, with a single soil resistance measurement, the average soil salinity within the whole root zone can be determined.

5.2 Measuring Soil Salinity within Depth Intervals

While a measurement of average soil salinity to a given depth in the soil is valuable, there are instances where information of salinity distribution with depth or within discrete depth intervals is desirable.

Data demonstrating the high correlation between interval soil salinities predicted with Eq [8] and those determined from soil analyses are presented in Fig. 10. It is apparent from these data that soil salinity by depth intervals within the root zone can be assessed with this method in soils without marked textural horizonations with sufficient accuracy for practical salinity appraisal purposes without taking soil samples or making laboratory analyses. This assessment cannot be applied to soils with marked textural horizonations; for such cases the EC-probe is recommended with individual calibration relations used for the different soil strata.

Data of soil EC by depth within the root zone of a citrus tree are given in Fig. 11 to illustrate the utility of the soil EC-probe. While this device can be used to determine soil salinity distributions more accurately than with the surface positioned four-electrode equipment, it has some of the same limitations as soil samples and _in situ_ salinity sensors (Oster and Ingvalson, 1967), i.e., soil must be removed with a soil sampling tube (although no analyses are required); and it responds to a relatively small localized region within the soil. For this reason, while this technique can be used to diagnose soil salinity by taking several readings in the soil landscape to obtain a representative value, EC_a readings determined with the surface positioned Wenner array seem to provide a better index of bulk soil salinity. However, where more precise information of soil salinity is desired, either for depth interval, in soil profiles with marked discontinuities in soil texture, or localized soil regions, the soil EC-probe is recommended. Thus the two techniques may be used together to great advantage. The EC-probe can also be used in place of an _in situ_ sensor if water content information is available.

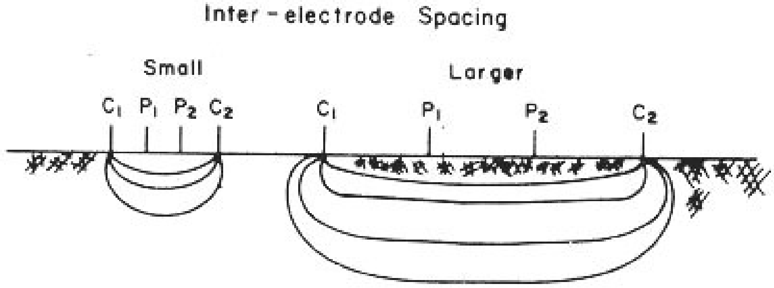


Fig. 9 SCHEMATIC SHOWING INCREASED DEPTH AND VOLUME OF EC_a MEASUREMENT WITH INCREASED INTERELECTRODE SPACING

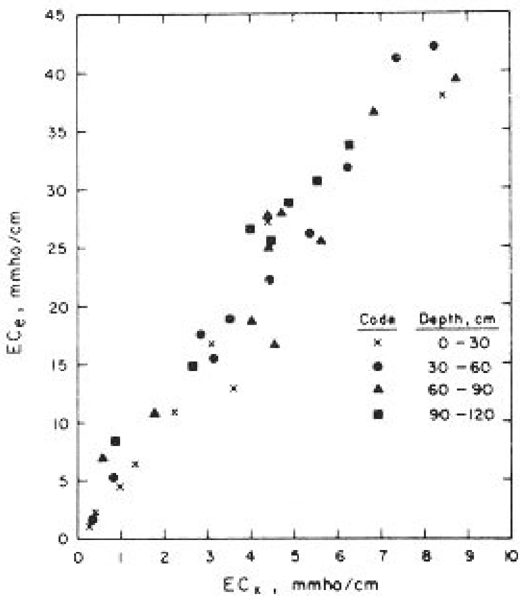


Fig. 10 RELATION BETWEEN EC_x, AS CALCULATED WITH Eq [8], AND DETERMINED EC_e VALUES FOR 0-30, 30-60, 60-90, AND 90-120 cm INTERVALS OF SOIL DEPTH

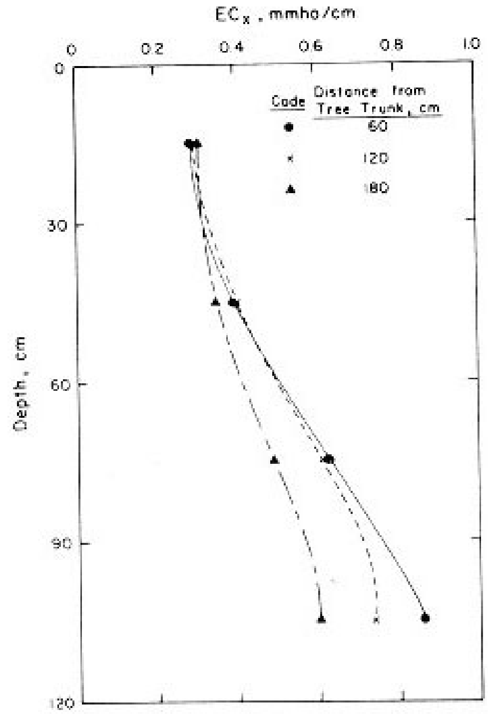


Fig. 11 DISTRIBUTION OF EC_x VALUES UNDER A TRICKLE-IRRIGATED CITRUS TREE WITH RADIAL DISTANCE FROM THE TRUNK AND DEPTH BELOW THE GROUND SURFACE

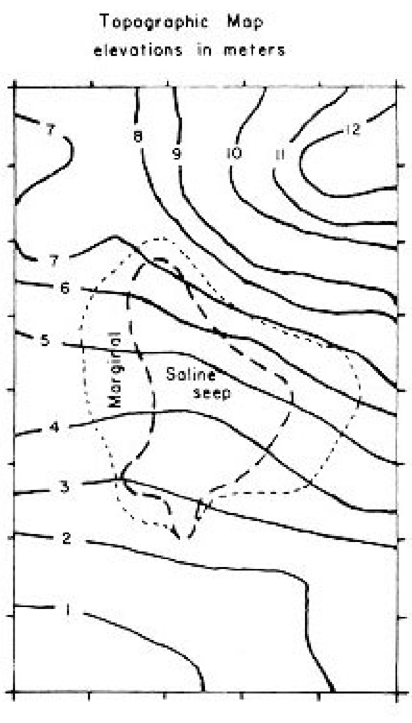


Fig. 12 MAP SHOWING SURFACE TOPOGRAPHY AND LOCATION OF SALINE SEEP, AND MARGINALLY AND UNAFFECTED ALFALFA CROP SURROUNDING IT (AFTER HALVORSON AND RHOADES, IN PREP.)

5.3 <u>Mapping Soil Salinity</u>

Both near surface and subsurface salinity can be mapped using the methods described above in Sections 5.1 and 5.2, respectively. Determinations are made at successive sites along a traverse or at grid stations; the data are displayed as a map of isolines of soil resistance, EC_a, EC_x, or EC_e, depending on purpose and preference. Figures 12 through 15 illustrate the utility of the technique. Salinity was mapped in and about a saline seep in eastern Montana, of a 153 x 244 m area (of rolling foothill topography), gridded at 30.5 m intervals (Halvorson and Rhoades, in prep.). Figure 12 shows the location of the saline seep and marginally affected area around it, and the corresponding surface topography. The area labelled as saline seep had almost no plant growth, while that labelled marginal showed visual signs of reduced alfalfa (<u>Medicago sativa</u>) growth and poor stand. The rest of the area had a good stand of alfalfa. Figures 13, 14 and 15 show isolines of EC_x for the 0 to 30, 30 to 60 and 60 to 90 cm soil depth intervals, respectively, calculated with Eq [8] from EC_a measurement with interelectrode spacings of 30, 60 and 90 cm, respectively. These EC_x maps clearly differentiated the soil salinity in this soil body (as verified by soil sampling and laboratory analyses) both laterally and vertically. The soil body mapped with the 0 to 30 cm depth EC_x isoline, corresponding to $>$ 1.5 mmho/cm, corresponded quite closely to the saline seep boundary, while the body of soil mapped within the 0.5 to 1.5 mmho EC_x isolines corresponded to the marginally affected land. The land mapped with EC_x of $<$ 0.5 mmho/cm corresponded to the area with good alfalfa growth. Figures 14 and 15 illustrate the use of this technique to map subsurface salinity distributions in soil bodies. The increased volume of saline soil with depth and its variation with respect to topographic position is clearly illustrated. The subsurface dimensions of the salt affected soil body, which was produced from the presence of shallow saline groundwater, were readily established with the four-electrode soil conductivity mapping technique.

While in this example successive EC_a determinations were made at each grid location for different interelectrode spacings, sufficient information on soil salinity levels within the root zone depth could have been obtained from single determinations of EC_a by making a traverse with one interelectrode spacing. Figure 16 is such a map which could be made very quickly by one operator using a "fixed-array" setup like that illustrated in Fig. 17. The advantage of the "fixed-array" setup is that one does not have to measure out the electrode positions, wind in and out the electric cable, or connect and disconnect the wiring at each location.

5.4 <u>Detecting a Shallow Saline Water Table</u>

The four-electrode technique may be used for detecting the presence of a saline shallow water table as well as for measuring soil salinity. For this use,

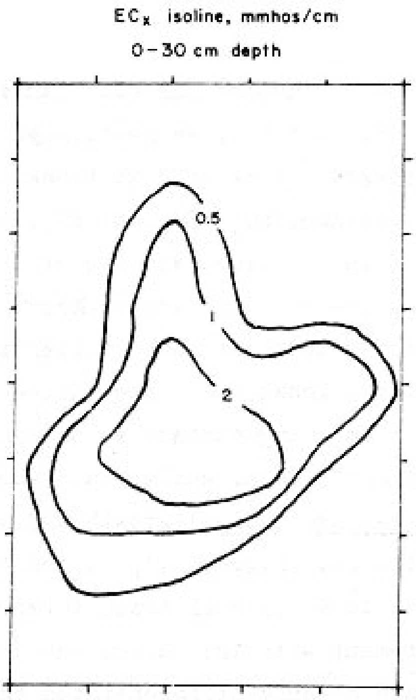


Fig. 13 MAP OF EC_x ISOLINES FOR THE SOIL DEPTH INTERVAL 0-30 cm (AFTER HALVORSON AND RHOADES, IN PREP.)

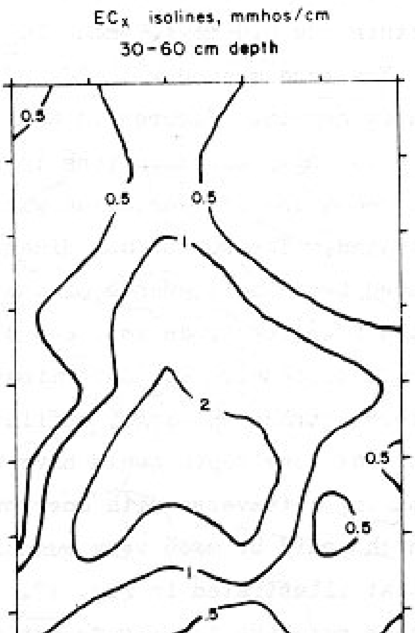


Fig. 14 MAP OF EC_x ISOLINES FOR THE SOIL DEPTH INTERVAL 30-60 cm (AFTER HALVORSON AND RHOADES, IN PREP.)

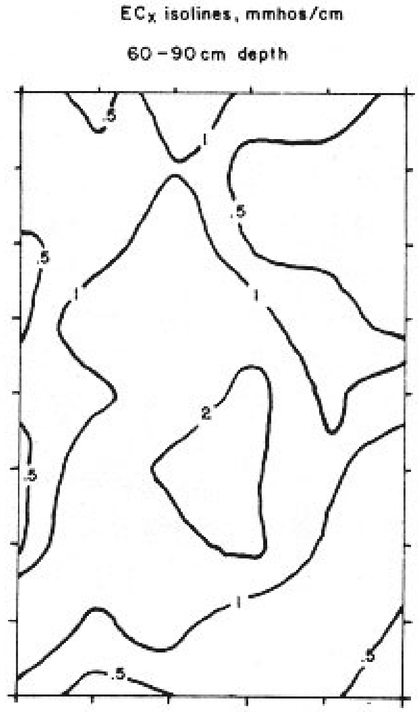


Fig. 15 MAP OF EC_x ISOLINES FOR THE SOIL DEPTH INTERVAL 60–90 cm (AFTER HALVORSON AND RHOADES, IN PREP.)

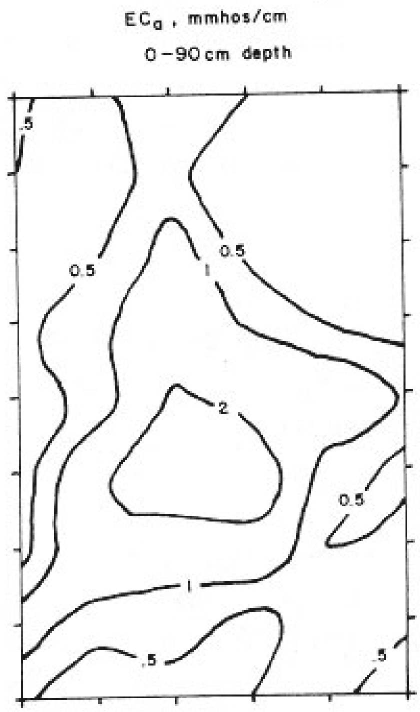


Fig. 16 MAP OF EC_a ISOLINES FOR THE SOIL DEPTH 0–90 cm (AFTER HALVORSON AND RHOADES, IN PREP.)

EC_a determinations are made with successively wider interelectrode spacings, thus causing the depth of current penetration to increase as illustrated in Fig. 9. Figure 18 shows EC_a - a data for two alluvial soils, one in which the water table was at 1 m and the other at 3 m. At the time these determinations were made, the soils had been recently irrigated, planted to wheat (the seedlings were just developing), with no visible differences between the two sites. The presence of the shallow water table at location A is clearly indicated in Fig. 18 by the "inverted" EC_a readings, i.e., EC_a readings were very high (indicating high, near-surface soil salinity) at small "a" spacings and decreased as "a" spacing increased. The EC_a - a curve obtained at location B illustrates that expected of well-leached soils where the salt concentration increases with depth.

Depths to water were estimated for these two locations from plots of accumulated EC_a vs. "a", according to the Moore cumulative method (Moore, 1945). As shown in Fig. 19, these estimates of depths to water table agreed quite well with the depths measured in nearby observation wells. Such breaks in slope may not always be so readily associated with water table levels if the soil profile is markedly stratified and complex, but in rather uniform soils the method should work. For such cases, I recommend the complementary use of seismic refraction and four-electrode conductivity determinations. Seismic refraction soundings are made to detect the presence and depth within the profile of dense textural horizonations so that the above mentioned breaks in slope, associated with a water table, can be distinguished from textural discontinuities. Inexpensive pocket seismographs are now available; seismic soundings can be easily and quickly made with such equipment for this purpose. An illustrative seismic refraction graph is shown in Fig. 20 for a situation where textural discontinuities were found at 1.9 m and 6.5 m depths in the profile. Hence, breaks in slopes of accumulated EC_a - a plots at such depths would be ascribed to textural discontinuities and not to the presence of a water table. Such seismic refraction information is also useful for showing the need for changes of EC_x - EC_e calibrations below certain depths in the soil profile because of textural changes and the depth limit of applicability of EC_a - EC_e calibrations.

The presence of a saline water table near the soil surface may allow salts to "sub" into the soil profile if the net water flux is not maintained downward with proper irrigation management (Fig. 18). Figure 21 shows the relation between EC_a of the top 30 cm soil depth and water table depth determined in glacial till soil of Montana under conditions of dryland agriculture where this "subbing" could not be prevented with proper irrigation management (Halvorson and Rhoades, 1974). Wherever the water table was within about 1.2 m of the soil surface, the salinity of the surface soil increased markedly above its normal "leached" value of about 0.25 mmho/cm. For this case the value EC_a (a = 30 cm) > 0.5 was recommended for

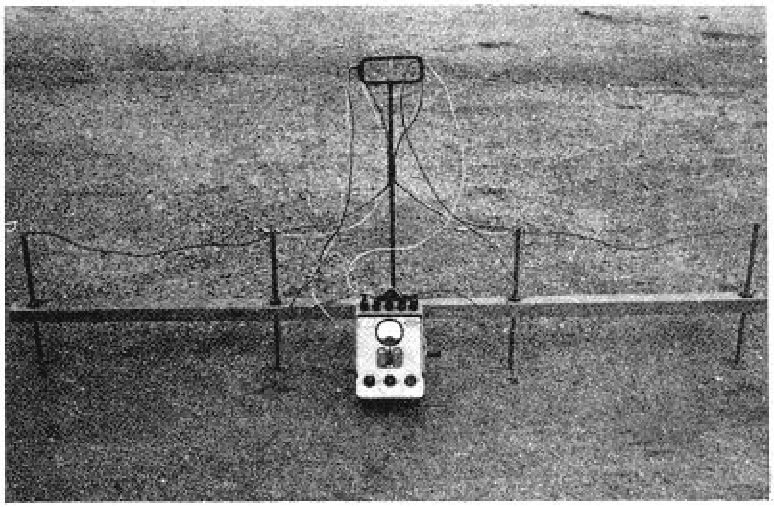


Fig. 17 FIXED-ARRAY RIG USED FOR RAPID EC_a TRAVERSES

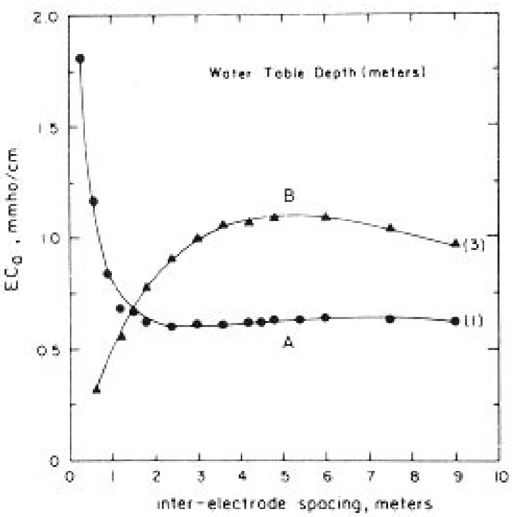
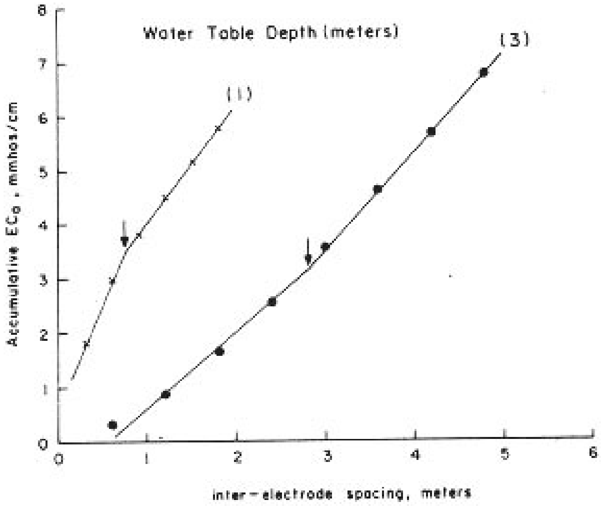
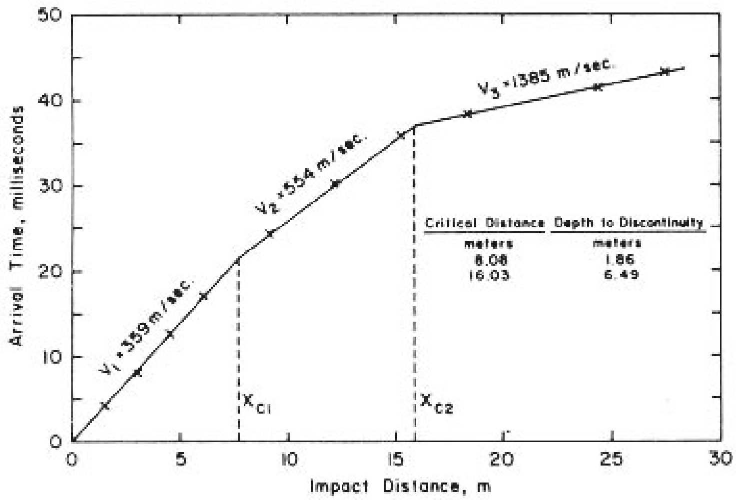


Fig. 18 RELATIONS BETWEEN EC_a AND INTERELECTRODE SPACING FOR CASES OF SHALLOW (LOCATION A) AND DEEP (LOCATION B) WATER TABLES



<u>Fig. 19</u> RELATIONS BETWEEN ACCUMULATIVE EC_a AND INTERELECTRODE SPACING FOR CONDITIONS OF WATER TABLES AT ONE AND THREE METER DEPTHS



<u>Fig. 20</u> SEISMIC REFRACTION GRAPH OF PROFILE WITH DENSER MATERIALS UNDERLYING OVERBURDEN MATERIALS AT DEPTHS OF 1.9 and 6.5 METERS

delineating the land under the influence of a shallow water table. Under similar conditions of "subbing", the presence of shallow water tables in irrigated lands can be mapped. Whenever the net flux of water is downward, the soil surface depths (0 to 30 or 0 to 60 cm) should be low in salinity; where the flux is upward, salts sub into the upper soil profile, and the EC_a readings would be atypically high for the region and soil type.

5.5 Monitoring Soil Salinity and Water Table Depth

Methods described can be used to monitor changes over time in soil salinity or water table depth in irrigation projects or individual fields. The number and location of monitoring sites would depend on local conditions and degree of information desired. In principle, however, they should be selected so that the data collected present a representative picture of the different topographic situations within the region, soil types, cropping patterns, and irrigation and drainage methods and facilities.

I recommend establishing such salinity monitoring programmes in place of salt balance evaluations for assessing the adequacy of leaching and drainage in irrigation projects. Seismic refraction soundings should also be made to assist in the characterization of the subsurface properties of the monitoring sites.

5.6 Determining the Leaching Fraction

In assessing the efficiency of irrigation of irrigation projects and in establishing "minimum leaching" irrigation management systems, information is required on the fraction of applied water being percolated beyond the root zone. The four-electrode soil conductivity technique has potential for determining LF.

It is possible to predict, under steady state conditions, the EC_w of the water that will drain from the soil profile as a function of LF (Oster and Rhoades, 1975). Since EC_w can be determined from EC_x determinations, four-electrode techniques can be used to estimate LF. The EC_x determinations may be made with either Eq [8] or [9] and corresponding EC_w values calculated by using Eq [3] or [5]. LF would then be determined from an appropriate EC_w-LF relation like that illustrated in Fig. 22. Alternatively, LF could be obtained by establishing an empirical correlation between EC_x readings and LF values obtained from analyses of chloride in soil samples taken from below the crop root zone. The "chloride" method for determining LF is discussed by Lonkerd and Donovan (in press).

Applications may include large-scale monitoring of irrigation efficiency, spot checks of LF by fields, or utilization as feedback for managing minimum leaching irrigation systems.

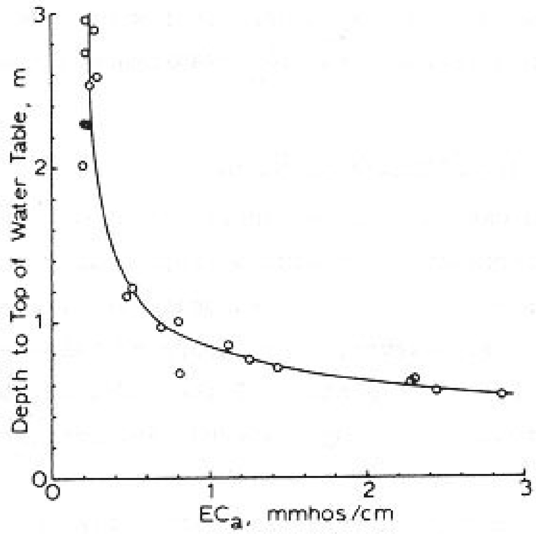


Fig. 21 RELATIONSHIP BETWEEN EC_a (a = 30 cm) AND DEPTH TO WATER TABLE IN DRYLAND GLACIAL FILL SOIL (AFTER HALVORSON AND RHOADES, 1974)

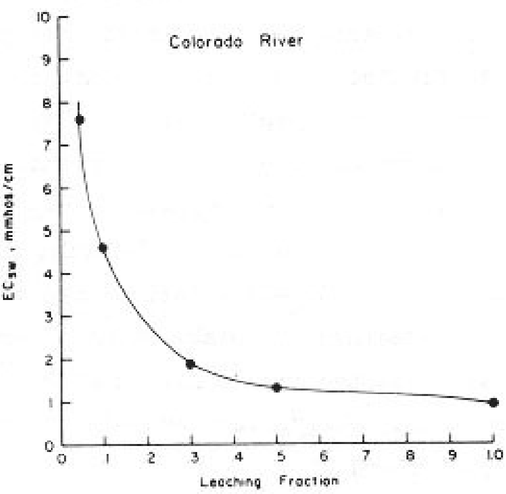


Fig. 22 RELATIONSHIP BETWEEN EC_{sw} AND LF FOR COLORADO RIVER WATER, AS CALCULATED BY METHOD OF OSTER AND RHOADES (1975)

5.7 Identifying Non-saline, Sodic Soils

As shown by Eq [5], Section 2, EC_a is a measure of a liquid phase and a solid phase contribution. The liquid phase contribution is related to soil salinity; the soil phase contribution (surface conductance) is a measure of the extent and mobility of the exchangeable cations. Surface conductance is negligible as compared with liquid conductance in normal saline soils (Rhoades and Ingvalson, 1971; Rhoades et al., in prep. (b)). Surface conductance increases with sodium saturation of clays, especially those low in surface-charge density, and decreases as electrolyte concentration increases (Cremers and Laudelout, 1966; Shainberg and Kemper, 1966; van Olphen, 1957). Hence, high EC_a values without high salinity should indicate high, exchangeable sodium levels, i.e., sodic soils. The four-electrode soil conductivity technique previously discussed could be used to identify and especially to map sodic soils, if these soils are known to be non-saline as in slick spot soils in the Great Plains States. Large amounts of sodium in saline soils should not distrub the normal EC_a - EC_e relations previously discussed because of the reduced mobility of exchangeable sodium in the presence of high electrolyte strength and the large effect of the latter on EC_a.

6. CALIBRATING SOIL ELECTRICAL CONDUCTIVITY IN TERMS OF SOIL SALINITY

EC_a- soil salinity calibrations may be obtained in one of three ways depending on the availability of equipment and time and the desired accuracy. The calibration method used most frequently to date has been to take four-electrode resistance readings and soil samples to determine EC_a and EC_e, respectively, at numerous field locations to obtain a suitable range in soil salinity and sampling population to establish an EC_e- EC_a correlation (Rhoades and Ingvalson, 1971; Halvorson and Rhoades, 1974). Since soil salinity is typically quite variable from spot-to-spot and with depth in saline soils, numerous samples were taken from below and within the centre two-thirds of the spread of electrodes to obtain an EC_e value representative of the relatively large volume of soil measured by the four-electrode technique. To obtain a representative EC_e value to correlate with the EC_a value corresponding to the 0 to 1 m soil depth, a soil volume of about 3 m^3 must be adequately sampled, necessitating a fair amount of work if an accurate calibration is desired. Further, the EC_a - EC_e calibration is limited to whatever EC_e range is found in the field at the time of sampling. A typical calibration of this type is shown in Fig. 23 and labelled conventional calibration.

A more accurate calibration technique was developed using specially built four-electrode cells (Rhoades et al., in prep. (a)). Undisturbed soil cores are taken from field sites representative of the soil type for which the calibration is

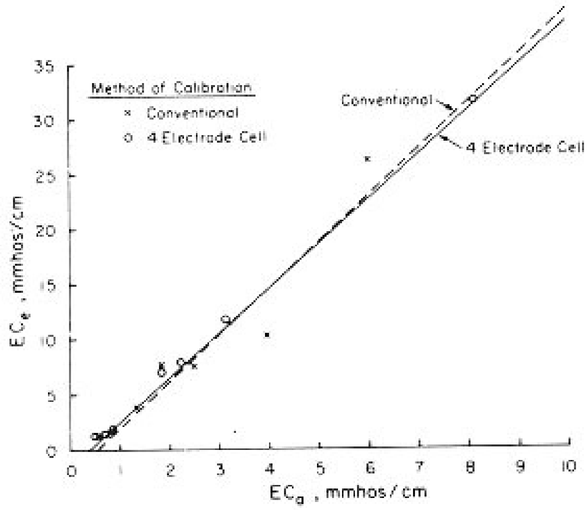


Fig. 23 COMPARISON OF EC_a - EC_e CALIBRATIONS AS DETERMINED BY CONVENTIONAL AND FOUR-ELECTRODE CELL METHODS (AFTER RHOADES *et al.*, IN PREP. (a))

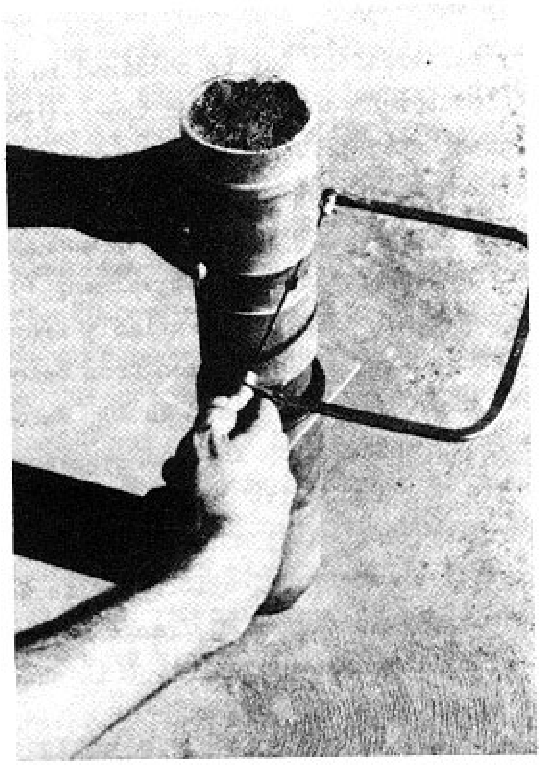


Fig. 24 FOUR-ELECTRODE CELL WITH "UNDISTURBED" SOIL AFTER REMOVAL FROM SOIL CORER

desired, using lucite column sections as inserts which fit the dimensions of the corer. Figure 24 shows several such lucite columns after they were slipped out of the corer being segmented to obtain a "four-electrode cell". These cells are similar to those used by Gupta and Hanks (1972) in their laboratory column studies; the four-electrode cell is tapped so that upon its removal from the corer, the stainless steel electrodes can be inserted into the soil (Fig. 6) to a fixed depth (cm). The EC_a of the undisturbed soil sample is then determined using an appropriate resistance meter. Appropriate cell constants are determined for the four-electrode cells by filling them with known EC-solutions and measuring their resistance using Eq [10]:

$$k = EC_{25} \cdot R_t \cdot \frac{1}{f_t} \qquad [10]$$

where EC_{25} is the electrical conductivity of the reference conductivity solution at 25° C, R_t is the measured resistance of the reference solution at its determined temperature t, and f_t is the appropriate temperature factor for correcting resistance and conductivity data (Table 2 or USSL Staff, 1954). When the four-electrode cell is filled with soil, soil EC_a is then calculated from the measured resistance, soil temperature and established cell constant using Eq [11]:

$$EC_a = k \frac{f_t}{R_t} \qquad [11]$$

If desired, the soil filled, four-electrode cells can be leached with solutions of desired salinities and then adjusted to desired reference water content before determining their EC_a. (This will be necessary if there is an insufficient natural salinity range in the field.) Alternatively, if there is sufficient range in salinity in the field, which is at the desired water content, usually field capacity, three or four undisturbed soil samples can be collected in four-electrode cells from field spots, ranging from low to high salinity, and their EC_a determined. In either of the above two calibration approaches, the whole soil sample on which the EC_a was determined is then removed from the cell for determination of EC_e (and water content if desired). This method maximizes the accuracy of the calibration because exactly the same bulk volume of soil is used for measuring both EC_a and EC_e.

A typical calibration obtained with this method is illustrated in Fig. 23. This figure clearly shows that the four-electrode cell calibration technique yields essentially the same EC_a - EC_e calibration as that achieved with the conventional field method discussed above (so that one has confidence that the "four-electrode cell" calibrations can be applied to field array measurements) but are more reliable since they result in higher correlation coefficients and lower standard errors of estimate in the $EC_e = f(EC_a)$ regression (data not given).

The simplest method of EC_a - EC_e calibration makes use of the soil EC-probe to determine the EC_a value of small bodies of soil which have been adjusted in the field to give a desired range of salinities. To accomplish this salinity adjustment, saline waters are impounded in 30 cm dia. x 45 cm long column sections driven into the soil. The infiltrated waters bring the soil beneath the impounded area to the desired range of salinity. When the soil has drained to about "field capacity", (i.e., the reference water content), 1 or 2 days later, soil samples are removed from the salinized body of soil (0 to 30 cm) with an Oakfield soil sampler. Then the soil EC-probe is centred in the hole and the EC_a value corresponding to the 0 to 30 cm depth interval determined. A soil sample (0 to 30 cm) is then taken (after the probe is removed) of the soil volume surrounding the hole; the EC_e of this soil sample is then used to establish the EC_a - EC_e relation for that soil type and reference water content.

This latter calibration procedure is by far the quickest. Only three or four EC_a readings and soil sample EC_e's need to be determined. Very satisfactory calibrations may be obtained (Fig. 25).

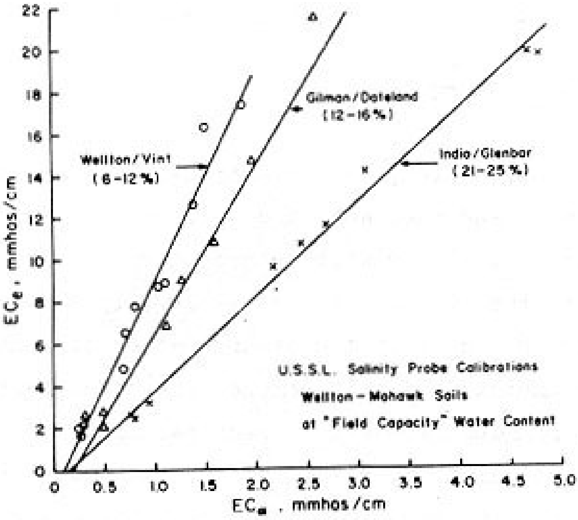


Fig. 25 EC_a - EC_e CALIBRATIONS FOR DIFFERENT SOILS OBTAINED WITH THE EC_a-PROBE TECHNIQUE

7. SUMMARY AND CONCLUSIONS

Sufficient data on the various discussed applications of the four-electrode soil EC_a technique have now been obtained to recommend its adoption both for general and special purpose salinity appraisal, mapping and monitoring both in large, bulk soil volumes, like the whole root zone, and discrete intervals of soil depth. The possible application of the technique for mapping non-saline, sodic soils is discussed. Methods are given for detecting where salts are subbing into the upper soil layers from a shallow water table and for delineating or mapping boundaries of salt affected soil bodies. A monitoring programme based on the measurements of soil electrical conductivity is recommended as a more suitable approach to assessing the adequacy of leaching and drainage performance of large irrigation projects than the currently used salt-balance evaluations. A new method for determing leaching fraction, under field conditions based on EC readings with depth in the soil is presented. To make the adoption of these recommendations easier, a brief discussion of equipment needs and calibration procedures are given. So that the recommended procedures are not abused, the method's limitations are discussed.

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Paper 13

c. LA MORPHOLOGIE DES SOLS AFFECTES PAR LE SEL, RECONNAISSANCE ET PREVISION - SURVEILLANCE CONTINUE

par

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Avant d'essayer de montrer comment on peut prévoir quels sols seront affectés par des sels solubles ou par des ions provenant de leur dissociation et susceptibles de provoquer, directement ou indirectement, leur dégradation et quelles mesures doivent permettre de suivre ce phénomène et d'en surveiller constamment le développement, il paraît utile de préciser quelles transformations morphologiques subit le sol affecté par l'excès de sels et quelles variations de ses caractères il enregistre au fur et à mesure que cette dégradation se poursuit.

1. CARACTERES MORPHOLOGIQUES DES SOLS AFFECTES PAR LE SEL (sols salsodiques)

La richesse du sol en sels solubles ou en ions alcalisants tel que le sodium se répercute dans sa morphologie en surface et plus ou moins en profondeur.

1.A Surface des sols

1. Il est fréquent que la surface de ces sols et celle de leurs agrégats dans les horizons superficiels soient plus ou moins couvertes d'efflorescences salines, cristaux d'espèces minéralogiques solubles telles que bishofite, epsomite, mirabilite, tachyhydrite, natrite, thénardite, gypse etc...

Elles sont dues au dépôt, après évaporation, des sels contenus dans la solution du sol et déposés à sa surface à la suite d'une remontée capillaire. Si le sol est nu, l'accumulation se produit tout à fait en surface ou dans les quelques centimètres supérieurs ; si une végétation, par exemple de pelouse, s'est maintenue, elle est moins concentrée et se répartit dans les décimètres les plus superficiels, en fonction de l'effet du système racinaire de cette végétation.

Ces efflorescences peuvent être de types très différents :

a. Elles peuvent être d'un gris, plus ou moins clair ou foncé, ou blanches : salant blanc. Ce sont alors essentiellement des chlorures et sulfates de sodium et magnésium, plus ou moins mêlés de sels de calcium.

b. Elles peuvent être noires ou brunes : salant noir. Les bicarbonates et carbonates de sodium dominent, formant une croûte saline superficielle, le plus souvent – lorsque la teneur du milieu en matière organique est suffisante – recouverte d'une pellicule brune ou noire de produits humiques.

c. En d'autres points, en sols riches en éléments calciques et magnésiens, l'accumulation porte en particulier sur des sels hygroscopiques, chlorures de calcium et de magnésium ou sels mixtes, tels que tachyhydrite ou bischofite. Des efflorescences ne s'y forment pas, mais des taches sombres apparaissent dues à la forte rétention d'eau que ces espèces provoquent à la surface du sol.

2. La structure des horizons de surface est aussi très modifiée par la présence des excès de sels solubles ou d'ions alcalisants tels que le sodium.

a. Très fréquemment, à la surface de sols très salés et très sodiques, en période humide, l'horizon superficiel n'est qu'une boue fluide et visqueuse d'argile salée, très sodique, gorgée d'eau. Elle donne peu à peu naissance, au cours de la dessication, à un horizon superficiel à structure lamellaire, à découpage polyédrique hexagonal, puis à une structure poudreuse en pseudosables, due à l'éclatement des pellicules de surface en éléments beaucoup plus fins sous l'influence de grandes baguettes de chlorure de sodium (J. Servant, 1975).

b. En d'autres cas la structure de cet horizon superficiel reste diffuse, sous l'influence du sodium échangeable en excès. La compacité y est très forte et le profil hydrique très défavorable, l'eau pénétrant lentement et peu profondément dans le matériau sodique – surtout s'il est originellement très argileux – dont le pouvoir de rétention est augmenté d'autant.

3. La réaction du sol peut être modifiée. Enrichi en sels de la série neutre, sulfates et chlorures de Na, Mg, Ca, il présente une valeur de pH légèrement abaissée ; enrichi en bicarbonate ou carbonate de sodium, il atteint un pH à l'eau dont la valeur s'élève rapidement jusqu'à 9 ou 10. Pauvre en sels solubles, mais enrichi en sodium échangeable, cet horizon possède une réaction intermédiaire : pH aux environs de 8,8 à 9,2. 1/

1/ Valeurs de pH aussi obtenues en présence de bicarbonate de magnésium.

4. Enfin, comme il sera indiqué ultérieurement par d'autres, au fur et à mesure que les horizons superficiels du sol s'enrichissent en sels solubles ou présentent un complexe de plus en plus enrichi en sodium et une structure de plus en plus dégradée, leur <u>couverture végétale</u>, naturelle ou culturale, tend à se dégrader - et d'abord à se "spécialiser" dans le cas d'une végétation naturelle - devenant plus rare, par taches irrégulières, jusqu'au stade où elle disparaît complètement sur de larges surfaces puis sur tout l'ensemble de la zone.

1.B <u>Moyenne profondeur</u>

Si l'excès de sels solubles et d'ions alcalisants comme le sodium, modifient largement les caractères morphologiques des horizons supérieurs, ils peuvent avoir aussi une influence très importante sur ceux de moyenne profondeur.

1. Dans les sols salés assez argileux, comportant une nappe phréatique salée à moyenne profondeur apparaissent entre 30 cm et 1 m en général, un pseudomycélium dit "gypso-salin", mais en fait, essentiellement gypseux. Il se forme par remontée capillaire des sels de la solution du sol, échange de cations, Na de la solution contre Ca du complexe absorbant du matériau traversé, et dépôt du gypse lorsque sa teneur dans le solution du sol dépasse son taux de solubilité en fonction de la salinité de celle-ci.

Si, dans la plupart des cas, le gypse déposé ne l'est qu'en fins filaments de très petits cristaux - d'où son nom de pseudomycélium - orientés dans les canalicules vides, en d'autres cas, il constitue une masse plus importante, véritable encroûtement, généralement intégré suivant le type intramatriciel dans le matériau (J. Servant). Ailleurs, surtout en profondeur, il peut s'agir d'une réelle croûte gypseuse, plus ou moins épaisse.

2. La <u>couleur</u> des horizons de ces sols est très variable. Habituellement, elle ne paraît pas liée à leur degré de salinité. Quelques cas particuliers doivent cependant être signalés.

a. Les horizons plus ou moins profonds peuvent être gris ou noirs sur l'ensemble ou par taches. Cela peut indiquer la présence de sulfures provenant de la réduction de sulfates dans des horizons engorgés par la nappe, ou très compacts, caractère généralement lié à la richesse en sels du sol.

b. Il est fréquent que les sols salés présentent des taches et traînées d'oxydes de fer, dues à une réoxydation de ces composés après leur réduction sous l'influence d'un engorgement par l'eau. La couleur qui apparaît alors peut être un rouge vermillon à la place du brun rouille habituel.

c. Enfin les sols sodiques présentant souvent un profil textural très différencié peuvent être soumis à une hydromorphite de moyenne profondeur (sommet de B_t) qui peut favoriser le lessivage de A_2 et l'éclaircissement de sa base (solonetz plus ou moins planosoliques), ou même – surtout en pays tropical à température élevée – une hydrolyse au sommet de B et l'apparition d'une ligne ou d'un horizon, à la limite inférieure souvent très irrégulière, d'un blanc très clair, composé principalement de silice, résidu d'une hydrolyse très poussée (sols solodisés et solods).

3. La <u>structure</u> de ces horizons peut être également très modifiée. Elle est normalement rendue très massive et même diffuse par l'excès de sodium échangeable (sols à alcali) s'il n'y a pas en même temps une forte teneur en sels solubles. Très souvent, lorsqu'en outre le profil textural s'est profondément différencié, la structure du B_t devient plus ou moins largement prismatique, ou columnaire si les sommets des prismes s'arrondissent, probablement sous l'effet d'une hydromorphie plus ou moins circulante (solonetz et certains solods).

1.C <u>Morphologie des profils</u>

La morphologie des profils de sols affectés par le sel – ou par l'ion sodium – peut être très varié, en fonction des modifications indiquées ci-dessus de leurs horizons de surface, de moyenne profondeur ou de profondeur. Il faut cependant signaler deux types de différenciation du profil qui leur sont souvent liés, correspondant à l'apparition d'un profil argileux plus ou moins fortement contrasté comportant un horizon B argillique, sodique et à pseudogley, à structure massive ou en colonnettes des solonetz, souvent accompagné de l'horizon blanchi au sommet du B_t des sols solodisés et solods, comme indiqué ci-dessus.

Cependant la morphologie du profil solodique peut apparaître même en dehors de toute sodification du complexe, si un horizon ou une couche de matériau assez perméable en recouvre un plus argileux, très massif en larges prismes, très peu perméable, la séparation en étant abrupte, ce qui permet à ce niveau une plus ou moins facile circulation d'eau provoquant une hydrolyse d'autant plus poussée, le cas échéant, que la température du sol est plus élevée.

2. PREVISION DES DANGERS DE SALURE DU SOL

Cette prévision doit se faire principalement en fonction de facteurs autres que les caractères morphologiques du sol lui-même. C'est ainsi qu'interviennent les conditions climatiques d'aridité du lieu, la position topographique locale et d'ensemble du sol (place dans la toposéquence et dans le bassin versant), ainsi que la présence possible, dans ce bassin versant, de dépôts contenant des sols solubles ou susceptibles d'en former par altération (granites à minéraux sodiques) ou d'eaux salées, en particulier en zone d'artésianisme, la proximité et la position sous le vent par rapport à une mer, un océan ou un lac salé, ou par rapport à des étendues déjà salées et recouvertes d'efflorescences salines ou de pseudosables, l'irrigation ou l'inondation par des eaux salées si le drainage naturel ou amélioré par l'homme est insuffisant ... etc. Cependant les caractéristiques physiques du matériau, perméabilité et porosité surtout, sont aussi des éléments à considérer. Un sol sableux sera rarement un sol salé ou pourra être facilement récupéré dès que le drainage du paysage sera assuré.

Un sol argileux risquera plus facilement d'être salé si les sels lui sont apportés en surface par des eaux d'irrigation ou d'inondation ou par le vent. Si leur origine est au contraire dans la nappe phréatique, c'est le sol finement sablo-limoneux qui sera le plus en danger, la remontée capillaire y étant facile et, pratiquement, plus élevée que dans les autres matériaux.

Les sols d'alluvions (ou de colluvions) risquent souvent d'être salés - en conditions climatiques arides - si des roches riches en sels existent dans le bassin versant. Dans le cas de sols subissant un alluvionnement actuel, en de telles conditions écologiques, il est indispensable de se méfier particulièrement des dépôts de crues de fin de période sèche.

Enfin dans la mesure où, par sa morphologie, le sol renseigne sur son bilan hydrique, il permet aussi de connaître son danger d'accroissement de salure. Tout signe de confinement, et, plus encore, d'hydromorphie, peut être considéré comme un signe de salure potentielle, si les conditions climatiques y prédisposent.

3. SURVEILLANCE DE LA SALURE DES SOLS

L'apparition et l'extension des caractères morphologiques signalés précédemment comme caractéristiques des sols salés, et en particulier de ceux de surface, tels qu'efflorescences et types de structures, peuvent permettre de juger du développement des processus de salure des sols en un secteur déterminé.

Cependant ces caractères sont eux-mêmes très variables et peuvent disparaître ou apparaître ou se modifier au cours de l'année ou d'année en année. Certaines de ces transformations sont d'ailleurs significatives.

3.A <u>Variations saisonnières</u>

1. <u>Salure</u> - L'une des expressions directes et caractéristiques de la salure est l'apparition des efflorescences à la surface du sol. Elles ne sont cependant visibles que si le type de profil salin du sol correspond à cette accumulation superficielle et en période suffisamment sèche.

On distingue généralement deux types de profils salins (répartition des taux de salure dans les divers horizons du sol en fonction de la profondeur) : le profil ascendant dans lequel le maximum de salinité est en surface, normalement couverte d'efflorescences, et le profil descendant, où il se trouve en profondeur, l'horizon de surface n'étant habituellement pas assez salé dans ce cas pour qu'y apparaissent les efflorescences salines. Récemment J. Servant en a défini deux autres types, l'un à maximum de salinité à moyenne profondeur et l'autre à deux maxima.

Si dans certains cas le profil salin n'est pas sensiblement modifié entre les deux périodes sèches et humides de l'année, il n'empêche que très souvent il en est autrement. Par exemple, le profil ascendant peut perdre en saison de pluies son maximum superficiel, qui peut s'établir, alors, à une moyenne profondeur ; le même sol peut ainsi présenter une succession de plusieurs types de profils salins au cours de l'année.

Sur ce plan, l'observation des efflorescences et de la salure du sol semble devoir être faite principalement en pleine saison sèche ; secondairement, à la fin de la saison de pluies.

2. Structure - La structure des sols salés varie également de saison en saison. Dans le cas de sols salés peu alcalisés, elle est bien développée en saison sèche, mais instable, elle disparaît en saison de pluies, la surface paraissant massive. En sol alcalisé dès la surface elle est massive et diffuse en saison sèche ; elle le reste en saison de pluies et la percolation de l'eau est lente.

En sols très salés à alcali, l'horizon superficiel perd toute structure en période humide, puis, lorsque se développe la saison sèche, une structure lamellaire très massive apparaît qui présente, peu à peu, un système de fentes en polygonation hexagonale, puis se résout en une multitude de petits éclats qui constituent le pseudosable. C'est donc au moins deux ou trois fois dans l'année que la structure doit être observée.

3. Couverture végétale - Dans certains sols salés, la couverture végétale, ou abondante et variée (sols peu salés ou à profil descendant), ou très réduite et très spécifiques (sols très salés) reste assez constante au cours de l'année.

Dans les cas intermédiaires elle varie, au contraire, en fonction des variations mêmes de salure et de structure, tout un cortège d'annuelles peu spécialisées pouvant apparaître. L'observation doit alors être faite deux fois dans l'année : en pleine saison sèche et dans la seconde moitié ou avant la fin de la saison de pluies.

4. Action de l'homme - Par ses interventions et, principalement, par l'irrigation, l'homme peut modifier profondément les évolutions saisonnières indiquées ci-dessus.

3.B Variations dans le temps, au long des années

1. L'extension des sols salés au cours du temps peut être suivie à condition de réaliser les observations sur les secteurs concernés à la même période écologique - ou climatique - chaque année ou tous les deux ou trois ans.

Cette extension peut être due aux remontées de la nappe phréatique, soit à la suite d'irrigations, soit lors d'une année très humide. Aussi doit-on réaliser les observations de façon plus régulière, et même deux fois par an, lors du développement d'un système d'irrigation ou à la fin et après les années très humides. L'accroissement de la salure du sol dans un secteur déterminé peut être due à l'irrigation si l'eau que l'on utilise est salée. Il n'est que limité si le drainage est assuré, si l'irrigation est rationnellement menée et si le SAR de l'eau employée est assez bas (CRUESI).

Si l'irrigation provoque la remontée de la nappe là où elle est réalisée, elle produira aussi un accroissement de la salure du sol et une extension des terres affectées par ce processus.

Aussi la surveillance des nappes phréatiques est-elle l'un des moyens les plus sûrs pour réaliser celle du développement de la salure du sol.

2. Dans le cas des sols peu salés à alcali, ainsi que des solonetz, sols solodisés, etc..., l'extension du phénomène paraît peu probable, à notre échelle, ou au moins, très difficile à suivre. L'observation paraît très délicate et peu efficace. Par contre, il peut être indispensable dessurveiller le développement d'une des conséquences des caractères morphologiques de ces sols ; l'érosion par les pluies.

Cette érosion est de deux types:

- en sols peu salés à alcali en surface, elle est en nappe et surtout en nappe ravinante.
- en solonetz et sols solodisés, elle prend un aspect beaucoup plus catastrophique, avec enlèvement très étendu - souvent aussi sous l'effet de l'érosion éolienne - des horizons A puis érosion ravinante très rapide en B.

3. Sur le plan de l'érosion des sols salés, il serait utile de surveiller l'érosion éolienne des sols à pseudosable. Cela paraît difficile à réaliser du fait que ce dernier, s'il est enlevé, tendra à se reformer.

4. MESURES PRATIQUES POSSIBLES

Il semble que l'on puisse d'abord séparer le cas des zones non irriguées de celui des secteurs d'irrigation ou des zones en aval de ces secteurs.

4.A **Zone non irriguée**

En zone non irriguée - sans nappe phréatique ou à nappe très profonde - l'extension du phénomène de salure des sols est difficile à prévoir et à surveiller. Aucune mesure pratique particulière ne paraît envisageable. Si dans cette zone existe une nappe phréatique, même faiblement salée, il est indispensable de suivre ses mouvements, soit si c'est réalisable, par l'utilisation de "Censeurs" de satellites ou de radars, soit par l'installation de quelques piézomètres.

4.B **Secteur irrigué**

En secteur irrigué et dans les zones situées à leur aval, la surveillance des mouvements de la nappe phréatique, si elle existe, ou de sa non formation, si elle n'existe pas encore, doit se faire par utilisation de moyens de détection aérienne, le cas échéant, ou par installation de piézomètres. La mise en place de ces instruments d'observation doit être réalisée en fonction du mode d'alimentation de la nappe (irrigations, inondations, oueds et cours d'eau souterrains, etc...). Leur nombre dépend de chaque cas ; il faut souvent atteindre 1 par 1 000 hectares ; leur mesure ou lecture doit être faite au moins deux à quatre fois par an.

4.C **Zone avec des dangers de salure**

Enfin en toute zone présentant des dangers de salure ou déjà atteinte par les sels, l'observation, par détection aérienne, de l'aspect de la surface du sol (couverture végétale, structure, efflorescences, érosion) doit être réalisée au moins une fois par an - si possible - en fin de saison sèche et, mieux, deux fois dans une même année en fin de saison sèche et en pleine période humide.

Cette surveillance est particulièrement nécessaire en bordure des zones déjà salées, principalement à leur aval, ou dans les secteurs qui en sont sous le vent.

d. SURVEY METHODS FOR PERFORMANCE, MONITORING AND PROGNOSIS OF NATURAL VEGETATION AND ECONOMIC CROPS WITH SPECIAL REFERENCE TO SALT AFFECTED SOILS

by

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1. INTRODUCTION

Vegetation, "the green blanket of the earth," is an attribute of land and consists of individual plants either spontaneously sown and growing, or sown or planted and managed by man. Vegetation types growing mainly uninfluenced by man are called natural vegetation, while those whose existence depends mainly on conscious human activity (pastures, orchards, gardens, tree plantations, agricultural crops) can be called cultivated vegetation. In between there is a wide scale of transitional semi-natural vegetation, such as randomly sown but managed rangelands, forests, shrublands, etc. Even purely cultivated vegetation like cereals on arable land contain quite a number of species that are spontaneously sown (weeds). In general, therefore, natural and cultivated vegetation consists of more than one species. The individuals belonging to a species are the building stones of the three-dimensional body of the vegetation, which has form and shape (structure), can be recognized, classified and mapped by properties known from the structures and from the building stones (plant taxa itself). This principle applies to natural as well as cultivated vegetation.

Vegetation is of interest to man because:

a. it is the original source of food, shelter and raw material for products and fuel;

b. it is a main constituent of the landscape influencing the other land properties;

c. it is, being itself dependent on other land factors, an indicator of environmental conditions that cannot always be readily and directly observed.

Each land attribute is at the same time a building stone, an independent variable and a dependent variable in the whole complex of the land or "ecosystem." It is important to realise that a strict relation exists between all attributes only in four dimensional space, including time as the fourth dimension. In other words, the adaptation of one factor to another needs time. So at one moment certain relations may seem less strict than others. Change (adaptation to new conditions) of one factor may be more rapid than of another. This is the main reason why in land survey it is necessary to map and classify not only the soil or vegetation or other attributes of the complex ecosystem of land, but to pay attention to all of them. The pattern forming in the process of time, i.e. the fourth dimension, makes it necessary and also possible to prognosticate.

Examples of the three utility aspects to man of vegetation in relation to this meeting on salt affected soils are as follows:

a. The direct utilization aspect as a food and raw material source is evident. The quantity of the product at present and in the future should be known when planning any development endeavour.

b. Vegetation always influences the soil by determining the soil microclimate, by extracting water and minerals and by adding organic matter to the mineral soil. Plants transport minerals selectively from lower layers to the topsoil either by liberation of minerals after the decay of plant tissues or by excretion in the living condition. The second case refers mainly to easily soluble components like NaCC, etc.; the first involves elements like Ca, Si, P and is often a favourable process in the sense of ecological production, leading to soil improvement unless, as in agriculture, the minerals are carried away with the crops. Less favourable effects also exist: e.g. accumulation of sulphur. Phreatophytes (plants rooting in groundwater) tend to lower the water table and, as with most other plants, improve the structure of the soil surface layer by improving the microclimate and adding organic matter. The effect of these two actions is that capillary transport of salts to the soil surface is reduced, as compared with soils with open or no vegetation and direct surface evaporation. On the other hand it results in stronger salinization of the groundwater if the plants present do not take up large quantities of salt in their roots and the groundwater is stagnant. Contrariwise, plant species that root only in the superficial soil layers stimulate the superficial evaporation of the top layers with increased salinization as a result. So the life form (see Section 3.2) of the component plants of the vegetation determines the overall effect of vegetation on soil conditions, including salt effect, in combination, as in all ecological processes, with all other environmental factors, such as climate, lithology, landform, hydrology, man and animal behaviour, in the course of space and time. These influences by natural and cultivated vegetation should certainly be taken into account when setting up models for salt balance in natural and cultivated stages of land use. The type of influence should be known and as different plants, hence vegetation types, have a different behaviour in this respect, the type of vegetation whether cultivated or natural should be recorded, classified and mapped.

c. Knowledge about the dependence of vegetation on other landfactors is the main reason for this meeting. On the one hand, man wants to adapt such environmental factors as soil and water to the crops to be grown and on the other, the behaviour of the vegetation, cultivated and natural, indicates the environment by its spontaneous adaptation to that environment. Since the days before civilization man has used vegetation as an indicator of the environment. In recent times vegetation survey has been widely used as an indicator of the environment; for such dynamic factors as climate, hydrology and salinization there have been successful results from the application of this method (see examples in FAO/Unesco Irrigation, Drainage and Salinity, An International Source Book, Hutchinson, London, 1973). No further proof is needed of the usefulness or possibility of vegetation as an indicator; therefore this paper needs to concentrate only on the way of implementing a survey and the evaluation of its results (survey methodology and survey methods).

Survey involves: i) observation, ii) classification of the survey objects, iii) mapping, producing a two dimensional image on paper and iv) interpretation, that is evaluation of the results for practical use. The following sections will deal with these subjects, although, as will be clear, the subjects are very much linked to one another; none of them can be treated independently of the others.

2. OBSERVATION

2.1 Basic Observation Required

For the preparation of a map two types of observations are needed:

a. observations that lead to the delineation of boundaries, often called mapping *sensu stricto*;

b. observations that lead to description of the mapping units (the content between the boundaries), often called sampling.

Where a classification system is already available the sampling observations are used to determine the vegetation. Where a classification does not yet exist, these data are used to design a classification system first, and later to use this for classification of the units.

In most detailed surveys sampling and mapping are done simultaneously and are in fact inseparable. The sampling points, arranged at random or in a rigid grid or line system, are so close together that the boundaries are drawn on the basis of the sampling, i.e. point observation. Such surveys are done on foot in the field. Aerial photographs may be used mainly for orientation in the field as a detailed base map which can also give more information than merely finding the way (see section 2.2). In surveys of slightly salt affected crop lands this is the only effective method of making a vegetation map. It may not always be necessary to make a separate map. Observations can be made on vegetation during a soil survey, as additional data, or they can be made without the intention of putting them on a map with accurate boundaries. (A farmer observes his field regularly to follow the growth process in all its aspects, salinity included; however, he also needs some classification and interpretation (see section 3)).

In cases of full crop cover, more intensive airphoto interpretation with reduced field sampling is impossible because the indicative plant species are mainly hidden under the crop or do not give sufficiently characteristic patterns to make recognition on airphotos possible. The main boundaries however may show up in the density, colour and structure of the crop which, on rather detailed photos (1: 5 000 or 1:10 000), preferably in colour or false colour, may show clearly and make it possible to reduce sampling. In smaller scale surveys, especially those of more natural vegetation, a much stronger separation exists between the mapping of boundaries and observation of the content of the mapping units. This is most obvious if photo interpretation is used as the main method of observation. This aspect will therefore be dealt with first.

2.2 Photo Interpretation Methodologies

Three methods of photo interpretation useful for survey of the green cover of the earth can be distinguished. Strictly, they cannot be separated but nevertheless represent a distinct difference in approach.

a. the photo key method

b. the landscape (or physiographic) method

c. the photo-guided field survey

The key method starts with observation in the field resulting in annotations of photos with data on ground truth. Each subject to be surveyed is compared with the image it shows on the photo. In this way keys are prepared which are used to determine each feature on the photo during the systematic interpretation. The final keys can comprise a series of photos (cutouts from the original airphotos) or be made up from the dichothomic determination keys (as in florae, soil classification books, etc.). In this case the criteria of division are grey tone or colour, hue, value and chroma, texture/structure (horizontal pattern) and vertical size and shape (stereoscopic) of the image. In the classification of the image convergence of evidence plays a part, but only for details of vegetation (land use), not for land features as a whole. During his work, the interpreter must concentrate point by point on features in the same way as the terrestial surveyor does in a ground survey. After interpretation, some field checking is done to correct and elucidate doubtful interpretations.

The landscape physiographic approach, developed especially in soil survey at ITC, starts with a preliminary interpretation of mapping units. The interpreter concentrates on the photo image as a whole. Just as a photograph of a person reveals to a psychologist much of the character of the person, without defining details of his skin or the form of his nose and colour of his eyes, a photograph of the land gives an impression of the total character of the land in a holistic way. Convergence of evidence of all kinds of land features (not only strict vegetational features) thus plays an important part in the delineation of boundaries and classification of the content. The result is a map showing units, and a preliminary legend showing a certain hierarchy. Similar units of land are grouped together, different land units appear in separate legend classes. The content is however not yet known in detail. The interpreter makes use of his general landscape ecological knowledge in which geomorphology especially, and natural and cultural vegetation and other land use aspects play an important role, but the relation between these land attributes and climate and geology are also taken into account. The more he knows already of the particular area under survey, the more he may suspect the content of the units. However, in principle, the fieldwork after the photo interpretation is the appropriate stage at which the units are translated into vegetational terms. The fieldwork is in fact not a 'check', it is a sampling stage.

A most important aspect is that the photo interpretation provides a basis for stratified sampling. This is the great advantage of survey with photographs over surveys without photographs. There are survey schools teaching that sampling in the field should be done either randomly or in a rigid grid, or on lines (see section 2.1). However, for reconnaissance type surveys especially such a system is a waste of time because large mapping units will be thoroughly over-sampled and/or the smaller units under-sampled. On the other hand, if one works without photos, and selects sampling points in the field, a great danger of bias exists. This is especially true for vegetation surveys. If stratification is done on photos the great advantage is that the details of the subject (single plants and species), in most cases, cannot be distinguished on the photo (see later). Within homogeneous photo interpretation units the sampling can be done at random, which prevents the surveyor from being biased on the terrain by too obvious, but on the whole less interesting, local vegetation differences. It regularly happens that differences in vegetation do not appear on the photo because they are either not able to influence the photographic process (only slight colour differences not shown up in grey tones) or because the scale is too small, or because there is a dominant layer hiding the undergrowth (certain forests, certain crops), or the photo quality is too poor (often heterogeneous).

If there is, however, another physiographic or landscape feature (relief, macro-pattern) correlated with the vegetation difference, the unit will be distinguished and can be included in the stratified sampling. It is clear that this advantage is more evident in small scale surveys and in more natural areas, and less important in large scale and strongly man-influenced vegetation where distinct vegetation differences may often not be correlated by any geomorphological or hydrological land property.

A third method is described by Küchler, which could be called the photo-guided field survey in which first the whole area is delineated into mapping units without hierarchy or classification. This means that boundaries are drawn only on the main vegetation differences obvious on the photo. After that, each plot is visited in the field and described according to field observation. This method is suitable for certain detailed vegetation surveys, and can hardly be called photo interpretation. It is at best comparable with a grid system survey in which the rigid grid is replaced by a more flexible one. It has the advantage that under- and over-sampling of small and respectively large areas is prevented.

In high quality surveys of various types (soil, geomorphology, vegetation, geology), it will be clear that almost every practical method makes use of the principles of each of the above systems. In a clear key type interpretation survey some landscape aspects may be included. A pure landscape type survey always has some similar classification procedures as in the key. In a pure key interpretation the collection of ground truth will be guided mostly by the photo image, and in the landscape type survey it will not always be possible to have a strict land (mapping) unit classification and hierarchy ready before the sampling stage starts, which means that a check of various plots belonging to the same mapping type will be necessary. Nevertheless, one of the methodological principles mentioned will dominate, depending on aim, scale, type of area and experience of the surveyor (see also section 4).

2.3 Sampling (Point Description)

Sampling is the process designed to gather data on which a classification of the subject (vegetation in this case) can be based. In detailed surveys it is also used to delineate the boundaries at the same time (see section 2.1). Sampling can vary from a quick look with a ready classification system (simple or complex, see section 3) at hand or can be a detailed description of the vegetation and environmental features.

In most cases it is dangerous to use existing classification systems derived from remote areas (section 3), so data in the area itself will have to be collected. Moreover it is always necessary to collect environmental data of at least a representative part of the sampling points in order to be able to interpret the vegetation data into environmental features that relate to the vegetation. In the case of salt affected lands these are at least the water table, the salt contents figures of soil and water and other soil features associated with water and salt (structure especially). General vegetation structure, pattern, stratification lifeforms and species composition are the most common vegetation properties from which vegetation classification characteristics will be derived (section 3). In the case of surveys of crop performance, not only the occurrence but more phenotypical quantitative measurements have to be observed. A good method is to combine direct measurements (of yields on limited sample plots) with an estimation of yield in the field. Large differences in yield will often be visible on photos, at sufficient scale, taken in the right season.

However these possibilities should not be overestimated. For instance, a cereal crop with a reasonably dense cover, and therefore the same photo-image as another crop, may differ considerably in grain yield. Moreover, the photo images in surveys of a larger area are not always of the same day and the difference in time can make a considerable difference in the photo image. In both natural and cultivated vegetation, certain pheno-typical features caused by a deficiency of minerals or by physiological drought, both due to salinization, may be of importance for the survey, and may even be visible on the airphoto. However, these are at most rather temporal phenomena which have less meaning for more potential aspects of the land; they may however be important on account of this.

Sampling for classification is mostly done by stratifying either by landscape, physiographic methods (see section 2.1 and this is the most objective) or otherwise on spots considered representative for mapping units or key-areas. In not too detailed surveys (ca. 1:25 to 50 000), in cultivated areas, it might be useful to use parcels as sampling units unless obvious inhomogeneity exists. In surveys without photos this is the best way in areas without much landscape variation. In most cases however the sampling area should not be too large. In arable land 50 to 100 m^2 is an empirical size which works reasonably for collection of classification data. For quick sampling for check points during the routine survey, with or without aerial photographs, the sampling area is not very relevant. For most crop-performance surveys the size mentioned is also useful unless great inhomogeneity exists. One remark on the intensity of sampling should be made: the density of sampling points depends on the heterogeneity of the area, the scale and the balance between the time (money) available and the required accuracy. The details which are described in one sample plot depend on the same factor, however it is not a strict rule that at detailed survey level the sampling points are more intensely studied than at reconnaissance survey level. The opposite may often be true.

3. CLASSIFICATION - TYPOLOGY OF VEGETATION

3.1 Floristic Systems

If our aim is to use vegetation to indicate the salt status of the land and water, the simplest way of classification is to try to divide the plant kingdom into two groups: halophytes (plants adapted to high salt concentrations) and glycophytes (plants that cannot stand salt at all). In between transitional groups of plants could be distinguished that can stand a bit more salt than pure glycophytes but not so much as true halophytes, and also there is the possibility of plants that grow equally well under saline and non-saline conditions. Plants from these groups can then be used as indicators after their salt tolerance has been established in the laboratory, or empirically in the field.

Indeed this method is used in practice, and not without success for some generalities. However, in principle, this way of using indications by plants is very dangerous and may easily (and has done so) lead to large mistakes. There are two reasons for this. The behaviour of plants is always a result of ALL environmental factors. Most plants grow within climatological limits because their physiology is adapted to certain temperature and air humidity ranges which may be different at various growth stages. A general, clearly observable trend is that plant individuals occurring in the middle of their distribution area (in their optimal climatological environment) show less sharp a preference for edaphic factors. On the contrary, near the boundary of their plant geographical areas they may be more precise in 'selecting' their habitat. This means that one plant species (taxon) may behave rather differently in relation to soil fertility - moisture or salinity, in remote areas. The problem is more complicated by the fact that local genetic types, 'ecotypes' of a species with different ecological behaviour, but difficult to separate morphologically, may have developed in places at a great distance from each other.

This means that one cannot give to one species an absolute indication value. The value depends on the area. If vegetation types[1/] are used instead of single species, and the vegetation type is evaluated on its indication value instead of

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1/ The term "vegetation type" is in certain Russian and also other literature reserved for large world-wide vegetation zones. This is however a confusing use of the term. Type should be a general term for a classification (typology) unit of any rank.

the single species, this problem is much reduced. Exactly the same reasoning is known in soil science. A soil type based on the total soil morphology of horizons, etc., is better suited for evaluation than a 'single soil value' alone.

The second narrowly related reason is that plants influence one another. Sometimes they assist each other (one giving the other protection, etc.) and often they compete. The absence of a certain halophyte at a certain place within its plant geographical area does not mean this place is not salty enough, or too salty, for this plant, but is often due to the fact that another plant (maybe indifferent to salt, or another halophyte) is stronger and has occupied the niche of the weaker one. Here also the use of vegetation types instead of single species solves the problem. A general rule therefore is that, if plant species are used to indicate the environment (floristic method), one should always work with species combinations, which means plant communities such as associations, etc., or vegetation types of higher or lower rank.

This means that classification should concentrate on statistical or semi-statistical determination of plant communities. If one uses only one, or a few dominant species to characterize the vegetation, it is a form of single value use described as unfavourable above. Halophytic vegetation has one advantage for floristic treatment above many other types. The amount of halophytic species is not very large and many of them belong to a limited number of genera such as Salicornia, Sueda, Atriplex and several others, of which many belong to only one family: the Chenopodicacea, and even for non botanists are a distinct group.

3.2 Structure and Life Form

For vegetation survey in general it is also possible to use (or even exclusively) other than floristic criteria. The structure of the vegetation as such, or the life form composition, may be used as the main characteristic in classification. Although, as an indication of salt-land conditions such classification systems without the use of floristic criteria in general are not appropriate, some mention should be made of them. Moreover for photo interpretation the structural criteria are most useful and life forms can be used in combination with floristic criteria for the environmental interpretation of the floristically defined units.

Vegetation structure refers to the form, shape and size of the vegetation as a three-dimensional body. 'Life form' refers to genetically fixed, morphologically visible adaptation to environmental conditions. There is a relationship between structure and life form as a classification criteria. The main structural types of vegetation are strongly determined by the dominant life form. So Steppic vegetation are composed of a combination of xerophytic (adapted to drought) perennials, geophytes and therophytes (annuals). The forests are formed by phanerophytes, which are plants with a woody structure and unconcealed reproductive organs, etc.

But within the same structural unit a variety of life forms can occur. Life forms can be used also if the floristics are not well known. However life form classifications work optimally in combination with floristic classifications. Each species (taxa) has in general one life form (genetically determined). The floristic composition can be translated into a life form spectrum which already reveals, without environmental studies, many of the environmental factors. Various life form systems exist. The criterion can be climate, in which case the way plants overcome the most stressful winter or dry season is the guiding principle. Plant adaptation to waterlogging, or lack of water, is used successfully as a criterion for classification. Adaptation to mechanical influences of wind and water is another important starting point for classification and interpretation of the indicative value of vegetation. Examples of the relationship between life form spectra and environment are to be given during the presentation of this paper.

In a way, the concept of the halophyte could be considered as a life form, although the directly visible morphological aspects are not strictly bound to halophytes as such. Salt in the soil moisture or groundwater may act via osmotic pressure through the same adaptation as does drought (succulence, xeromorphism). One speaks often of "physiological" drought. Similar action may be caused by low temperatures hampering the uptake of water by roots. It is not well known which influence of salt is more important: the physical one via osmotic pressure, or the chemical one (ion balance in the physiological processes). It is clear that adaptation to ion balance problems is not readily visible even if the process was known in detail (which is not the case). Many true halophytes are characterized by the fact that they can take up large amounts of salts, like NaCl, contrary to all true glycophytes that will die as soon as large quantities penetrate, or which cannot act against the osmotic pressure in the root environment and so die from physiological drought. Other halophytes do not take up salts like NaCl but increase their osmotic value by producing organic salts in their tissues, in order to be able to counteract the osmotic pressure in the soil moisture. Several halophytes have a special design for getting rid of very high salt concentrations in their tissues. They either excrete salts, which appear as crystals at leaf edges, etc., or concentrate it in special organs (salt hairs or bladders). Halophytes absorbing salts can be morphologically recognized in the field because they taste salty unless they grow in a soil without salt. These latter are facultative halophytes which can only be used as an indicator if they contain salt.

So only certain halophytic morphological adaptations can be used directly for indication. The same is true of the structure of halophytic vegetation. Main structural classes such as forest, steppe, grassland, thicket, scrub, savanna, are observed on saline and alkaline soils. These structures as such are not related to salt conditions. However, in the context of the landscape, they may be of great use for the delineation of legend units in a preliminary photo interpretation, or even after previous study in photo key interpretation surveys. Thus, also, the typical structure of certain salt water mangrove forests is indicative of coastal solonchaks.

In the interior of West Africa (Nigeria) the author could map accurately alkaline soils (solodized solonetz) from the occurrence of tree savanna-like vegetation structures on river terraces, and in uplands where these structures contrasted with savanna-woodland and woodland types, and more cultivated areas. In greater detail also specific structures can be useful in classification and recognition; for example, certain species belonging to Scirpus and Juncus have a typical 'centrifugal' form of rhizome development. They develop therefore in circular stands. This often makes it possible to distinguish such species from others, after some field work to identify the groups, occurring within the area. Phalaris species have an open stand of crescent-like forms, etc. In this and similar ways it is often possible to recognize on large scale photos (1:5 000 - 1:10 000) vegetation types and even single plants due to peculiar structural features. This refers also to halophytic vegetation types, although one cannot recognize specific patterns of halophytic vegetation in general. Terrain studies should reveal the pattern of halophytic vegetation in a study area. In this way structural vegetation properties can yet be of use in vegetation classification as well as in the recognition process during the mapping on photos or directly in the field. It will be clear that this type of structural differentiation will occur more in natural vegetation than in strongly human-influenced vegetation where crops dominate the more natural structures. Nontheless the pattern of damaged plots in crops may reveal to a skilled interpreter the source of damage. Waterlogging and salt damage are not always easy to distinguish from one another but the specific features of both can easily be separated from damage by other causes such as insect disease, storms, etc.

4. MAPPING

In many cases it is ultimately necessary to have the data on the effect of salt in map form. In land evaluation studies done as a base for regional planning this is a sine qua non. On the other hand, even without the need to transfer the data to planners, etc., via maps, a thorough study of land can only be done via a mapping stage. The map reveals features and relationships which appear only after the map image provides the whole. From the foregoing (Section 2.1), it is clear that in a more classical landscape photo interpretation approach the first product is a map that serves as the basis for further work such as sampling and classification. In surveys without photo interpretation or pure key-interpretation, the maps appear later. Their boundaries are drawn either on the photo, directly in the field, or interpolated from a more or less dense system of sample points in a grid, line or random distribution pattern. This is not the place to deal with details of mapping and cartographic procedures; some general aspects only will be mentioned.

It is not always necessary to print maps for eternity. In virgin areas which will be reclaimed, however, it is wise to make good documents of the original situation. In this case, a proper landscape vegetation map will be a good basis for development because such a map can even serve as a holistic landscape map, especially because under natural conditions of vegetation, soil and hydrology, inclusive salinity data are very closely related in cases where salinization exists. It is wise to collect also sufficient soil and geomorphological data during the survey and in the legend. The best survey methodology in such a case can be a holistic land survey (ITC, VII.4, see Zonneveld). For stages in development, or after degeneration of agricultural areas (salinization by irrigation without sufficient drainage, etc.) cheaper methods should be contemplated. For monitoring at short intervals computerized mapping procedures could be considered in which the input is in the form of cells, but this will only be of interest in experimental conditions.

Sequential survey (monitoring) however has its own special problems which will be treated in section 6.

5. EVALUATION AND INTERPRETATION

To be well done, the vegetation data to be mapped must be chosen in such a way that they will give optimal information on the proposed aim. This means a good indication of the salt condition of the land will be given usually in combination with moisture and waterlogging features. As far as crops are concerned, data on crop performance can also be used for indication, and moreover for the direct recording of actual and potential yields. Crops in this context do not only mean introduced agricultural plants like cereals, etc. The natural, more or less halophytic, vegetation often has a high value as a grazing resource. Several grass species such as Festuca, Agrostis, Poccinellia and the Chenopodiaceae (like Atriplex and many others) contribute strongly in many coastal and inland salt marshes to production of animal stock and wildlife.

An idea about the type of data known and to be collected can be gathered from the preceding chapters and moreover they are similar to those used in routine range land and crop survey in non saline areas. Some general aspects of halophytes and the basic origin of their indicative character has been given in section 3, where it has also been made clear that the interpretation of the occurrence of certain plant combinations should be done empirically on the spot. From basic physiological reactions sufficient is known to be sure that they are too complex to be used and that not sufficient knowledge exists to predict in detail what can be expected. However, experience shows that a good ecologist working on the spot is able to describe the rather narrow relationships between the vegetation types occurring and the environmental factors, in practical useful terms. Examples are given of the work of the author and collaborators in various parts of the world in coastal and inland saline and alkaline areas.

It is very important to realize that some environmental factors show strong fluctuations. This is especially the case with salt content itself. Natural vegetation and crops can readily act as a kind of average milieu indicator, at least on a mean of seasonal changes. Annuals react rather quickly to changes within the season and are therefore to be judged differently from perennials. Gradual changes over the years will affect perennials and annuals equally. The time lag between the reaction of the vegetation on increasing or decreasing salt content is important to know. No absolute figures can be given however.

Accessibility also plays a part. This means that seeds or other diaspores should be available at a place from where they can be quickly transported. Many halophytic plants disseminate easily. Within one or two seasons of salinity it can be expected that even in remote areas halophytes have reached the place. The fact that salinization is usually connected with waterlogging and waterlogging attracts water birds, and natural halophytic areas (because of non-intensive human use) are usually still rich in birds, seeds and diaspores will be brought in easily by "long distance airtransport" on natural wings. So far, the author has not found exact data on the speed of occurrence of halophytes in remote areas with increasing salinization.

In the following section the methods of recording and predicting change will be discussed. As in any evaluation of land features, the various steps of evaluation should be distinguished: basic survey, quality classification suitability, recommended use. For this paper the first two steps are relevant. Basic survey should be done unbiased by subjective evaluation ideas. The translation of basic data into indicative value can be called in land-appraisal jargon: quality classification (see Approaches to Land Classification, Soils Bulletin 22, FAO, Rome 1974; Land Evaluation for Rural Purposes, ILRI 1972 and Zonneveld, ITC Handbook, VII.4).

The indication value of vegetation will also serve in combination with soil and hydrological survey results as a basis for suitability classification for land use and amelioration measures. Data on biomass and production are other important 'qualities' of the vegetation.

6. PLANT SUCCESSION, MONITORING AND PROGNOSIS

6.1 General

A study of the dynamic aspects of vegetation (succession study) is not only essential for an understanding of the vegetation and its ecosystem(s) but also for the application of the results. The nature of most observations is that (only) a moment is recorded. In order to understand the quality at that moment, knowledge of the past is required and especially for practical application a demand exists to know what the position (and change) will be in the future. If one only has the data of the moment (the actual situation), one can make a guess about the past using experience on situations occurring elsewhere (e.g. one practical aspect of this understanding is the discussion in the preceding chapter on the time required before indicative vegetation elements have settled at the spot). The future can only be approached by prognosis.

Prognosis can best be made on the basis of the past and present observations together indicating lines likely to develop. So monitoring changes is a means to improve understanding of the present and for prediction of the future. Before reviewing the methods of monitoring, several types of changes in vegetation have to be discussed.

For the purpose of our study of salt affected lands the most important plant succession is the allogenic type. This is a change in the vegetation induced by a change of the environmental factors. Due to an alteration in the hydrological situation (caused by man for example), the environment to which a certain vegetation was adapted changes so much that several components of that vegetation disappear hence and make way for other plants that can stand, or even prefer, the new situation. In the case of halophytic vegetation the change in the situation may be an increase of salt content in soil and water due to impeded drainage, or just a decrease of salinity by leaching. Also direct impact on vegetation by reclamation, planting crops, or the reverse, putting arable land into fallow, induces obvious plant successions.

Allogenic successions also occur under pure natural conditions. The sedimentation in estuaries, salt lakes and coastal areas causes a gradual or even abrupt allogenic change giving rise to plant successions in all brackish and marine foreland vegetation.

The opposite of the allogenic succession is the autogenic succession, whereby the change is induced by plants growing in a certain place themselves. In this case, one observes a change in the environment but it is the plants themselves that induce it, extracting water and minerals or by adding organic matter, etc. Such a succession tends to lead from a pioneer stage to what is called a 'climax' vegetation where the latter and the environment are in a certain type of equilibrium, remaining more or less constant over a relatively long period.

A distinct separation between both types of succession cannot be made. Even in saline vegetation, which usually has a pioneer character, allogenic and autogenic activities may coincide; e.g. sedimentation is influenced by the plants, salinization and desalinization are also partly influenced by the behaviour of the plants (see section 1). In practice it may be of importance to know whether an observed succession is more allogenic or autogenic. Man might make use of autogenio influences of vegetation for his own benefit.

Especially when prognosticating the future, a certain knowledge is required about the process of change of the environment under the influence of those very changes taking place in the environment as well as of the vegetation components themselves.

6.2 Succession Study and Monitoring

The most accurate type of succession study is sequential sampling on permanent sample plots and sequential mapping. These are time consuming and therefore very expensive methods, but for real studies in experimental areas they are however indispensable. Also, here, aerial photography can be of great help, in the same way as for a single survey. However aerial photography has an extra advantage in this case because the amount of ground truth sampling per survey can be reduced. Several aspects of mapping units in the sequential stages might not need resampling during the subsequent stages. For sequential surveys once a year, or more often, normal aerial photography is most useful. For more frequent changes however such a survey is too costly.

At this point the great (and the main) advantage of satellite imagery has to be introduced. At present satellite imagery gives (provided atmospheric conditions are ideal) a picture of the same area every 18 days; in the future it will be possible to reduce that numbers of days. The satellite image, even the digital displays of it, do not give the same information that can be produced by airborne photography (minimum detail area 10 meters down to 10 cm on photos), but the sequential aspect is of great value. The loss of detail can be overcome by a combination of satellite imagery with normal large scale photography.

The very frequent recording possible with satellites is only necessary for following seasonal fluctuations and some erratic changes due to natural or anthropogenic factors. But as soon as there are regular permanent satellites for vegetation and crop recording, satellite imagery can also be used for the recording of yearly changes. Several proposals for satellites are already under study in various countries (for high frequency, with special construction for "privacy of data" for the using country. Speculation exists on the possibility of recording directly chemical characteristics of materials (e.g. salts) at the earth's surface by remote sensing. Theoretically there are certainly possibilities, but practically it is not likely that a feasible operational system will be discoverd within foreseeable time that would be of use in the study of salt affected lands in general. Monitoring of changes can also be done from a fixed point (an existing tower or pylon, or a contraption built for such a purpose). Any type of sensing can be done from such a platform. Examples are given of monitoring vegetation in allogenic succession by the author (see Zonneveld 1974). For certain experimental or fundamental studies long-lasting succession studies are valuable. However in most practical cases one cannot wait some decennia.

In cases of one or several sequential data, prognoses have to be made for the vegetation that can be expected in the future, either because of the value of the vegetation in itself (food source) or for the environmental condition that might be there in the future (increasing or decreasing the management system at the place, if any exists). In those cases empirical comparative study of the actual situation is the only way. If the results of long years of studies in a similar area are available, these data can be of great use in the estimation. In sedimentary areas often various stages of sedimentation (and also erosion) occur side by side. A careful study of these stages may allow the setting up of a scheme of succession lines which can be used in prediction. However, not all schemes in literature are too reliable. So the surveyor should use his own common sense. In areas where older maps and airphotos exist, both are of great value in studying succession lines, and especially also the time involved in the processes of change. The author gives various examples of how, with the help of old aerial photos, a former situation could be interpreted making use of the knowledge of the present land and vegetation features. In certain cases not only maps but written and oral information about times past, may be of use.

The prognosis of possibilities for agricultural and other use are not only based on vegetation data. The expected evolution, negative or positive, of the environment derived among other things from the vegetation as an indicator, may, expressed in for instance salt contents of water and soil, lead via known relations between salt content and crops to the prediction of possibilities for these crops on certain lands. The prognosis of production of vegetation as a grazing resource on saline lands does not differ from that in other grazing areas. For detailed accurate knowledge, sequential mass determination are the basis for such prognosis by clipping on sample plots, for repeated determination of the standing crop.

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MODELLING OF SALT MOVEMENT THROUGH THE SOIL PROFILE

by

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The management of irrigated soils or the reclamation of saline soils requires a knowledge of the way salts move through the soil profile. The accuracy or the completeness of the processes involved in this movement may vary greatly: from the simple displacement of the soil solution by the displacing solution without mixing to complete description involving considerations of unsaturated flow, ion exchange, solubilization and precipitation reactions, biological oxidations and reductions, etc. Whatever the sophistication of the model that purports to describe the salt movement, various constraints of an economic or agricultural nature may be used for arriving at an optimization of the irrigation or reclamation process according to the methods used in econometrics.

Clearly, this is the most easily identifiable objective in any attempt at the development of such a model and fields other than irrigated agriculture may benefit from its use, such as minimizing contamination of water reserves by pesticide or nitrate. This is the reason why studies along these lines are becoming more and more current in many countries. Besides this obvious practical utilization of the mathematical model, two other benefits should not be overlooked; the first consists in enabling one to extend greatly the scope of a field experiment once its results have been quantitatively described by a model; the second is the positive interaction between model building and field or laboratory experimentation, the former pointing out gaps in the knowledge of relationships or parameters in the processes involved in salt movement.

Since this is not intended as a review paper but rather a support for a discussion on the problem of model building in salt movement, no attempt will be made to quote the many valuable contributions that have been made to this question in several countries.

The description of the movement of salt through the soil must be based on the relevant form of the Fokker-Planck equation which, for unidimensional flow, reads:

Time change of concentration between depth Z and Z + dZ = Decrease of salt flow from Z to Z + dZ

or

$$\frac{\partial c}{\partial t} = - \frac{\partial}{\partial x} \quad (\phi)$$

if the flux of salt results from the superposition of a diffusive ($-D \frac{\partial c}{\partial x}$) and a convective flux ($+ vc$), for constant D and v, we have:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - \frac{v \partial c}{\partial x}$$

There exist analytical solutions of this partial differential equation satisfying appropriate boundary conditions, the most general of which seem to be for a column of finite length L

at $x = 0$ for $t > 0$

$$vc - D \frac{\partial c}{\partial x} = vc_0$$

which expresses the fact that at the soil surface the rate of salt inflow vc_0 must be equal to the combined diffusion and convective flows.

Furthermore, at the bottom of the soil column:

$$\frac{\partial c}{\partial x} = 0 \quad \text{for} \quad x = L, \quad t \geqslant 0$$

in order to "avoid the unacceptable condition that the solute concentration passes through a maximum (or minimum) in the interior of the medium", an intuitive reason that can be replaced by a more rigorous reasoning.

The analytical solution satisfying these conditions is an infinite sum of terms alternating in signs and as soon as the absolute magnitude of the first term is above a certain value, no convergence can be obtained due to rounding-off errors. This already obtains at values of the dimensionless time $t = vt/L$ which are well within the maximum values of experimental interest for values of the Péclet number $P = vL/4D$, well below those commonly found for actual soil profiles. Fortunately an asymptotic formula may be found which converges at all times and everywhere within the practical range of Péclet numbers. The derivation of the Fokker-Planck equation precludes any interaction of the solute with the soil column. This ideal case may be more or less exactly realized with solutes such as chloride or, better still, tritiated water. Even though, in most circumstances, this assumption will not hold, experiments with solutes for which it is reasonably valid are extremely useful. This is due to the fact that the analysis of the breakthrough or elution curve of a solute through or from a soil column will supply two important parameters: the dispersion coefficient D and the actual porosity of the column.

In doing an experiment of this type, the length of the column L is fixed as well as the Darcy velocity V through it, the average pore velocity v being given by V/ϕ , ϕ being the porosity, which is a priori unknown and may differ from one solute to the other; this is to be expected since for a migrating anion or tritiated water the molecule will "see" the water-filled porosity in quite a different way. The other parameter which is a priori unknown is D the dispersion coefficient or what amounts to the same once ϕ is known, the Péclet number. Empirical methods based on numerical relationships have been proposed for arriving at these two parameters from the analysis of breakthrough curves. They are based on the fact that most of the points from such a curve are log-normally distributed. We have found it more convenient to use an automatic search programme for the two parameters which optimize the fit between the experimental points and the asymptotic solution mentioned above. It is true that much simpler formulations of the solution exist and have been frequently used in the literature, even through the boundary conditions and when the values of the Péclet number were not such as to ensure their validity. Since the burden of the work rests on the computer once the search programme has been programmed, there is no reason for not using the most general form of the solution. Two important parameters characteristic of the soil will thereby be provided: its dispersion coefficient and the fraction of the water-filled porosity which is accessible to the moving solute.

Another advantage of applying the analytical solution is that numerical solutions may be tested against it with respect to their convergence and stability before being adapted to sub-routines describing exchange or solubilization reactions. It is of course impossible to solve the partial differential equation describing diffusion with convection with due regard to the possible exchange or precipitation reactions unless drastic simplifications are accepted with regard to the formulation of the equilibrium or kinetics relationships. This does not disregard the fact that fairly elaborate treatments have made it possible to account for convection-diffusion processes coupled to simple ion-exchange relationships with simple kinetics. There is at least one example of a numerical treatment of the solution being followed by a rather elaborate derivation of the analytical solution for the most simple cases considered with the conclusion that, since the analytical and numerical approaches led to the same results in the most simple cases, it could be expected that the same would obtain when the analytical method was powerless.

The basis of the still most commonly used method of finite differences consists in replacing derivatives by finite differences divided by the time or space increments. For instance, if instead of a vanishingly small time or space increment we take a finite time or space step k or h respectively, the values of c at x and t, $c(x,t)$ will be denoted by $c(ih,jk)$ where i and j are integers.

Consequently the time derivative will be expressed by:

$$\frac{\partial c}{\partial t} = \frac{c_{i,j+1} - c_{i,j}}{k}$$

and the second order differential with respect to x by:

$$\frac{\partial^2 c}{\partial x^2} = \frac{c_{i+1,j} - 2c_{i,j} + c_{i-1,j}}{h^2}$$

the first formulation being obvious, the second resulting from a fairly simple derivation.

Several ways of formulating the finite difference equivalent of a partial differential equation are possible such as for instance taking the backward difference $(c_{i,j} - c_{i,j-1})/k$ instead of the forward difference as above.

One of the possibilities seems worthy of a more detailed examination since it has been used quite frequently in several publications by soil scientists. If we consider a soil with a cation exchange capacity B in a column where the soil-water ratio is r(g soil/l water) a number R can be defined by:

$$R = \frac{Br}{c_o}$$

where c_o is the concentration of the displacing solution in meq.l^{-1}. If at time 0 all charges in the soil are compensated by Ca^{++}, passage through a NaCl solution will cause a Na-Ca exchange which will be expressed at any time or level in the column by the fraction of Ca^{++} in the solution (x) and by its fraction of the cation exchange capacity (Y), the change in the latter fraction being expressed by z.

Between the level x and $x + \Delta x$ we will have for the change in the amount of Ca^{++} present:

$$\frac{\partial}{\partial t} (X + RY) \Delta x = - D \frac{\partial X}{\partial x} + vX \quad \text{(in flux)}$$

$$- \{- D \frac{\partial}{\partial x} (X - ZR) + v(X - ZR) \} \quad \text{(out flux)}$$

or

$$\frac{\partial X}{\partial t} + R \frac{\partial Y}{\partial t} = D \frac{\partial^2 X}{\partial x^2} - v \frac{\partial X}{\partial x} - DR \frac{\partial^2 Z}{\partial x^2} + vR \frac{\partial Z}{\partial x}$$

The finite difference form will then be:

$$X_{i,j} - X_{i,j-1} + R\,(Y_{i,j} - Y_{i,j-1}) =$$

$$\frac{Dk}{h^2}\,(X_{i+1,j} - 2X_{i,j} + X_{i-1,j}) - \frac{k}{2h}\,(X_{i+1,j} - X_{i-1,j})$$

$$- \frac{DkR}{h^2}\,(Z_{i+1,j} - 2Z_{i,j} + Z_{i-1,j}) + \frac{vRk}{2h}\,(Z_{i+1,j} - Z_{i-1,j})$$

If we define the numbers α, t and λ by:

$$\alpha = \frac{D}{vL}\,, \quad t = \frac{vt}{L}\,, \quad \lambda = \frac{\lambda}{L}$$

Choosing the dimensionless time and space increments (for which we keep the same symbols) in such a way that:

$$2\,\alpha k = h^2$$

Thereby taking care of the convergence of the numerical solution since its condition is:

$$\frac{\alpha k}{h^2} \leqslant \frac{1}{2}$$

Since α will always be smaller than unity, we can fix h such that:

$$h = 2\alpha$$

We then have:

$$X_{i,j} = \frac{1}{2}\,\{X_{i,j-1} + X_{i-1,j}\} - \frac{R}{2}\,Z_{i-1,j}$$

since

$$Y_{i,j} = Y_{i,j-1} + Z_{i,j}$$

In the absence of ion exchange the same reasoning would lead us to:

$$C_{i,j} = \frac{1}{2}\,\{C_{i,j-1} + C_{i-1,j}\}$$

this is a formulation which has been used by several authors under the guise:

$$C_{i,j} = RF.C_{i,j-1} + (1 - RF)C_{i-1,j}$$

where RF is the so-called "retention factor".

The following justification was presented for the use of this formulation.

The profile being partitioned in a certain number of layers, the movement of water is described by the fact that a given layer fills up to saturation and then empties into the layer below returning to field capacity before filling up again. If the saturation content of layer i is denoted by SP_i and its field capacity by FC_i then applying the salt conservation principle to each layer and supposing that perfect mixing occurs in each layer we have:

$$C_{i,j} SP_i = C_{i-1,j} (SP_i - FC_i) + C_{i,j-1} FC_i$$

or

$$C_{i,j} = (1 - \frac{FC_i}{SP_i}) C_{i-1,j} + \frac{FC_i}{SP_i} C_{i,j-1}$$

Since the retention factor defined by FC/SP will be close to 0.5 for most soils, this explains the fairly wide use of this formulation in spite of its inconsistent physical justification. Turning back to the expression involving ion exchange as expressed by Z, the amount by which the fraction of adsorbed Ca^{++} decreases when a solution of Na^{+} is passed through the soil column. The problem would be fairly simple and in fact amenable to an analytical solution if a linear exchange isotherm obtained.

As a rule however the selectivity coefficient:

$$K_c = f(X,Y) = 2c_0 \frac{Y(1-X)^2}{X(1-Y)^2} \frac{\gamma_+^2}{\gamma_{++}}$$

(where the γ refer to the solution activity coefficients) is not constant, nor can it be expressed as a simple function of γ with the exception of the uni-univalent exchange which again makes it possible to find an analytical solution for the problem. The common practice so far has been to replace the selectivity coefficient as defined above by some other expression which is fairly constant over a wide enough range of composition. This is the case for Gapon's formulation of the selectivity coefficient and explains its common use.

There is an alternate possibility which is making use of the cubic relationship which is commonly observed between the selectivity coefficient as defined above and the adsorbed fraction of the divalent cation. This allows us to define a function f by:

$$f(X,Y,c_o) = K_c - (a + bY + cY^2 + dY^3) = 0.$$

If X and R are not equilibrium value, Y must be increased by an amount Z such that:

$$f\{(X - ZR), (Y + Z), C_o\} = 0$$

Z is thus a root of the above equation. At each time step, X can be calculated, the root Z is then found, X and Y adjusted and the process is repeated for the next step. This procedure has the advantage that, once an exchange isotherm has been established, full use is made of it over its entire range.

Progress is modelling salt movement in soil will depend on the acquisition of further knowledge on the kinetics of the processes. If ion exchange chromatography can be described fairly easily when exchange equilibria are assumed to be instantaneous, this is no longer the case if incomplete equilibrium obtains, the same situation obtains in the case of solubilization and precipitation reactions where kinetic considerations are even more crucial.

For some irreversible reactions the kinetic aspect becomes the only one of importance, and this is obviously the case in the movement of nitrogen compounds through the profile.

CONCLUSION

Mathematical modelling is not an end in itself but should be considered as a tool to arrive at a better management of irrigated soils. Consequently taking account of the very great lateral heterogeneity of the soil, great accuracy of the prediction of a model should not be aimed at. On the other hand, models can also be considered as tools for integrating, mathematically and figuratively speaking, knowledge gathered on the rate laws of important soil processes; then the requirements regarding the predictive value of a model, without ad hoc adjustment of the parameters, would be entirely different to those for optimizing management or reclamation.

D. Tentative Guidelines

Paper 16

INTERPRETATION OF QUALITY OF WATER FOR IRRIGATION

by

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SUMMARY

1. Quality of water has meaning only in relation to a particular use. In agriculture water quality is related to effects on soils, crops and management necessary to compensate for problems linked to water quality.

Not all agricultural problems of salinity, soil permeability, toxicity, etc., can be related to quality of the water applied. Quality of water must be placed in proper perspective with all the other factors affecting crop production.

2. A water analysis is essential to water quality evaluation. Analyses or determinations needed are EC_w, Ca+Mg, Na, CO_3+HCO_3, Cl, SO_4, B, NO_3-N, pH.

3. Water analyses can be evaluated in relation to four general problem areas - Salinity, Permeability, Toxicity and Miscellaneous.

4. "Guidelines for Interpretation of Quality of Water for Irrigation" have been prepared based on the above four problem areas and including three degrees of the problem expected - No Problem, Increasing Problems, Severe Problems. Guideline values for each degree of problem are given.

5. Crops vary greatly in their tolerance of poor quality waters and therefore the suitability of a water for irrigation will vary with the crop. Crop tolerance tables for salinity are presented.

6. Leaching Requirement (LR) is the minimum amount of water that must percolate through the active root zone to prevent excessive accumulation of salts. Leaching requirements for various crops for specific qualities of water are given in the Crop Tolerance Tables with the new method of calculation of LR now being discussed by the U.S. Salinity Laboratory.

7. Prevention of a potential problem is just as important as correction of a problem. By using the guidelines for evaluation of the problem potential, such as salinity, and the crop tolerance tables to select a crop compatible with the available quality of water, and by following other suggested corrective management alternatives in the guidelines, a water user may be able to understand the potential problems related to water quality and make good management decisions to adjust to existing water quality.

8. Permeability problems due to water quality are usually related to either extremely low salinity of the water or to an imbalance of sodium, calcium and magnesium (the sodium adsorption ratio). Guideline values are given at which permeability problems are expected from low salt waters or from waters with high sodium adsorption ratio (now modified by carbonate-bicarbonates and reported as adjusted SAR). Corrective action is suggested.

9. Toxicity problems are often very specific for a certain water constituent and crop. Guidelines recognize toxicities due to sodium, chloride, or boron due either to root absorption from soil solution or to foliar absorption from leaves wetted by sprinkler applied water. Management alternatives are suggested.

10. Miscellaneous problems include a mixed group of unrelated problems - excessive vegetative growth due to nitrogen, white deposits from sprinkler irrigation, etc. Corrective actions are suggested.

11. A few typical water analyses with brief guideline interpretations of the quality-related problem potential are given.

1. WHAT DOES WATER QUALITY MEAN?

Quality means different things to different people. Quality is difficult to evaluate except in terms related to the specific use. For household use, the taste, hardness and possible effects on health, food, drink, clothes and fixtures are all quality factors. For industrial use, corrosion, scaling, or certain other adverse effects on manufacturing or processing become the quality factors of paramount importance. For irrigation, water quality is related to its effects on soils and crops, and on the management that may be necessary to control or compensate for the water quality related problem.

2. HOW DOES IRRIGATION WATER QUALITY AFFECT AGRICULTURE?

Water diverted from springs or streams or pumped out of wells from under ground is never pure but always contains measurable quantities of soluble salts. These dissolved salts, if present in sufficient quantity, can adversely affect yield of crop or accumulate to affect productivity of soils. Significant adjustments and changes in farm practices may be required to attempt to compensate for these water quality related effects.

Crops and soils are affected in different ways by the several different types of dissolved salts. A water analysis is needed to determine what types of salts are present; then these must be evaluated in terms of their expected impact upon soils and crops.

3. WHAT SHOULD BE INCLUDED IN A WATER ANALYSIS?

The usual laboratory determinations needed to evaluate the suitability of an irrigation water should include 1) electrical conductance (a measure of the total salts present), 2) chemical analysis for sodium, calcium and magnesium, chlorides, sulphates, carbonates and bicarbonates, and 3) further determinations as may be needed to evaluate other specific chemical constituents or general quality factors (usually including boron, nitrates and pH and infrequently other solubles such as lithium, potassium, iron or ammonia).

4. HOW ARE WATER ANALYSES EVALUATED?

A general water quality evaluation can be made by interpreting the above listed laboratory determinations in relation to four general problem areas - Salinity, Permeability, Toxicity and Miscellaneous.

i. Salinity Problems

These are associated with the total quantity of dissolved solids (salts) in the water and their effect upon crop growth. Salinity is usually measured and reported as electrical conductance (EC_w) or total dissolved solids (TDS).

ii. Permeability Problems

Certain water constituents reduce soil permeability. The resultant poor permeability makes it more difficult to supply crops with needed water for good growth and may greatly add to cropping difficulties through waterlogging of surface soils accompanied by disease, salinity, weed and nutrition problems. The permeability problem potential is evaluated from a comparison of the quantity of sodium present in the water relative to the calcium and magnesium.

Carbonates and bicarbonates will also effect soil permeability under certain conditions and must be evaluated.

iii. Specific Ion Toxicity

Certain specific solubles (ions) have a direct toxic effect on crop growth. Toxic solubles included are boron, chlorides and sodium.

iv. Miscellaneous Problems

In this special unrelated group are included such crop production problems as excessive plant vigour or excessive vegetative growth resulting from nitrogen in the water supply, white deposits on fruit or leaves due to sprinkler irrigation with high bicarbonate water and problems that may be related to pH such as high acidity or high alkalinity.

5. GUIDELINES HELP IN WATER QUALITY EVALUATION

"Guidelines for Interpretation of Quality of Water for Irrigation" using the four problem areas mentioned were prepared by the University of California Committee of Consultants (1972). These "guidelines" (see Table 1) have evolved from a long line of former guidelines used over the years and are believed to correlate well with field conditions. Several assumptions regarding their preparation along with comments on their use are also given (see Table 2). Many of the recent research findings and reports from the U.S. Salinity Laboratory have been used in formulation of these "Guidelines". (Refer to papers by Drs. Van Schilfgaarde and Rhoades presented at this Consultation.)

Each of the four problem areas - salinity, permeability, toxicity and miscellaneous - are further separated into three degrees of severity based on expected seriousness of the problem after several years of irrigation. "Water Quality Guideline" interpretive values are shown that are associated with a "No Problem", "Increasing Problems" and "Severe Problems" potential. The "No Problem" potential indicates that for waters containing less than this listed value the water user would not ordinarily recognize a soil or cropping problem due to water quality. In contrast, the "Severe Problems" evaluation indicates the water user would ordinarily recognize there were some fairly severe soil or cropping problems associated with the continued use of this water. From "No Problem" to "Severe Problems" the water user should experience gradually "Increasing Problems". In addition to evaluating the potential problem an indication of the corrective action to be taken is also presented. The water user should try to compensate for an indicated potential quality problem by adopting practices to prevent the problem from developing or try to correct or compensate for an existing problem.

Table 1 GUIDELINES FOR INTERPRETATION OF QUALITY OF WATER FOR IRRIGATION

Interpretations are based on possible effects of constituents on crops and/or soils. Guidelines are flexible and should be modified when warranted by local experience or special conditions of crop, soil, and method of irrigation.

PROBLEM AND RELATED CONSTITUENT	WATER QUALITY GUIDELINES		
	No Problem	Increasing Problems	Severe Problems
Salinity 1/			
EC_w of irrigation water, in millimhos/cm	<0.75	0.75 - 3.0	>3.0
Permeability			
EC_w of irrigation water, in mmho/cm	>0.5	<0.5	<0.2
adj.SAR 2/	<6.0	6.0 - 9.0	>9.0
Specific ion toxicity 3/			
from ROOT absorption			
Sodium (evaluate by adj.SAR)	<3	3.0 - 9.0	>9.0
Chloride (me/l)	<4	4.0 - 10	>10
(mg/l or ppm)	<142	142 - 355	>355
Boron (mg/l or ppm)	<0.5	0.5 - 2.0	2.0 - 10.0
from FOLIAR absorption 4/ (sprinklers)			
Sodium (me/l)	<3.0	>3.0	----
(mg/l or ppm)	<69	>69	----
Chloride (me/l)	<3.0	>3.0	----
(mg/l or ppm)	<106	>106	----
Miscellaneous 5/			
NH_4-N, NO_3-N mg/l or ppm, for sensitive crops	<5	5 - 30	>30
HCO_3 (me/l) [only with overhead sprinklers]	<1.5	1.5 - 8.5	>8.5
(mg/l or ppm)	<90	90 - 520	>520
pH	normal range = 6.5 - 8.4		-----

1/ Assumes water for crop plus needed water for leaching requirement (LR) will be applied. Crops vary in tolerance to salinity. Refer to tables for crop tolerance and LR. (mmho/cm X 640 = approximate total dissolved solids (TDS) in mg/l or ppm; mmho X 1000 = micromhos)

2/ adj.SAR (Adjusted Sodium Adsorption Ratio) is calculated from a modified equation developed by U.S. Salinity Laboratory to include added effects of precipitation or dissolution of calcium in soils and related to $CO_3 + HCO_3$ concentrations.

To evaluate sodium (permeability) hazard:

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

pHc is a calculated value based on total cations, Ca+Mg, and CO_3+HCO_3. Calculating and reporting will be done by reporting laboratory. NOTE: Na, Ca+Mg, CO_3+HCO_3 should be in me/l.

Permeability problems, related to low EC or high adj.SAR of water, can be reduced if necessary by adding gypsum. Usual application rate per acre foot of applied water is from 200 to about 1000 lbs. (234 lbs. of 100% gypsum added to 1 acre foot of water will supply 1 me/l of calcium and raise the ECw about 0.1 mmho). In many cases a soil application may be needed.

3/ Most tree crops and woody ornamentals are sensitive to sodium and chloride (use values shown). Most annual crops are not sensitive (use salinity tolerance tables). For boron sensitivity, refer to boron tolerance tables.

4/ Leaf areas wet by sprinklers (rotating heads) may show a leaf burn due to sodium or chloride absorption under low-humidity, high-evaporation conditions. (Evaporation increases ion concentration in water films on leaves between rotations of sprinkler heads.)

5/ Excess N may affect production or quality of certain crops, e.g. sugar beets, citrus, avocados, apricots, grapes etc.
(1 mg/l NO_3-N = 2.72 lbs. N/acre foot of applied water).
HCO_3 with overhead sprinkler irrigation may cause a white carbonate deposit to form on fruit and leaves.

Symbol	Name
EC_w	Electrical Conductivity of water
mmho/cm	millimho per centimeter
<	less than
>	more than
mg/l	milligrams per liter
ppm	parts per million
LR	Leaching Requirement
me/l	milliequivalents per liter
TDS	Total Dissolved Solids

Symbol	Name	Equiv. Wt.
Na	Sodium	23.00
Ca	Calcium	20.04
Mg	Magnesium	12.16
CO_3	Carbonate	30.00
HCO_3	Bicarbonate	61.00
NO_3-N	Nitrate-nitrogen	14.00
Cl	Chloride	35.45

17.1 ppm = 1 grain per gallon

Table 2

Assumptions and Comments on Guidelines for Interpretation of Quality of Water for Irrigation Developed by UC-Committee of Consultants.

1. These "guidelines" are flexible and intended for use in estimating the potential hazards to crop production associated with long term use of the particular water being evaluated. "Guidelines" should be modified when warranted by local experience and special conditions of crop, soil, method of irrigation or level of soil-water-crop management. Changes of 10 to 20 percent above or below an indicated guideline value may have little significance if considered in proper perspective along with all other variables that enter into a yield of crop.

2. It is assumed that the water will be used under average conditions - soil texture, internal drainage, total water use, climate, and salt tolerance of crop. Large deviations from the average might make it unsafe to use water which under average conditions, would be good, or might make it safe to use water, which under average conditions, would be of doubtful quality.

3. The divisions into "No problem - Increasing problem - Severe problem" is more-or-less arbitrary but based on large numbers of field studies and observations, as well as carefully controlled greenhouse and small plot research conducted by various researchers over the past 40 years or more. Guidelines of one sort or another have been proposed by U.S. Geological Survey, University of California, U.S. Salinity Laboratory and many others starting as early as 1911. As new research and observations have developed additional information for assessing water quality,guidelines have been modified.

4. These "guidelines" apply to surface irrigation methods such as furrow, flood, basin, sprinklers, or any other which applies water on an "as-needed" basis and which allows for an extended dry-down period between irrigations during which the crop uses up a considerable portion of the available stored water.

5. The guidelines incorporate some of the newer concepts in soil-plant-water relationships as recently developed at U.S. Salinity Laboratory. Uptake of water occurs mostly from the upper two-thirds of the rooting depth of crop (the "more-active" part of the root zone). Each irrigation normally will leach this upper soil area and maintain it at relatively low salinity. Salts applied in the irrigation water under reasonable irrigation management concentrate in the soil water in this active root zone to about three times the concentration of the applied irrigation water and the salinity of this root area is representative of the salinity levels to which the plant responds. The salinity of the lower root zone is of less importance as long as plants are reasonably well supplied with moisture in the upper, "more-active", root zone.

These guidelines represent the 1974 consensus of the UC-Committee of Consultants. It is recognized they are not perfect and it is expected they will be modified from time to time as further knowledge and experience dictate.

6. SALINITY PROBLEMS

Salinity problems are associated with the dissolved salts in the applied water. There are two components to the salinity problem. The first concerns the salinity of the applied irrigation water and its direct, rapid effect on the crop. The second concerns the salinity that may develop more slowly in the root zone over a period of time due to accumulation of salts and their effect on the crop. The two need to be considered separately.

Salinity accumulating within the root zone can be controlled, within limits, by application of extra water to satisfy an indicated leaching requirement. But, there is a limit to the correction that can be accomplished by leaching or improved management. This limit is closely related to the actual salinity of the applied irrigation water. If the salinity (EC_w) of the applied water is excessive and exceeds the tolerance of the crop, less than a full potential yield is to be expected even though extra water is applied for leaching. Improved water management and extra leaching may produce better yields but only up to the yield limits imposed due to the salinity of the applied water.

Salinity problems and their management are often complicated by high or perched water tables. The usual corrective practices for salinity include use of extra water for leaching to remove the salts, and will very often include artificial or improved drainage (tile or open drains) to assure that leaching is effective. In some cases it may even be necessary to change the crop to one more tolerant of the salinity of soil or water.

7. SELECTION OF CROP TO MATCH IRRIGATION WATER QUALITY AND SOIL SALINITY

Cultural practices, crop selection and management to prevent salinity problems from developing are just as important as are corrective actions after problems develop. There are several management alternatives available to prevent or reduce salinity problems. One of the first alternatives relates to the choice of crop. Crops vary greatly in their salt tolerance and therefore the suitability of a relatively salty water for irrigation will also vary with the crop. For example, a water with EC_w=2 millimhos is poorly suited for irrigation of a salt sensitive crop such as field beans (tolerance of field beans at full yield potential is EC_w=0.7) but is excellent for corn (tolerance of corn at full yield potential is EC_w=2.2).

The crop tolerance tables (immediately ensuing pages) can be used to select crops to match the quality of the available water supply and the expected degree of soil salinity to which the crop will be exposed. These tables list tolerances of several representative field, vegetable, forage and fruit crops to both the salinity of the water applied (EC_w) and to the salinity of the soil (EC_e). Also

Table 3

CROP TOLERANCE AND LEACHING REQUIREMENT TABLES

Including Yield Decrement to be expected for Certain Crops Due to Salinity of Irrigation Water when Common Surface Irrigation Methods are Used 1/

FIELD CROPS

Crop	0%			10%			25%			50%			MAXIMUM
	ECe 2/	ECw 2/	LR 3/ %	ECe	ECw	LR%	ECe	ECw	LR%	ECe	ECw	LR%	ECdw 3/
Barley	8	5.3	12	12	8	18	16	10.7	24	18	12	27	44
Sugarbeets	6.7 4/	4.5	11	10 4/	6.7	16	13	8.7	21	16	10.7	26	42
Cotton	6.7	4.5	11	10	6.7	16	12	8	19	16	10.7	26	42
Safflower	5.3	3.5	12.5	8	5.3	19	11	7.3	26	14	8	28.5	28
Wheat	4.7 4/	3.1	8	7 4/	4.7	12	10	6.7	17	14	9.3	23	40
Sorghum	4	2.7	7.5	6	4	11	9	6	17	12	8	22	36
Soybean	3.7	2.5	10	5.5	3.7	14	7	4.7	18	9	6	23	26
Rice (paddy)	3.3	2.2	9	5	3.3	14	6	4	16	8	5.3	22	24
Corn (maize)	3.3	2.2	12	5	3.3	18	6	4	22	7	4.7	26	18
Sesbania	2.7	1.8	7	4	2.7	10	5.5	3.7	14	9	6	23	26
Broadbean	2.3	1.5	8	3.5	2.3	13	4.5	3	17	6.5	4.3	24	18
Flax	2	1.3	7	3	2	11	4.5	3	17	6.5	4.3	24	18
Beans (field)	1	.7	6	1.5	1	8	2	1.3	11	3.5	2.3	19	12

1/ From USDA-Ag. Inf. Bull. 283 and personal communication from Dr. Leon Bernstein, U.S. Salinity Laboratory, Riverside, California.

2/ ECe means electrical conductivity of saturation extract in millimhos per centimetre (mmho/cm)
ECw means electrical conductivity of irrigation water in mmho/cm.
LR = Leaching Requirement = $\frac{ECw \times 100}{ECdw}$. For an approximate conversion to TDS, mg/l, or ppm multiply mmho/cm by 640.

3/ ECdw is maximum concentration of salts that can occur in drainage water under crops due to ET (evapotranspiration). Use to calculate leaching requirement ($LR = ECw/EC_{dw}$) to maintain needed ECe in more active root area. Leaching Requirement (LR) means that fraction of the irrigation water that must be leached through the active root zone to control soil salinity at a specified level.
At 100% efficiency, applied water (needed to satisfy ET + LR) is equal to $\frac{ET}{1-LR}$

4/ Tolerance during germination (beets) or early seedling stage (wheat, barley) is limited to ECe = about 4 mmho/cm in the upper soil area where germination and early growth takes place.

Note: Conversion from ECw to ECe assumes that irrigation water salts increase 3 fold in salinity in becoming soil water salts (ECsw). This occurs in the more active part of ECw X 3 = ECsw; ECsw ÷ 2 = ECe.

Table 4

VEGETABLE CROPS

Crop	0%			10%			25%			50%			Maximum
	ECe	ECw	LR%	ECe	ECw	LR%	ECe	ECw	LR%	ECe	ECw	LR%	ECdw
Beets	5.3	3.5	11	8	5.3	17	10	6.7	21	12	8	25	32
Spinach	3.7	2.5	12.5	5.5	3.7	18.5	7	4.7	23.5	8	5.3	26.5	20
Tomato	2.7	1.8	8	4	2.7	12	6.5	4.3	19.5	8	5.3	24	22
Broccoli	2.7	1.8	7	4	2.7	10	6	4	15	8	5.3	20	26
Cabbage	1.7	1.1	4	2.5	1.7	6.5	4	2.7	10	7	4.7	18	26
Potato	1.7	1.1	5.5	2.5	1.7	8.5	4	2.7	13.5	6	4	20	20
Sweet Corn	1.7	1.1	5.5	2.5	1.7	8.5	4	2.7	13.5	6	4	20	20
Sweet Potato	1.7	1.1	5.5	2.5	1.7	8.5	3.5	2.3	11.5	6	4	20	20
Lettuce	1.3	.9	5	2	1.3	7	3	2	11	5	3.3	18	18
Bell Pepper	1.3	.9	5	2	1.3	7	3	2	11	5	3.3	18	18
Onion	1.3	.9	7.5	2	1.3	11	3.5	2.3	19	4	2.7	22.5	12
Carrot	1	.7	6	1.5	1	8	2.5	1.7	14	4	2.7	22.5	12
Beans	1	.7	7	1.5	1	10	2	1.3	13	3.5	2.3	23	10
Cantaloupe 1/	2.3	1.5	8	3.5	2.3	12	No Data			No Data			-
Watermelon 1/	2	1.3	8	No Data			No Data			No Data			-

1/ Assumes ECdw = 20 similar to potato.

Table 5

FORAGE CROPS

Crop	0%			10%			25%			50%			Maximum
	ECe	ECw	LR%	ECe	ECw	LR%	ECe	ECw	LR%	ECe	ECw	LR%	ECdw
Bermuda Grass	8.7	5.8	13	13	8.7	20	16	10.7	24	18	12	27	44
Tall Wheat Grass	7.3	4.9	11	11	7.3	17	15	10	23	18	12	27	44
Crested Wh. Grass	4	2.7	6	6	4	9	11	7.3	17	18	12	27	44
Tall Fescue	4.7	3.1	8	7	4.7	12	10.5	7	17.5	14.5	9.7	24	40
Barley (hay)	5.3	3.5	10	8	5.3	15	11	7.3	20	13.5	9	25	36
Perennial Rye	5.3	3.5	10	8	5.3	15	10	6.7	19	13	8.7	24	36
Harding Grass	5.3	3.5	10	8	5.3	15	10	6.7	19	13	8.7	24	36
Birdsfoot Trefoil	4	2.7	10	6	4	14	8	5.3	19	10	6.7	24	28
Beardless Wild Rye	2.7	1.8	6	4	2.7	10	7	4.7	17	11	7.3	26	28
Alfalfa	2	1.3	5	3	2	7	5	3.3	12	8	5.3	19	28
Orchard Grass	1.7	1.1	4	2.5	1.7	6.5	4.5	3	11.5	8	5.3	20	26
Meadow Foxtail	1.3	.9	4	2	1.3	5	3.5	2.3	10	6.5	4.3	18	24
Clover	1.3	.9	6	2	1.3	9	2.5	1.7	12	4	2.7	19	14

Table 6

F R U I T   C R O P S

Crop	0%			10%			50% 1/			Maximum
	ECe	ECw	LR%	ECe	ECw	LR%	ECe	ECw	LR%	ECdw
Date Palm	5.3	3.5	7	8	5.3	11	16	10	21	48
Fig Olive Pomegranate	2.7-4.0	1.8-2.7	6-10	4-6	2.7-4.0	10-14	9	6	21	28
Grape (Thompson)	2.7	1.8	7.5	4	2.7	11	8	5.3	22	24
Grapefruit Orange Lemon	1.7	1.1	7	2.5	1.7	11	5	3.3	33	16
Apple Pear	1.7	1.1	7	2.5	1.7	11	5	3.3	33	16
Almond Apricot Peach Prune	1.7	1.1	7	2.5	1.7	11	5	3.3	33	16
Walnut	1.7	1.1	7	2.5	1.7	11	5	3.3	33	16
Blackberry Boysenberry	1.0-1.7	0.7-1.1	5-8	1.5-2.5	1.0-1.7	7-12	4	2.7	19	14
Avocado	1.3	0.9	7.5	2	1.3	11	4	2.7	22.5	12
Strawberry	1.0	0.7	7	1.5	1.0	10	3	2.0	10	10

1/ Calculated values, assuming 50% decrease in yield results from doubling of salinity values for 10% yield decrement.

shown are probable yield reductions due to various degrees of salinity of applied water (ECw) or salinity of soil (ECe).

After the evaluation of the water analysis according to the guidelines and after referring to the tolerance tables for the crop tolerance to salinity, the water user should be able to predict whether there is or is not a potential salinity problem and being forewarned may be able to take steps to prevent its developing.

8. ADDITIONAL WATER FOR LEACHING

The application of extra water for leaching is a second alternative that is normally used by good cultivators and farmers to control salt accumulation. The minimum amount of this extra water that must percolate through the active root zone to prevent excessive accumulation of salts is known as the leaching requirement (LR) and is reported as a percent of the normal water requirement of crop (see footnotes 2 and 3 of Crop Tolerance and Leaching Requirement Table 3). The water user will need to supply this extra water (the leaching requirement) for salt control in addition to the water he must supply to meet his crop water requirements. In many areas rainfall plus the usual inefficiencies in irrigation may supply this extra water required for salinity control.

Included as part of the crop tolerance tables are data on leaching requirements (LR) and on the maximum allowable salinity of the drainage water (EC_{dw}) that can be tolerated by the crop at the bottom of the root zone with no more than a 10 to 15% loss in yield. This EC_{dw} is the specific drainage water EC_{dw} now being used to calculate leaching requirement (LR) values for the quality of water (EC_w) and crop grown, where $LR = \frac{ECw}{EC_{dw}} \times 100$.

The satisfying of a leaching requirement to achieve adequate salt management is much more easily attained on sandy soils where water infiltrates and percolates more readily than on clays where percolation rates are slow to extremely slow and leaching is difficult. To be effective the leaching waters must percolate through the soil and out at the bottom of the lower root zone.

The presence of a high water table makes the satisfying of a leaching requirement much more difficult or even impossible. If salts are leached, a high water table may quickly allow resalinization to occur as salty subsurface waters rise to the soil surface where the water evaporates and leaves salts behind to accumulate again in the crop rooting zone. Where high water tables are a problem, artificial drainage to lower and stabilize the water table is usually a first essential to reclamation and salinity control.

9. PERMEABILITY PROBLEMS RELATED TO WATER QUALITY

Referring to the guidelines, permeability problems due to quality of water are usually, but not always, related to too little calcium and magnesium or to excesses of sodium. Permeability problems may also be related to very pure, low salt water (EC_w less than 0.5 mmho/cm).

Low salt waters are corrosive and deplete surface soils of readily soluble minerals and all soluble salts. They often have a strong tendency to dissolve rapidly all sources of calcium from surface soils which then break-down, disperse and seal, resulting in poor water penetration (see Table 1 on guidelines). Soil and water amendments such as gypsum together with changes in cultural practices to promote improved water penetration are the usual preventive or corrective procedures used.

Permeability problems due to excesses of sodium or shortages of calcium are evaluated by a relatively new concept - the adjusted Sodium Adsorption Ratio (adj. SAR), formerly evaluated through the Sodium Adsorption Ratio (SAR) and the Residual Sodium Carbonate (RSC). This new concept adds to the older Sodium Adsorption Ratio (SAR), the effect of carbonate/bicarbonate through a theoretical and calculated pHc value added to the SAR. The pHc evaluates the tendency of the irrigation water to dissolve lime from the soil: adding to soluble calcium, or the tendency to precipitate lime: reducing the soluble calcium. The presence of appreciable carbonate/bicarbonate may markedly influence the calcium availability. This effect on SAR is evaluated by the new adjusted Sodium Adsorption Ratio equation (adj.SAR) as recently developed by the U.S. Salinity Laboratory as follows:

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

The values for sodium, calcium and magnesium (reported in milliequivalents per litre) are taken directly from the water analysis. The pHc is a calculated, theoretical value related 1) to the total salinity as measured by sodium + calcium + magnesium, 2) to the calcium + magnesium supply in the water, and 3) to the carbonate + bicarbonate present. Calculation of pHc is made by use of tables (see "Tables for calculating pHc Values of Waters" - Table 7). This particular adj.SAR procedure is most applicable at about 70% field efficiency of irrigation. At greater efficiency, these values may be a little low; at lower efficiency they may be a little high. Suggested guidelines for adj.SAR are given on Table 1.

There are still other permeability problems in agriculture that are unrelated to adj.SAR or to low salts which must be evaluated separately. These may include problems that are more closely related to soil texture, to compaction and plough pans, or to other soil physical as well as chemical properties.

Table 7 TABLES FOR CALCULATING pHc VALUES OF WATERS

pHc can be calculated, using the table below; $pHc = (pK_2' - pK_c') + p(Ca+Mg) + pAlk$ where

$pK_2' - pK_c'$	is obtained from	Ca+Mg+Na
p (Ca+Mg)	" "	Ca+Mg
pAlk	" "	CO_3+HCO_3

Tables for Calculating pHc

Conct. Ca+Mg+Na (meq/l)	$p(K_2'-K_c')$	Conct. Ca+Mg (meq/l)	p(Ca+Mg)	Conct. CO_3+HCO_3 (meq/l)	pAlk
.5 →	2.11	.05 →	4.60	.05 →	4.30
.7	2.12	.10	4.30	.10	4.00
.9	2.13	.15	4.12	.15	3.82
1.2	2.14	.2	4.00	.20	3.70
1.6	2.15	.25	3.90	.25	3.60
1.9	2.16	.32	3.80	.31	3.51
2.4	2.17	.39	3.70	.40	3.40
2.8	2.18	.50	3.60	.50	3.30
3.3	2.19	.63	3.50	.63	3.20
3.9	2.20	.79	3.40	.79	3.10
4.5	2.21	1.00	3.30	.99	3.00
5.1	2.22	1.25	3.20	1.25	2.90
5.8	2.23	1.58	3.10	1.57	2.80
6.6	2.24	1.98	3.00	1.98	2.70
7.4	2.25	2.49	2.90	2.49	2.60
8.3	2.26	3.14	2.80	3.13	2.50
9.2	2.27	3.90	2.70	4.0	2.40
11	2.28	4.97	2.60	5.0	2.30
13	2.30	6.30	2.50	6.3	2.20
15	2.32	7.90	2.40	7.9	2.10
18	2.34	10.00	2.30	9.9	2.00
22	2.36	12.50	2.20	12.5	1.90
25	2.38	15.80	2.10	15.7	1.80
29	2.40	19.80	2.00	19.8	1.70
34	2.42				
39	2.44				
45	2.46				
51	2.48				
59	2.50				
67	2.52				
76	2.54				

Example: To calculate adj.SAR of water from

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

With report of water analysis

Na	=	3.5 meq/l
Ca+Mg	=	1.0 meq/l
Ca+Mg+Na	=	4.5 meq/l
CO_3+HCO_3	=	3.0 meq/l

pHc = 2.21+3.30+2.5 = 8.01 (from tables)

$$adj.SAR = \frac{3.5}{\sqrt{1/2}}\left[1+(8.4-8.01)\right] = 4.95\ (1+.39)$$

adj.SAR = 6.88

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

(ref: L.V. Wilcox, U.S. Salinity Laboratory, mimeo 30 December 1966).

10. CORRECTIONS FOR PERMEABILITY PROBLEMS

Water quality problems related to soil permeability can often be prevented or corrected by either physical or chemical practices that will result in more water entering the soil.

Physical practices include:

- land grading for better water distribution and reduced run-off;
- holding the water on the field longer;
- decreasing the slope of land by land grading or by changing direction of irrigation to a lesser slope;
- collecting and recirculating tailwater runoff;
- with sprinklers, matching water application rate to less than the intake rate of soil;
- blending water supplies.

Chemical amendments for correction of soil permeability problems are sometimes remarkably successful. Gypsum is the usual amendment and is added either to water or soil. Rates for addition of gypsum to water vary from about 200 to 1000 lb per acre foot of water. Rates for application to soil range from 2 to as high as 10 or 20 tons per acre. Soil tests aid in predicting amendment needs. Water and soil analyses are essential in determining the rate of application as well as feasibility of adding gypsum.

11. TOXICITY PROBLEMS

Toxicity problems due to quality of water are often very specific for a certain water constituent and for a certain crop. In general, tree crops and woody ornamentals are especially sensitive to rather low concentrations of sodium and chloride; annual crops do not exhibit this same degree of sodium or chloride sensitivity. Boron affects a wide range of crops. The interpretation of toxicity effects in the guidelines recognizes toxicities resulting from either root absorption of sodium, chloride, or boron from the soil solution or from sodium or chloride by foliar absorption through leaves wet by sprinkler irrigation.

The boron problem usually is associated with boron applied in the irrigation water but in some instances boron is present in the soil. It can be leached, but with difficulty. In general, correction of a boron problem is accomplished by changing water supplies or selecting a crop more compatible with the boron in the water supply (see table on Boron in Irrigation Waters).

Corrective or preventive action for toxicity problems due to root absorption, usually includes improved water management, leaching, and sometimes the addition of

Table 8 BORON IN IRRIGATION WATERS

Boron toxicity in many areas is traceable to use of irrigation waters with boron content in excess of 1 ppm. The UC Ag. Extension laboratories are using the following interpretation as regards boron content of irrigation water:

Below 0.5 mg/l	Satisfactory for all crops.
0.5 - 1.0 mg/l	Satisfactory for most crops; sensitive crops may show injury (may show leaf injury but yields may not be affected).
1.0 - 2.0 mg/l	Satisfactory for semi-tolerant crops. Sensitive crops are usually reduced in yield and vigour.
2.0 -10.0 mg/l	Only tolerant crops produce satisfactory yields.

There is no economically feasible method of removing boron from irrigation water. Similarly, there is at present no chemical or soil amendment which can economically be added to the soil to render the boron nontoxic. However, growers in some areas are learning to live with marginal boron and salinity conditions by: 1) maintaining fertility levels slightly above the usual "optimum," and 2) irrigating a little more frequently than "normal."

RELATIVE TOLERANCE OF PLANTS TO BORON

(In each group the plants first named are considered as being more sensitive and the last named more tolerant)

SENSITIVE	SEMI-TOLERANT	TOLERANT
0.5 mg/l	1 mg/l	2 mg/l
Lemon	Lima Bean	Carrot
Grapefruit	Sweet Potato	Lettuce
Avocado	Bell Pepper	Cabbage
Orange	Tomato	Turnip
Thornless Blackberry	Pumpkin	Onion
Apricot	Zinnia	Broad Bean
Peach	Oat	Gladiolus
Cherry	Milo	Alfalfa
Persimmon	Corn (maize)	Garden Beet
Kadota Fig	Wheat	Mangel
Grape (Sultanina & Malaga)	Barley	Sugarbeet
Apple	Olive	Palm (Phoenix canariensis)
Pear	Ragged Robin Rose	Date Palm (dactylifera)
Plum	Field Pea	Asparagus
American Elm	Radish	Athel (Tamarix aphylla)
Navy Bean	Sweet Pea	10 mg/l
Jerusalem Artichoke	Pima Cotton	
Persian (English) Walnut	Acala Cotton	
Black Walnut	Potato	
Pecan	Sunflower (Native)	
1.0 mg/l	2 mg/l	

Adopted from USDA Tech. Bull. No. 448

soil or water amendments. The foliar absorption problems (from overhead sprinkling) occur most generally during periods of high winds or low humidity. A change to night irrigation along with faster rotation of sprinkler nozzles to at least 1 rotation of the head per minute has sometimes greatly reduced the problem. Less frequent irrigations by sprinklers may also reduce opportunity for leaf absorption to occur.

12. MISCELLANEOUS PROBLEMS

As briefly mentioned previously, miscellaneous problems include a mixed group such as excessive nutrients, white deposits on fruit or leaves, and other occasional abnormalities that may be suspected to be caused by the water used for irrigation. Guideline values are given.

Nitrogen sometimes occurs in water supplies. Nitrogen is a recognized fertilizer nutrient which promotes growth of both crops and algae. If present, it may need to be considered, particularly in planning the crop fertilizer programme or in selection of an adapted crop. Certain crops such as sugar beets, grapes, apricots, citrus and a few others are sensitive to excessive nitrogen. The type of problem will depend on the crop but may include reduced yield, lower quality, or delayed maturity.

Bicarbonates in water applied by sprinklers has caused objectionable white deposits to form on fruit or leaves of some crops (grapes, leafy ornamentals, apples). The occurrence and correction is similar to that discussed for correction of foliar absorption problems - change to night irrigation, increase speed of rotation of sprinkler heads, decrease numbers of irrigation where possible.

Under this grouping of miscellaneous problems pH is included; pH values for waters normally fall within the range of 6.5 to 8.4 and if outside this range, may indicate that other problems may be present and should be studied.

13. TYPICAL WATER ANALYSES FROM WESTERN USA

For comparison purposes, several typical water supplies are evaluated in Table 9.

Table 9

		Colorado River (Imp. Dam-9/8/71)	Pecos River (1945-46 USDA Handbook 60)	San Joaquin River (Vernalis 9/14/71)	Calif. Aqueduct (San Luis Res.-8/7/68)	Sacramento River (Fremont weir 5/17/72)
EC_w	(mmho/cm)	1.3	3.2	0.9	0.5	0.19
Ca+Mg	(meq/l)	7.3	26.5	4.2	3.6	1.40
Na	(meq/l)	6.1	11.5	4.4	1.4	0.83
CO_3+HCO_3	(meq/l)	3.1	3.2	3.1	1.4	1.51
Cl	(meq/l)	3.1	12.0	4.2	2.9	0.28
B	(mg/l)	0.2	–	0.4	0.2	0.1
NO_3-N	(mg/l)	–	–	0.8	0	0.3
pH		8.1	–	8.0	7.9	7.6
SAR		3.2	3.2	3.0	1.0	1.0
adj.SAR		6.5	7.8	5.8	1.6	1.2
		Moderate salinity problem expected; low potential to develop permeability problem; select crops for salinity and sodium tolerance; supply extra water to meet LR for crop and water supply.	Severe salinity problem expected. Permeability problem not expected since high salinity should maintain permeability. Probable sodium and chloride toxicities to sensitive crops. Select crops carefully, meet LR for crop and water. Monitor crops and soil.	Low to moderate salinity problem expected. Some slight toxicity effects if crop leaves are wet by sprinklers. Select crops for moderate tolerance to salinity. Monitor soil and crop.	No potential water quality problems indicated.	A moderately severe permeability problem expected due to low salt content. Evaluate amendments.

Table 10

		Friant-Kern Canal (Friant Dam 5/9/65)	#1 Well Water	#2 Well Water	#3 Well Water	#4 Well Water	#5 Well Water
EC_w	(mmho/cm)	0.04	0.6	0.4	1.1	0.9	0.35
Ca+Mg	(meq/1	0.22	2.59	0.66	1.7	6.4	0.2
Na	(meq/1	0.17	3.90	3.46	9.4	2.6	3.3
CO_3+HCO_3	(meq/1	0.28	4.70	3.27	7.1	1.25	1.1
Cl	(meq/1)	0.06	0.83	0.59	2.0	2.0	1.0
B	(mg/1)	0	-	-	1.2	0.12	-
NO_3-N	(mg/1)	1.6	0.12	0.06	0	28.0	-
pH		7.2	-	-	8.1	6.8	8.8
SAR		0.5	3.4	6.0	10.2	1.4	10.4
adj.SAR		-	6.4	7.3	14.9	2.5	3.2
		A very severe permeability problem is expected due to extreme purity of the water. Evaluate use of water amendments.	No more than a slight permeability problem is expected due to adj.SAR. Possible sodium toxicity for sensitive crops.	Slight to moderate permeability problem is expected. Possible sodium toxicity for sensitive crops. Evaluate need for amendments.	Moderate potential for salinity problem. Strong probability of permeability problem. Select crops carefully; meet LR for crop and water; monitor soil and crop and evaluate need for amendments.	Low to moderate potential for salinity problem. Very high nitrogen (76 lb N/acre ft of water). Select crops, especially for high N adaptability.	Moderate permeability problem expected due to low salts and high SAR (in absence of source of Ca). If sprinklers used, adjust application rate and evaluate need for an amendment.

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Paper 17 PREDICTING SOIL SALINIZATION, ALKALIZATION AND WATERLOGGING

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1. INTRODUCTION

Soil salinization, alkalization and waterlogging are complex phenomena; they are closely related to water movement in the soil profile and affected by several factors such as:

i. climatic conditions;
ii. soil properties including texture, topography, presence of indurated layers and hydraulic conductivity;
iii. groundwater characteristics including depth, slope, direction and salt concentration and composition;
iv. irrigation, including amount of water added at each irrigation, frequency and method of irrigation; surface or subsoil;
v. water quality; salt concentration, cation and anion composition;
vi. vegetative cover;
vii. human activities.

Predicting that a certain area is subject to salinization or alkalization is not difficult. The complexity of the problem arises when attempts are made to quantify the prediction. The role of the factors mentioned has been demonstrated, but the quantitative evaluation of their effect in relation to each other still needs further consideration.

This report presents results and findings of interest in the processes of salinization, alkalization and waterlogging related to some of these factors; others, not discussed herein, have been aptly presented by members of this panel. Tentative guidelines for prognosis are suggested.

2. THE SALINIZATION PROCESS

2.1 Climatic Conditions

The components of the climatic conditions which are involved in the soil salinization phenomenon are those related to evaporation from bare soil surfaces and evapotranspiration from soils with vegetative cover. These components are air temperature, rainfall, relative humidity, wind velocity, relative duration of bright sunshine and solar radiation.

Using meteorological records, several investigators were able to evaluate evaporation from bare soils and evapotranspiration from cultivated soils. Among the methods used for predicting potential evapotranspiration are those of Blaney and Criddle, Penman and Rijtema. If the salt concentration in the soil solution is known, an estimation of the accumulated amounts of salts due to evaporation and evapotranspiration processes can be made. Use of sub-irrigation makes such calculation feasible since a regular flow of water from underground to the soil surface and/or the plants takes place.

In an attempt to express quantitatively the process of salinization due to capillary movement and subsequent evaporation, the writer (Balba and Soliman, 1969) used the following relationship:

$$\Delta S = \Delta W_R C_W + W_E C_W$$

where ΔS is the increase in soil column content of salts after a period of time, W_R is the liquid water retained by the soil column, W_E is the evaporated water in the period of time and C_W is the salt concentration in the saline groundwater. If plants are growing in the soil, the problem is not so simple, as shown in an unpublished work by the writer and his co-workers (Balba and Soliman, 1975). When applying saline water in sub-irrigation, actual evapotranspiration decreased with the increase in the salt concentration of water. Accordingly, the term $W_E C_W$ does not equal the amount of salt accumulated in the soil due to evapotranspiration when the value of W_E is calculated from any of the above-mentioned methods.

Calculated evapotranspiration of Sudan grass using the Rijtema equation (1973) was 5.72 mm/day or 4.378 l in the period of the experiment (25 days). The actual ET was 5.79 mm/day or 4.651 l when tap water was used for irrigation and 4.234 l and 3.886 l with the use of solutions containing 15 or 30 meq/l. Thus, the calculation of the term $W_E C_W$ is not correct under saline conditions.

Evaporation and evapotranspiration depend on climatic conditions. Balba and Soliman (1969) showed that evaporation from a loamy soil with a shallow water table was 0.43 mm/day in July and dropped to 0.11 mm/day in September. Rijtema and Aboukhaled (1973) prepared tables for maximum atmospheric evaporative demand in several agroclimatological regions in Egypt; the values varied each month and in each region.

2.2 Soil Properties related to Water Movement

It has been mentioned above that soil water movement is the basic criterion in salt accumulation in the soil. This movement is controlled by the potential differences between different points in the soil-water system. The water tends to move from a position of higher to one of lower potential. Several factors are involved in the capillary movement of water in soil among which are:

i. Soil texture

From a water table 50 cm deep, the water reached the soil surface after 1 day in columns of loamy soil, 16 days in sandy soils and 28 days in clay soils (Balba and Soliman, 1969). Balba and Soliman showed that rates of evaporation from loamy, sandy and clay soil columns in July were 0.43, 0.20 and 0.12 mm/day.

ii. Depth of groundwater table

The water content of the upper part of the loamy soil column (0-10 cm) decreased from 33 to 27 and 25 percent with the increase in the length of the soil columns above the water table from 50 cm to 80 cm and 110 cm, respectively. As the water decreases, the suction of the soil surface layers increases and the evaporation rate approaches a limiting value which cannot be exceeded no matter what the potential evaporation rate. After 100 days, the rates of evaporation from the loamy soil columns, 50, 80 and 110 cm long above the water table, were 0.35, 0.29 and 0.17 mm/day, respectively. The concentration of salts in the upper 0-2.5 cm layer in the soil columns was 112, 74 and 63 meq/1, respectively (Balba and Soliman, 1969). Elgabaly and Naguib (1965) studied the effect of depth and salt concentration of the groundwater table on the soil salinization process using lysimeters planted with cotton and with under surface irrigation. Their study showed that: when the groundwater table was kept at 50 cm from the soil surface, the increase in the salinity of the upper 20 cm was very pronounced. At a depth of 90 cm, the soil salinity was less than 1/3 of its level at a depth of 50 cm, and the effect of differences in the salinity of the groundwater was not very pronounced. They concluded that the depth of groundwater contributed more to the salinity of the soil surface than the salinity level of the groundwater.

2.3 Soil Salinization due to Irrigation with Saline Water

If salt accumulation in the soil due to surface application of saline water is considered separately from other processes such as capillary movement of water, plant absorption or evaporation, the following equation represents the salt balance:

$$S_F = S_i + RC - S_o$$

where S_F and S_i are the final and initial salt content of a soil layer, R is the amount of water retained by the soil layer, C is the salt concentration of the applied water and S_o is the amount of salts removed from the soil layer with the water front during its passage from one layer to the other. Under free drainage conditions the writer and his co-worker (Balba, 1965) showed that:

i. the soils differ in the amount of salt retained according to the amount of water retained;

ii. using Na^{22}, the amount of salts removed from the soil was found to decrease with the increase in the salt concentration of applied water;

iii. when the soil columns were leached with increasing amounts of the salt solution, the final salt content of the soil column did not materially vary with variations in the amount of added water;

iv. the final soil salt content after one leaching with saline water was almost the same after 2 or more leachings. An equilibrium state takes place in which the retained amount of salt from the applied water equals the removed amount in each application.

2.4 Effect of Vegetative Soil Cover on Soil Salinization

Several investigators have studied the role of soil vegetative cover on soil salinization. Unpublished work by Balba and Soliman shows that:

i. the amount of water lost to the atmosphere from bare soil drums with a shallow water table was almost doubled when Sudan grass was grown in August (2.172 vs. 4.651 l in 25 days);

ii. the absorption of water by plants greatly exceeded the absorption of salts dissolved in the applied water - hence salts accumulated in the root-system zone of the soil;

iii. the increase in salt concentration of the applied water decreased the evapotranspired water (4.651 l of tap water vs. 3.886 l from a solution containing 30 meq/l of NaCl);

iv. typical salt distribution in bare soil profiles with a shallow, saline groundwater under arid conditions is characterized by a maximum concentration at the soil surface followed by a sharp drop in the subsoil and a gradual decrease with depth to a minimum concentration which is equal to the salt concentration of the groundwater. Under vegetative cover, the salt distribution in the soil profile changes. The following features characterize salt distribution in cultivated soil (as if in the case of subsurface irrigation), as compared with bare soil. It was noted that maximum salt accumulation was not at the soil surface, but rather at a depth of about 10 cm; actually it followed the intensity of the root system. The bare soil drums accumulated 181.6 meq of salts, of which 115.7 meq were in the upper 5 cm, while the cultivated soil drums accumulated 236.1 meq with 38.2 meq in the upper 5 cm after 25 days using a solution containing 30 meq NaCl/l.

Salt accumulation as a result of the soil vegetative cover varies considerably according to all factors which affect plant growth since evapotranspiration is a biological process. Among these factors are: plant morphology especially the root system distribution, rate and pattern of planting, plant tolerance to salinity, water regime, water salinity, depth of groundwater table and the climatic conditions, and the method of irrigation: surface vs. subsurface.

THE ALKALIZATION PROCESS

The processes which result in an increase in the exchangeable sodium and sodium carbonate in the soil are:

- i. desalination of saline sodic soils which do not contain a supply of calcium;
- ii. irrigation of soils with water containing residual $CO_3^{=} + HCO_3^{-}$ and high SAR values;
- .ii. groundwater rich in $HCO_3^{-} + CO_3^{=}$ and with high SAR values have the same effect as irrigation water of the same quality;
- iv. the microbial processes of sulphate reduction under anaerobic conditions.

WATERLOGGING

Soils saturated with water are said to be waterlogged. In waterlogged soils, anaerobic conditions, unfavourable to plant growth, may prevail. Salinization is usually due to the upward movement of water and subsequent evaporation as mentioned above. Alkalization also may occur because of waterlogging.

Conditions which cause waterlogging are:

- i. seepage of water from irrigation canals;
- ii. rise of the groundwater table due to excessive irrigation;
- iii. presence of impermeable layers in the soil profile;
- iv. areas of low relief adjacent to or surrounded by areas of relatively higher relief which usually receive water from these surrounding areas.

Egypt first suffered from waterlogging when irrigation was changed from basin to permanent irrigation depending on an elaborate network of canals. A drainage system had to be established. The problem also became acute in the newly reclaimed area (200 000 ha) west of the delta "west of the Nubaria Canal Project", threatening the whole project and the adjacent low-lying area east of the Nubaria canal which has been under cultivation for a very long time.

The problems of salinization and waterlogging are related to each other. Wherever waterlogging takes place, salinization is a result.

5. TENTATIVE GUIDELINES

Predicting soil salinization, alkalization and waterlogging requires extensive investigations directed towards the groundwater, the soil, the irrigation system, the quality of irrigation water, the cropping system and the climatic conditions.

5.1 Predicting Waterlogging

To predict that waterlogging will take place in an area the following groups of investigations must be carried out. These investigations aim to analyse the problem in its various elements and to determine their individual characteristics. Thus there should be an understanding of how these elements - or groups - interrelate and function.

Group A Groundwater investigations

These investigations should cover all aspects concerning the groundwater such as: depth from soil surface, salt concentration and composition, the hydraulic properties including slope, direction and rate of flow.

Group B Soil investigations

These include: the soil profile, the soil texture, soil-water constants, presence of indurated layers and their composition, hydraulic conductivity and exchangeable cations.

Group C Irrigation investigations

These include: the method of irrigation (surface or subsoil), design of the network of canals, the amount of water to be delivered, and the frequency of irrigation.

Group D Agronomic investigations

Include: the most suitable cropping system, the water consumptive use of each crop and each rotation, and the water regime of each crop.

The necessary meteorological records should also be available. Investigations relating these four groups together should be carried out and calculations made:

i. from the irrigation method, the distribution network of the canals, the amount of water and frequency of irrigation, the amount of water seepage from the canals downward to the groundwater and through the canal borders to the adjacent land;

ii. from the amount of water applied at each irrigation, the number of irrigations, the evapotranspiration of each crop and each crop rotation and the soil properties, the amount of excess water which replenishes the groundwater; in this group of calculations any artificial drainage system should be taken into consideration;

iii. of the water balance, since the inflow of water to the groundwater and its outflow are known.

Thus it is possible to know the rate of the groundwater table rise towards the soil surface.

The time after which the groundwater reaches the critical depth as well as the time it needs to saturate the soil can be calculated.

If this study is not feasible, the alternative is to establish a pilot project and measure the necessary records.

5.2 Predicting Soil Salinization due to Upward Movement of Groundwater and its Subsequent Evaporation

The above-mentioned groups of investigations, which constitute the basic elements of the problem of waterlogging, are the same for predicting soil salinization. For the interrelationships between these elements from the standpoint of their effect on soil salinization, the following points should be considered:

i. The following conditions enhance the salinization process:

shallow groundwater table, 50-75 cm,
salt concentration in the groundwater,
medium soil texture,
arid warm climate,
long periods between each irrigation,
subsurface irrigation,
inefficient drainage system,
water consumptive use of crops,
water regime of crops (cereals vs. rice),
fallowing in dry seasons.

ii. <u>The following conditions retard the salinization process</u>:

deep groundwater,
surface irrigation,
efficient drainage,
crops grown under ponded conditions,
humid, cold climates.

Quantifying the prediction requires weighting these factors in relation to each other. A mathematical model which takes into consideration these weighted variables simultaneously might give an answer to this problem.

5.3 Predicting Soil Salinization due to Irrigation with Saline Water

Several systems were established in different countries for classifying the suitability of water for irrigation according to its salinity levels. According to these systems, predicting soil salinization should be possible. However, the writer points out that the potential salinization of soils irrigated with saline waters depends not only on the water salinity level but on several other conditions such as:

the irrigation regime, especially the period between irrigations,
the amount of applied water,
the method of irrigation,
the depth of the groundwater,
the hydraulic conductivity,
the efficiency of drainage systems,
the climatic conditions,
the soil texture,
the presence of impermeable layers and their depth,
the kind of vegetative cover,
the soil topography.

To predict quantitatively the salinity level of a soil irrigated with water of a certain level of salts, the following information is required:

i. the amount of salts accumulated in the soil from each irrigation as a result of evapotranspiration by the growing crop under the prevailing conditions;

ii. the amount of salts displaced by the water of each irrigation and removed from the soil;

iii. the amount of salt which might be displaced and removed by the rainfall.

The salt balance can be calculated, from which the net amount of accumulated salt will be known. Two elements constitute the salt balance:

a. the gain of salts which can approximately be evaluated from the product of potential evapotranspiration times the salt concentration in water. Distribution of salts in the soil, however, remains to be studied;

b. the loss of salts displaced with each irrigation or with rainfall. This element might approximately be determined by applying equations used for calculating the salt movement with water, such as that suggested by Gardner and Brooks (1957), Terkeltraub and Babcock (1971) or other equations.

Studying the salt balance of irrigated soils, Szabolcs (1972) suggested the following equation:

$$b = \alpha + \left[d + \frac{CV}{Mt_{fs}} \quad 10^{-5}\right]$$

where:

b = soluble salt content of the soil at the end of observations, mg/100 g soil.

α = soluble salt content of the soil at the beginning of observation, mg/100 g soil.

c = salt concentration of the irrigation water g/l.

v = quantity of the irrigation water applied during the observation period, m^3/ha.

M = thickness of the soil layer for which the salt balance was established, m.

t_{fs} = bulk density of the soil.

d = salt regime coefficient of the soil, g/100 g soil.

He stated that the salt regime gives the change that occurred in the salt content of the soil during the observation period. It gives the difference between the amount of salts leached from the soil and the amount of salts that got into the soil from sources other than the irrigation water.

5.4 Predicting Soil Alkalization

The conditions leading to soil alkalization have been described earlier. Thermodynamic studies of the cation exchange reaction offer a means to calculate the exchangeable sodium percentage when Na rich water is used for irrigation. The concept of sodium adsorption ratio SAR, widely used in water classification according to its sodium hazards, is a direct application of the thermodynamic approach (Richards, 1954). Also, recognizing the effect of $CO_3^= + HCO_3^-$ on the solubility of calcium, the residual $CO_3^= + HCO_3^-$ concept was used as a parameter for potential alkalization of the soil when irrigated with waters containing residual $HCO_3^- + CO_3^=$ (Richards, 1954). Also in this regard, based on thermodynamic considerations and experimental results, the writers (Balba and Balba, 1972) showed that $SO_4^=$ rich waters are more Na hazardous than Cl^- rich waters. However, the exchange reaction between the sodium of the water and the soil exchangeable calcium takes place under flow conditions and not in a closed system under which SAR standards are calculated.

Brooks et al. (1957) showed the applicability of the following approximated equations for use in the field for irrigation waters containing a high proportion of sodium:

$$C_{Na} = \frac{1}{1 - K'} \left[C_0 - \sqrt{C_0 K' Q b \frac{Z}{D - fz}} \right]$$

and,

$$q_{Na} = \frac{1}{1 - K'} \left[- K' Q + \sqrt{C_0 K' Q b \frac{D - fz}{Z}} \right]$$

where: K' is the apparent second order equilibrium constant as approximated for exchange of cations having unequal valence, dimensionless.

- C_0 : total cation concentration of the irrigated water in meq/ml.
- Q : cation exchange capacity of soil in meq/g.
- D : depth of irrigation water applied, cm.
- q_{Na} : concentration of Na in the adsorbed phase at a specified depth (Z) in the column, meq/g.
- C_{Na} : concentration of Na in the solution phase at a specified depth (Z), meq/ml.
- Z : depth of soil, cm.
- b : dry bulk density of soil g/cc.
- f : ratio of void space occupied by dilution to total volume of column, dimensionless.

Balba and Bassiuni (1972) using Na^{22} calculated C_{Na} and q_{Na} from the Brooks et al. equations. Their calculated results did not agree with the determined results. Also, they obtained unsatisfactory results when they used the Bower and Goertzen equation (1958) to calculate the exchangeable sodium in soil columns after leaching with water. The writer is of the opinion that the exchange reaction under flow conditions as well as between more than two cations still needs further studies.

The potential alkalization during the desalinization of saline sodic soil might be predicted by the direct determination of the soil content of gypsum and calcium carbonate. In the presence of neutral salts and excess water, the supply of Ca^{++} from the soil gypsum and lime prevents soil alkalization.

Balba and El Laithy (1968) suggested the following simplified test: the soluble Ca is determined in the soil paste extract and in a 1:100 soil-water extract. The increase of Ca^{++} in the latter extract, per 100 g soil, above Ca^{++} in the former, indicates that the soil contains Ca-compounds which dissolve in excess water giving additional Ca^{++}. If otherwise, alkalization will develop in this soil during or after the completion of the leaching process.

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V. World Map of Desertization

A. DISCUSSION PAPER ON THE PREPARATION OF THE WORLD MAP OF DESERTIZATION WITH PARTICULAR REFERENCE TO SALINITY/ALKALINITY PROBLEMS

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1. BACKGROUND

Resolution 3337 (XXIX) of the UN General Assembly requests the preparation of a world map of the areas affected or likely to be affected by desertization.

The objective of this map is to serve as a background document for an intergovernmental Conference on Desertization planned to be held in 1977.

The map should be published by the end of 1976. Taking into account the time required for proof-checking and printing (6 months), the master copy of the map should be ready by July 1976. Considering other delays for recruiting personnel and for establishing arrangements with contributing institutions, the time left for the actual preparation of the map is less than one year.

2. GENERAL CONSIDERATIONS

2.1 Definitions

There is no agreed definition of desertization. The word "desertification" is something used instead of desertization. Some consider "desertification" to be man-made desertization - desertization encompassing both natural and man-induced causes of extension of deserts. In the context of the project it is proposed to use the following definition: "the development outside desert areas and within arid and semi-arid areas, of landscape features of the deserts".

This definition calls for discussion on several points:

i. it restricts desertization to arid and semi-arid areas;

ii. it does not specify either the causes or the processes of desertization;

iii. "Landscape features of the deserts" have to be defined. These may include sand dunes, rock debris, salt flats, badlands, hamadas, denuded mountains and barren plains;

iv. "the development of the landscape features" includes the consideration of all possible intergrades between the above desert features and

and those of the arid and semi-arid areas as well as the occurrence of these landscape features by patches.

2.2 The Scale

The time constraints set for the preparation of the map and its aims (e.g. consideration by a political gathering) imply the preparation of a simple generalized map of a rather complex set of features on which limited cartographic information is available.

Guidance is invited on the selection of the scale:

i. a scale of 1:10 million would require the publication of about six sheets which does not seem feasible in the time allotted for the preparation;

ii. a scale of about 1:25 million would match the scale of the Map of Meigs on arid homoclimates. However, very little information can be provided at this scale.

2.3 The Legend

The legend should comply with the requirements of the UN General Assembly resolution, e.g. it should theoretically distinguish between areas already affected and those likely to be affected by desertization. It should be noted, however, that an area already affected by a certain type of desertization is quite often likely to be affected by another. Moreover the likelihood of desertization depends both on the inherent vulnerability of the landscape to degradation (slope, soil texture, aggressivity of climate) and on human influences, either positive (protection, management, reclamation) or negative (degradation).

For this, guidance is invited on the elaboration of the legend:

i. by "areas already affected by desertization" it is proposed to understand essentially those areas which have already acquired strongly developed desert features, e.g. sand dunes, badlands, strongly saline areas; all the other areas would be considered as areas likely to be affected and would be assessed according to their inherent vulnerability (thus excluding human influences);

ii. among the areas likely to be affected, only those which are highly and moderately vulnerable would be indicated (as one single category) on the map; the slightly vulnerable areas would not be shown on the map. The most critical areas could be shown by a map symbol (e.g. without delineation of the areas);

iii. the legend would distinguish among different processes of desertization and for each of these processes would separate into two categories, e.g. "already affected" and "highly to moderately vulnerable" would be shown. Among the processes to be distinguished one may consider:

a. salinization and/or alkalization,

b. development of shifting sands,

c. denudation of vegetation,

d. denudation of hard rock or hard pan,

e. development of badlands on soft material.

iv. it is very clear that at the scale considered and with the information available the assessment of the vulnerability to desertization can only be made by judgement. However, it will be essential to develop criteria and a method of assessment which include consideration of soil characteristics, climate, land form and vegetation in order to ensure consistency in the assessment.

5. DESERTIZATION AND SALINITY/ALKALINITY

The development of salinity and alkalinity features in arid and semi-arid landscapes depends both on inherent factors (presence of saline rocks, depth of groundwater, occurrence of saline waters, land form and soil drainage) and on human influences (irrigation, reclamation, denudation or protection of watersheds, etc.).

Comments were invited on the aspects of salinity/alkalinity which should be included in the World Map of Desertization, such as:

i. should the areas undergoing salinization by irrigation be shown and how? - by map symbols or by special mapping units?

ii. can alkalinization be distinguished from salinization at the scale contemplated for the map?

B. DRAFT REPORT OF AN FAO EXPERT CONSULTATION ON THE PREPARATION OF A WORLD MAP OF DESERTIZATION 1/

1. BACKGROUND

1.1 The expert consultation met on 4 June 1975 at FAO Headquarters, Rome, under the chairmanship of Professor V.A. Kovda, Director of the Institute of Agrochemistry and Soil Science, USSR, and President of SCOPE 2/. The list of participants is attached in Annex 2.

1.2 The consultation was held as a follow-up to a decision by the Administrative Committee on Coordination of the United Nations to entrust FAO with the responsibility of acting as focal point in the UN system for cooperation for the preparation of a World Map of Desertization.

1.3 This undertaking stemmed from Resolution 3337 (XXIX) of the UN General Assembly to hold a UN Conference on Desertization in 1977. The resolution requested inter alia the "preparation of a world map of areas affected and areas likely to be affected by the process of desertification".

2. PURPOSE OF THE MAP

2.1 It was noted that the map should be published by the end of 1976. Taking into account the time required for proof-checking and printing (6 months), the master copy of the map should be ready by July 1976. Considering other delays for recruiting personnel and for establishing arrangements with contributing institutions, the time left for the actual preparation of the map was less than one year. The expert consultation therefore recognized that only a generalized map could be prepared in such a short time.

2.2 Taking this time constraint into consideration, the expert consultation considered that the main purposes of such a map should be:

i. to provide on a global geographical basis and with a uniform presentation, a preliminary synthesis of the available cartographic information on desertization;

ii. to mobilize social and political awareness of the problem;

1/ The consultation was held on the occasion of the FAO/ISSS Expert Consultation on Prognosis of Salinity and Alkalinity, FAO, Rome, 3 - 6 June 1975.

2/ SCOPE - Scientific Committee on Problems of the Environment

iii. to serve, with other background documentation, as a basis for stimulating international cooperation for further assessing and combatting desertization, in particular, for locating homogeneous areas and representative sites for regional cooperation of national activities for research, monitoring and conservation and development programmes;

iv. to serve as a framework for more detailed surveys in selected areas.

3. SCOPE OF THE MAP

3.1 It was noted that there is no agreed definition of desertization and that the term "desertification" was sometimes used instead of desertization. "Desertification" was sometimes considered to be man-made desertization - desertization encompassing both natural and man-induced causes of extension of deserts. In the context of the proposed project the Expert Consultation generally agreed to use the following definition: "the development outside desert areas and within arid and semi-arid areas, of landscape features of the deserts".

3.2 It was, however, stressed that the use of this definition would restrict the map to arid and semi-arid areas. While recognizing that desertization quite evidently occurs outside desert areas, the Expert Consultation recognized that the delineation of "true desert" areas would raise problems, especially the differentiation between man-made and natural deserts. It was generally agreed that consideration of precipitation alone would not provide a satisfactory criterion and that potential evapotranspiration and precipitation had to be considered together. It was felt that a revised version of the Unesco Map of Arid Homoclimates (Meigs) could provide a suitable basis for delineation of desert, arid and semi-arid areas for the purposes of a generalized map. The group finally agreed that the Desertization Map should include consideration of hyper-arid, arid and semi-arid areas and natural deserts outside these areas.

3.3 Other climatic factors which should be considered were, in particular:

i. the differences between cold, cool and hot deserts (as distinguished in Meig's Map of Arid Homoclimates);

ii. the reliability of the rainfall or, in other words, the frequency of droughts.

In this respect, it was recognized that the frequency of droughts was an important factor in assessing desertization and desertization hazards. However, many other factors had to be assessed concurrently since different degrees of desertization could develop under human influences within areas having the same drought hazard. In this connection the Chairman presented the outline of a World

Map of aridity and drought probability differentiating eight categories of arid areas on the basis of frequency of drought, soil and physiographic features. This map and its legend are reproduced in this report. While recognizing that other desertization features would have to be considered, the group agreed that this integrated approach deserved careful consideration and recommended that this map, with othersmentioned below in the report, should be used as an important input for the preparation of the desertization map.

3.4 The group also recommended the consideration of other factors such as:

i. the potential productivity (expressed in dry biomass) and the related data provided by the International Biological Programme;

ii. the present land use and present land productivity;

iii. human/"social" factors such as density of human population, availability of water from wells and streams and percentage of cultivated lands.

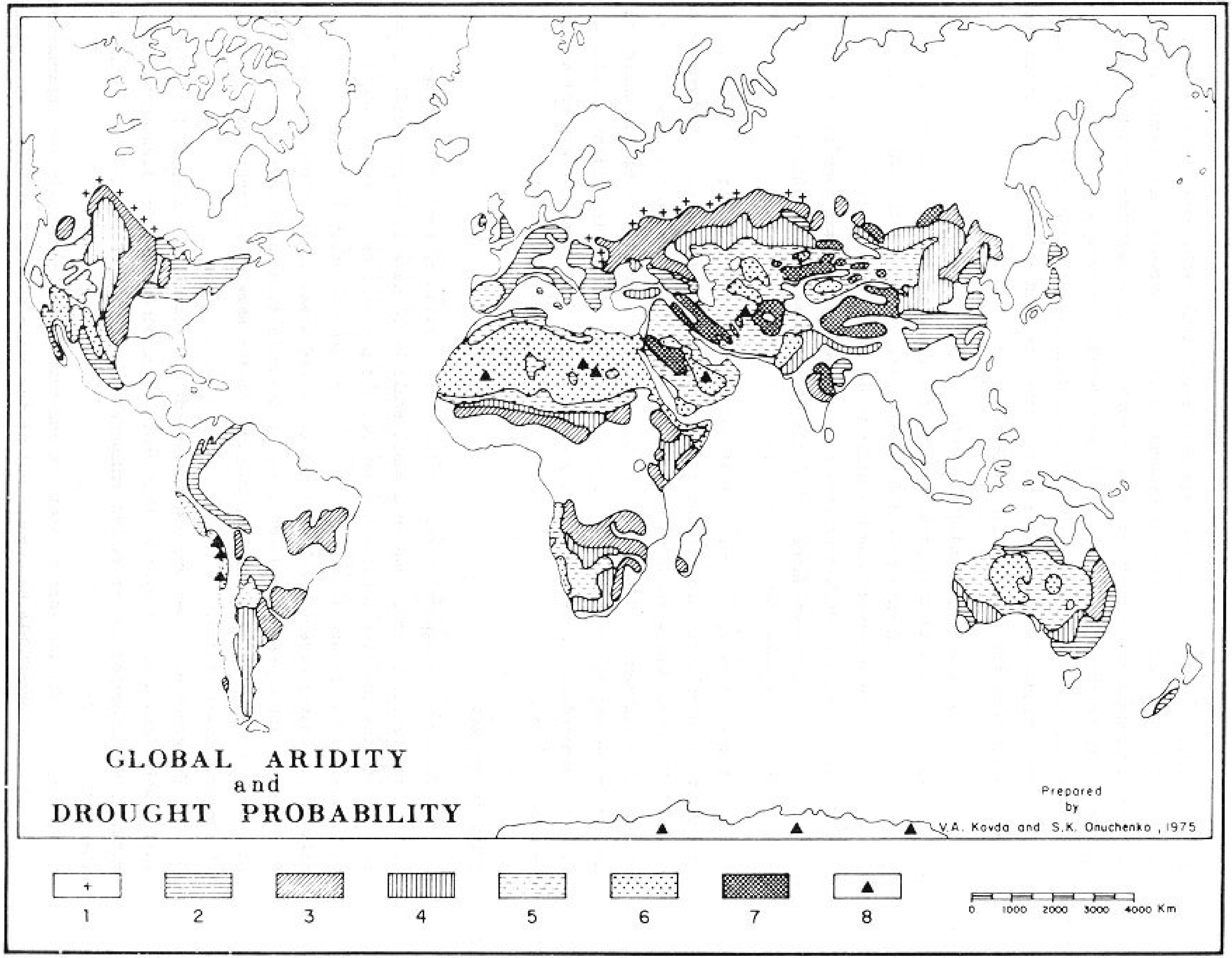
It was, however, recognized that information on these factors was often incomplete or unreliable and difficult to combine with the available information on physical factors. While these factors would have to be taken into account in the process of assessment of desertization, most of the relevant information would not appear on the map but rather in the accompanying report. To the extent possible, it was recommended, however, that the present limit of cultivated (rainfed) areas be shown on the map.

4. SCALE OF THE MAP

The group recognized that, for the consideration by government delegates at the Conference, a simple map on a small scale would have to be produced. It also recognized that the time constraints set for the preparation of the map would make it impossible to prepare a map at 1 : 5 million (some 18 sheets) or even 1 : 10 million (6 sheets) covering all arid and semi-arid areas of the globe. It was therefore agreed that a generalized world map of desertization would have to be prepared at a scale of about 1 : 25 million, possibly on the same cartographic base as that of the arid homoclimates.

The group was, however, doubtful about the scientific value of the information which could be conveyed at this scale if no other more detailed cartographic material was prepared and presented concurrently. It therefore strongly recommended that:

i. all the work of analysis and interpretation of data and information available be carried out at the scale of 1 : 5 million. This scale is that of the Soil Map of the World and the Map of Salt-affected


GLOBAL ARIDITY
and
DROUGHT PROBABILITY
Prepared
by
V.A. Kovda and S.K. Onuchenko, 1975
1
2
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4
5
6
7
8
0 1000 2000 3000 4000 Km

LEGEND TO THE GLOBAL ARIDITY AND DROUGHT PROBABILITY MAP

1. Areas of sporadic very rare droughts; probability 3-5%; areas transitional to humid zones; pH of order 7-6.5; $CaCO_3$ represented by residual concretions and irregular patches in subhumic strata.

2. Rare drought; probability of 10-15%; areas of accumulation of secondary compounds of sesquioxides and calcium carbonate; steppes, prairies, savanna, Mediterranean cinnamonic areas.

3. Frequent drought; probability 20-25%; areas of accumulation of considerable amounts of calcium carbonate, sometimes sodium bicarbonate; dry steppes, dry savanna.

4. Very frequent droughts; probability 40-50%; areas of accumulation of calcium carbonate, presence of sodium bicarbonate, sometimes considerable amounts of exchangeable sodium; semi-deserts, grey earth, chestnut soils and others.

5. Fine earth, lowlands, with accumulation of calcium carbonate, calcium sulphate with an admixture of soluble salts; extremely arid areas with droughts dominating up to 60-70% of the time (frequency).

6. Sandy and stoney surface deposits saturated with calcium carbonate, gypsum with admixture of sodium sulphate and sodium chloride; arid deserts with areas of shifting sand and salt dunes and with incidental irregular moist years, drought dominating up to 90-95% of the time (frequency).

7. Mountainous arid desert soils and parent rocks unleached with calcium carbonate, calcium sulphate, soluble salts; phenomena of erosion and deflation; absolute dominance of aridity in the order of 95% of the time.

8. The most extremely arid deserts of the globe; accumulation of soluble salts and particularly nitrates, iodates, calcium and magnesium chlorides; deep deposits of gypsum, sodium sulphate and calcium carbonate; absolute dominance of aridity with drought probability of 100% and with exceptionally rare rainy spells.

Soils, and will be the scale of the World Map of Soil Degradation[1/] which will proceed in close cooperation with the preparation of the desertization map;

ii a desertization map at 1 : 5 million scale be prepared concurrently for a region (Africa north of Equator was suggested as a sample region) to illustrate the nature of the simplification and generalization processes which were involved in the preparation of the map at 1 : 25 million scale;

iii a series of more detailed maps on sample areas should be presented at scales in the order of 1 : 100 000 in a few selected representative regions;

iv the mapping criteria and mapping legends of the maps at 1 : 25 million, 1 : 5 million and in the order of 1 : 100 000 should be consistent with each other in order to clearly show the relationships between the three levels of generalization. The preparation of these maps should therefore be carefully coordinated and prepared jointly.

5. THE MAP LEGEND

5.1 The legend should comply with the requirements of the UN General Assembly resolution, e.g. it should theoretically distinguish between areas already affected and those likely to be affected by desertization. It should be noted, however, that an area already affected by a certain type of desertization is quite often likely to be affected by another. Moreover the likelihood of desertization depends both on the inherent vulnerability of the landscape to degradation (slope, soil texture, aggressivity of climate and other natural factors) and on human influences, either positive (protection, management, reclamation) or negative (degradation). For instance, it was considered essential that, to the extent possible, a distinction should be made between the areas where sandy deserts develop naturally as part of a geological and geomorphological process and those where sandy deserts develop as a result of human influence.

5.2 The group generally agreed to the following guidelines for the elaboration of the map legend:

1/ The preparation of the World Map of Soil Degradation at 1 : 5 million is expected to proceed concurrently. However, it will not be completed for the Conference.

i. by "areas already affected by desertization" it is proposed to understand essentially those areas which have already acquired strongly developed desert features, e.g. sand dunes, badlands, strongly saline areas, hammadas, rock debris, and barren plains; all the other areas would be considered as areas likely to be affected and would be assessed according to their inherent vulnerability (thus excluding human influences). To the extent feasible, however, map symbols would be used to identify areas where desertization develops as a result of strong human influences;

ii. among the areas likely to be affected only those which are highly and moderately vulnerable would be indicated (as one single category) on the map; the slightly vulnerable areas would not be shown on the map. The most critical areas could be shown by a map symbol (e.g. without delineation of the areas);

iii. besides distinguishing among different kinds of present desert areas, the legend would distinguish within arid and semi-arid areas between different processes of desertization and for each of these processes separated into two categories, e.g. "already affected" and "highly to moderately vulnerable" would be shown. Among the processes to be distinguished one may consider:

   a. salinization and/or alkalization,
   b. development of shifting sands (encroachment) and wind blowing (deflation);
   c. destruction of natural vegetation1/,
   d. denudation of hard rock or hard pans,
   e. development of badlands on soft material.

iv. at the scale considered and with the information available the assessment of the vulnerability to desertization can only be made by judgement. However, to ensure consistency in the assessment, it is essential that criteria and a method of assessment be developed on the basis of soil characteristics, climate, land form and vegetation.

5.3 The group recognized that the experience already gained in the preparation of the World Map of Salt Affected Soil could be usefully extended to other kinds of

---

1/ in areas where no other degradation process occurs.

degradation processes, in particular, the concepts used for the construction of the legend. It was also noted that the FAO/Unesco Soil Map of the World could provide most of the required basic information on the development of shifting sands, the denudation of hard rock or hard pans and the development of badlands. The legend of the Soil Map of the World also provided a useful distinction in the moisture regime of the soils of arid and semi-arid areas (Yermosols and Xerosols). It was also noted that the use of remote sensing imagery would provide useful additional information.

5.4 The group considered that the assessment of the process of degradation of the natural vegetation would raise problems since there was no cartographic document available for vegetation on a worldwide basis similar to that for soil resources. It was, however, recognized that the degradation of natural vegetation was an integral part of the process of desertization in certain areas. The map could not therefore be based only on the consideration of physical factors such as soil, climate and physiography.

6. CONCLUSIONS

The Expert Consultation stressed that an integrated ecological approach should be used in the preparation of the map rather than an approach which would only consider individual physical factors of desertization. It recognized that the map would only represent a first approximation which would be used to promote national activities to arrive at a better assessment of the problems.

The group also considered that desertization was a major aspect but only one among many others which lead to the environmental degradation of land resources. Recognizing the importance of the problem, it recommended that the Director-General of FAO give consideration to the establishment of an advisory panel which would regularly review the state of degradation of land resources on a worldwide basis and guide the development of international cooperation for the assessment of land degradation and/or its monitoring and control.

ANNEX 1

EXPERT CONSULTATION ON PROGNOSIS OF SALINITY AND ALKALINITY

Rome, 3-6 June 1975

(FAO/ISSS Sub-Commission on Salt Affected Soils)

PROVISIONAL PROGRAMME

Tuesday 3 June

Opening of the Consultation

A. Extent, Evolution and Economic Classification of Salt Affected Soils

1. Evolution of soil salinity, alkalinity and waterlogging: Prof. V.A. Kovda

2. Present and potential salt affected soils (An introduction): Dr. I. Szabolcs

3. Economic land classification for the prevention and reclamation of salt affected soils: Mr. W. Peters

B. Factors to be considered for Prognosis

1. Natural factors: Dr. W. van der Molen

2. Man-made factors:

   a. Water management and salinity: Dr. J. Van Schilfgaarde

Wednesday 4 June

   b. Assessing the suitability of water for irrigation: theoretical and empirical approaches: Dr. J.D. Rhoades and Dr. S. D. Merrill

   c. Soil management and agronomic practices: Dr. F.I. Massoud

C. Methods of Prognosis and Monitoring

1. Soil and hydrologic surveys for the prognosis and monitoring of salinity and alkalinity: Dr. I. Szabolcs, Dr. G. Varallyay and Dr. K. Darab

2. Soil and hydrologic surveys: Dr. K. W. Flach

3. Use of satellite imagery for salinity appraisal in the Indus Plain: Dr. M. Rafiq

4. Laboratory and field characterization:

   a. Laboratory analyses of soil related to the prognosis and monitoring of salinity and alkalinity: Dr. K. Darab

Thursday
5 June

   b. Measuring, mapping and monitoring field salinity and water table depths with soil resistance measurements: Dr. J.D. Rhoades

   c. Soil morphology: Prof. G. Aubert

   d. Natural vegetation and performance of economic crops: Dr. I.S. Zonneveld

5. Modelling of salt movement through the soil profile: Dr. H. Laudelout

D. Tentative Guidelines

1. Interpretation of quality of water for irrigation: Mr. R.S. Ayers

2. Predicting soil salinization, alkalization and waterlogging: Dr. A.M. Balba

Friday
6 June

Special Session on Desertification: Mr. P.J. Mahler

Recommendations on Prognosis of Salinity and Alkalinity

Closing of the Consultation

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Rome, 3-6 June 1975

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