REGIONAL SALINITY - SODICITY ISSUES IN PUNJAB, PAKISTAN

CONSULTANCY REPORT

by

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PREFACE

This report is the result of a one-month consultancy during February 1996. The funding for this special consultancy was provided by the Government of The Netherlands under the project, *"Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan"*.

This particular consultancy required the services of an eminent soil chemist. The need was for a highly qualified researcher in soil chemistry, who also has considerable field experience, to review and render professional judgements regarding the salinity research program being conducted by the International Irrigation Management Institute (IIMI) in the Province of Punjab, Pakistan. Unfortunately, there was not sufficient time to include field visits to the Province of Sindh.

Dr. James W. Biggar, recently retired from the University of California, Davis, agreed to undertake this assignment. He is a citizen of Canada where he grew up on a farm in eastern Canada. He did his undergraduate studies at Guelph. He received a Ph.D. degree in Soil Science from Utah State University during the 1950s under the tutelage of Dr. Sterling Taylor, a prominent Soil Physicist. He served on the faculty at the University of California, Davis for more than 30 years.

Dr. Biggar was accompanied on field visits by two people: (1) Mr. Abdul Hameed of the Soil Survey of Pakistan (SSP); and (2) Dr. Muhammad Aslam on leave from the University of Agricuslture, Faisalabad (UAF) and working with IIMI-Pakistan. Together, they visited three sites: (1) lower Rechna Doab; (2) the three subsurface drainage trials in the Fordwah Eastern Sadiqia (South) Irrigation and Drainage Project being investigated by the International Waterlogging and Salinity Research Institute (IWASRI) in collaboration with The Netherlands Research Assistance Project (NRAP); and (3) four farms located in Fordwah Eastern Sadiqia (North) near Hasilpur, which are being studied by IIMI staff regarding salinity and sodicity.

The most profound finding by Dr. Biggar relates to farmers using both tubewell water and canal water for irrigating the same fields. Contrary to conventional wisdom, the use of low salinity canal water, following some irrigation events using more saline tubewell water, has a greater likelihood of creating a sodicity problem, with the result that the soil flocculates and the infiltration rate decreases depending on the degree of sodicity.

After completing his report, Dr. Biggar sent the accompanying figure regarding research in the southern San Joaquin Valley near Fresno, California. Fresno County is ranked as the most agriculturally productive county in the U.S.A. Historically, farmers had pumped groundwater with a total dissolved solids (salinity) of slightly more than 700 mg/l (ppm). The soils contained natural salts, so that farmers had to continually cope with salinity problems. When the State of California constructed the California Aquaduct (Canal) a few decades ago, water having a salinity of less than 100 ppm was transported from nothern California for hundreds of miles to be used in southern California. The farmers were quite jubilant about having access to such good quality water. But much to their dismay, they immediately ran into problems associated with significant decreases in infiltration rates on their croplands. They had created a sodicity problem for themselves by applying such good quality water.

The accompanying figure shows that the canal water had a penetration rate (a measure of infiltration) two-thirds that of tubewell water. Gypsum had to be applied along with the canal water in order to nearly double the penetration rate.

Clearly, this example, plus the findings reported by Dr. Biggar in this report, requires some rethinking regarding irrigation and salinity/sodicity management practices in Pakistan. Also, these findings indicate that sodicity problems are presently increasing, rather than decreasing. Thus, there is a growing need to introduce improved salinity management practices.

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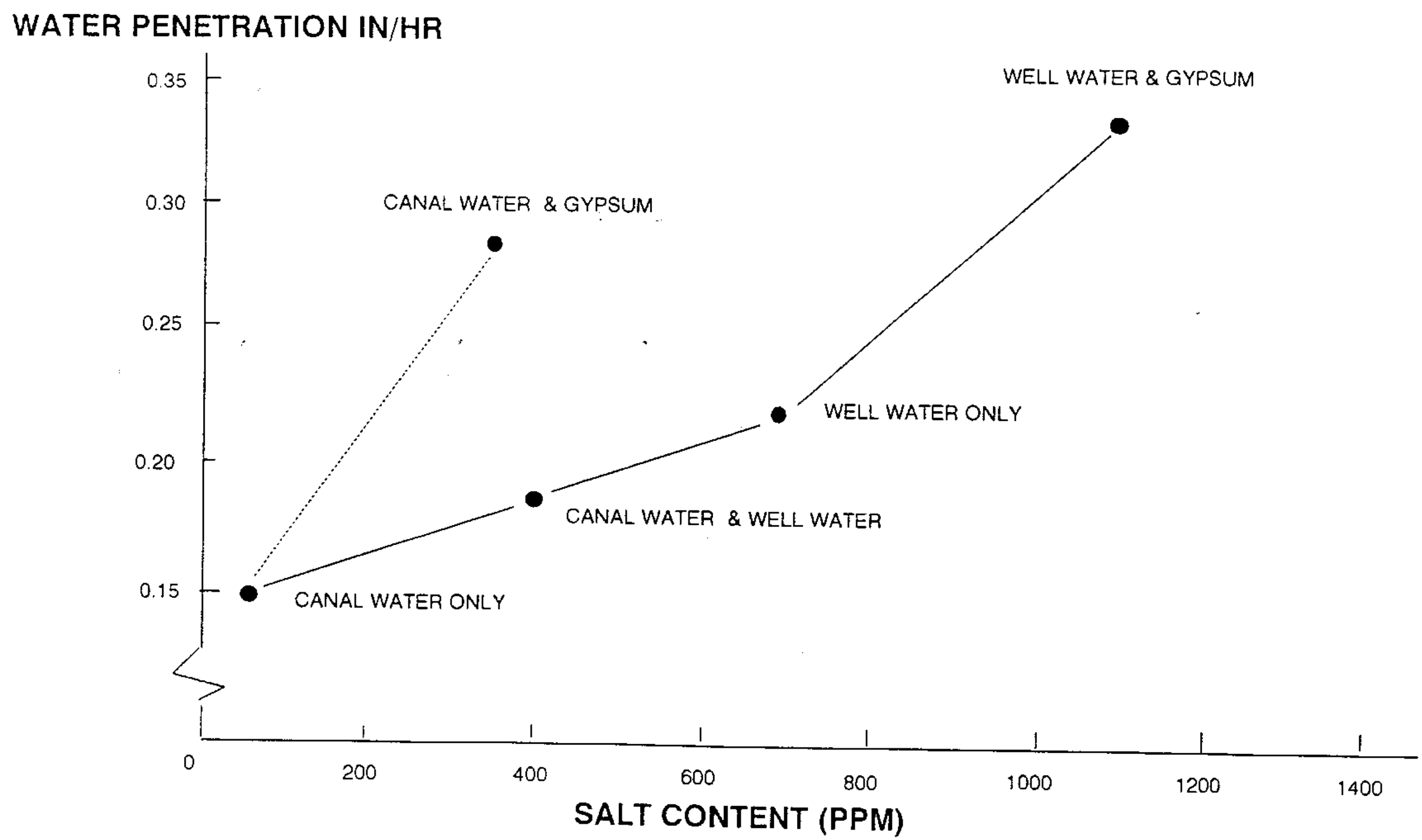

Impact of Canal Water and Tubewell Water, along with Gypsum, on Water Penetration (a measure of infiltration) while Irrigating Croplands in Southern San Joaquin Valley, California.

REGIONAL SALINITY - SODICITY ISSUES IN PUNJAB, PAKISTAN

This report will consist of several sections. The first sections will contain observations and comments related to visits in the Rechna Doab, Fordwah Eastern Sadiqia (South) Irrigation and Drainage project, and the IIMI field investigations in the Hasilpur region. Other sections will deal with specific issues. A section on suggestions contains summary comments on investigations planned or undertaken already in various forms or locations, but not shown to the writer. The annex contains specific observations pertaining to the field visit in the lower Rechna Doab. Opinions are those of the author and not necessarily those of IIMI.

FIELD VISITS

Rechna Doab Area

Large land areas in the lower Rechna Doab are now barren, which apparently were productive at one time. The salinization of the land occurred as a result of several different events. The occurrence of more prevalent saline-sodic or sodic soils in the Rechna Doab area results from the bicarbonate sulfate, sodium dominated groundwater. Although the river water, in general, may be described as calcium bicarbonate water, as a result of various processes in the soil and associated climate, they are converted to record saline-sodic waters. It is noteworthy that as the concentration of groundwater increases from < 300 mg/l to > 7000 mg/l, the ionic species shift from $Ca + Mg > Na$ and $HCO_3 > SO_4 + Cl$ to $Na > Ca + Mg$ and $Cl + SO_4 > HCO_3$. The processes of saline-sodic soil development are discussed in another section, but this shift in species is not unexpected.

The events alluded to in the beginning are often large in scale and sometimes localized, but gradual in development. In one location, the area was initially salinized by a break in a surface drain which salinized the surface soil and resulted in crop failures that drove farmers to abandon the area. In the recent 10 years, reclamation is being attempted.

In other areas, it has been a rise in the water table as a result of changing cropping patterns that has salinized the land. The building of sugar mills increased the acreage of sugarcane which led to more water application. As a general result of increasing irrigated acreage in many areas of the world, water tables become more shallow.

The increased use of tubewells of poorer water quality accelerated salt and sodium accumulation.

The effect of elevation is also evident. The so-called rim soils are less subject to waterlogging and salinity. But as the central region of the doab between the rivers is approached, where there are depressions, water and salts accumulate. The delivery of water through the various watercourses provides varying amounts of seepage. Regions nearer canals benefit from tubewells drawing seepage water. On the other hand, other areas subject to shallow water tables caused by seepage will experience salt accumulation. Certain tubewells used as partial or primary sources of water are responsible for sodification. Often, there does not appear to be a logical reason why some wells have poor water quality and others nearby are better in quality. However, this could result from old buried channels and pockets of residual saline water from earlier times. In view of the large number of analyses available, both temporally and spatially, it would be useful to perform temporal and spatial analyses of the water quality using time series and geostatistical analysis techniques. Recognizing that water may be drawn from more than one zone, wells could be selected or stratified on the basis of such information. Such an analysis would assist in identifying particular areas and wells for specific management decisions. However, regardless of such an analysis, the water quality of many are clearly in the questionable range for agricultural use unless specific management practices of leaching and amendment applications are followed. And adequate water table control is necessary.

In many areas, it was observed that where the system would allow (i.e. water table deep enough and some canal water available) crops of rather low salinity threshold were growing next to a field that was clearly saline-sodic. Both fields were farmed by the same personnel. Apparently, a decision had been made to protect the sugar crop and let the other field condition deteriorate. Although the sugarcane crop may not have reached maximum production potential, it was a viable crop. Such examples demonstrate the potential for returning these salt-affected areas to production for a variety of crops.

Fordwah Eastern Sadiqia (South) Subsurface Drainage Trials - International Waterlogging and Salinity Research Institute (IWASRI)

The first visit took place at the subsurface drains in Research Demonstration Field Site No. 2, where the field trials of drain design are most extensive. This soil type was chosen for the larger trial because it represents the largest percentage of soil type to eventually be drained. The soils are fine sandy loam with a dense layer at 3-5 feet that is strongly calcareous.

Waterlogging and surface salinity problems are evident in the area. However, there appeared to be less saline-sodic condition. The trial drainage installations of depth and spacing should provide good guidelines for expanded installations. The large number of piezometers should provide data for evaluation. The EM 38 measurements are important for accessing rapidly the qualitative changes in soil surface salinity to a depth of 75 cm, which may not be entirely adequate. The EM 38 probe does not provide information on ion species, which can only be obtained from more detailed chemical analyses. Tensiometer and Time Domain Reflectometry (TDR) measurements are being taken at one location to assist in model development. The weather station is poorly situated to represent conditions for crop production in the area. It provides radiometer, wind speed, rain gauge and evaporation data.

At the next site (Research Demonstration Field Site No. 3), the weather station is better located. It would be useful to have tensiometer and TDR measurements also. The Eucalyptus agroforestry lot is growing well and provides an opportunity to utilize poorer quality water and reduce the drainage volume that has to be disposed.

The surface drain which will receive drainage water from the tile field is poorly maintained. Crops are fair to good, being wheat, mustard and agroforestry.

The last subsurface drainage trial site (Research Demonstration Field Site No. 1) was in a saline area with the water table at 3 feet. The subsurface drains have been installed, but not in operation, pending completion of the lined open channel to carry drainage water to the surface drain. The farmer does not farm some fields because of a shortage of good quality water. The last stop was at the site of an interceptor drain test installation along the Malik Branch Canal.

Suggestions are made here to collect more data of varied content, recognizing that limited resources may not allow this. However, it would seem that one installation for measuring soil water in the field is minimal considering the area size and investment. Also, model validation and verification would be better served by having such data at more than one location.

The opportunity exists to follow the progression of reclamation by a program of analysing pipe drain effluent and a through analysis of piezometer water after pumping. Although the EM 38 measurements are very useful, some soil sample analyses for species analysis should be made.

Time series and geostatistical analysis would also be useful for following the reclamation process. More insight regarding salt balance evaluation, including specification, would be possible after a period of data collection. This would provide a better idea of whether the sodicity problem is increasing or decreasing.

Field Investigations in the Hasilpur Area

An excellent discussion and exchange of information took place on a number of topics related to the sodicity problems including formation, recognition, and effects. Some of these topics are covered under separate sections. The impact of exchangeable sodium (XNa), usually expressed as the sodium adsorption ratio (SAR) of the soil solution, and associated irrigation waters, varies somewhat from one soil type to another and is a function of the ionic concentration. The larger the concentration, the larger the SAR before the infiltration is adversely affected.

The soils in the area are varied, but more on the coarse rather than the fine textured side. Sandy loams, fine sandy loams, silty loams and silty clay loams exist. There are few clay loams to clay in textures. All are moderately to strongly calcareous. Some are now saline-sodic, pH 78.5 - 9.5, EC of saturation extract > 6, SAR > 10. Others have low SAR, EC and pH < 8.4.

There were examples of sodic soil formation at the surface 2 -3 mm as a result of irrigation with tubewells of high SAR and EC.

There were examples of water penetration problems with water standing in fields for long periods after application. Some of these soils may have relatively low infiltration rates due to their dense nature and because of compaction. However, they are probably susceptible to dispersion at relatively low SAR values. Illitic soils, such as these, are know to have weak structure and are low in organic matter. Irrigation with sodium water or waters with Mg > Ca will hasten dispersion. So-called black alkali soils were not found in this region, but were more obvious in the Rechna Doab area.

Water tables are a problem as they are mainly saline, and often are shallow. The texture of the soils in the area is susceptible to rapid capillary rise of saline water tables within 1.5 m of the surface; perhaps, more so than fine textured soils. While such characteristics are useful for plant utilization of groundwater for fulfilling ET requirements, they become rapidly salinized. Salt rise is a more efficient process than leaching, which is one practice for controlling salinization. In these soils, leaching may be difficult to achieve quickly due to the slow infiltration.

Much useful data is being collected and will serve to define existing and potential problems.

The salt balance question is being addressed. While not insisting that a chemical model should be developed (or adopted), it would seem to provide a tool for making better estimates of the direction that the system is going and the rate. It is doubtful if any model will ever be able to precisely describe the complex system, so one must be satisfied with good approximations.

As in other areas, geostatistical analyses might be applied to both soil and tubewell water data, providing sufficient data are available. With time series analyses, trends in the salt balance can be established. It would be useful to have more field measurements of soil water pressure and water content. Sodicity should be included in the crop yield production function, if possible. A rough estimation of infiltration characteristics could be obtained by using stick gauges in farmers fields, especially if measurements of water application are also being made.

BEHAVIOR OF SODIC, SALINE-SODIC SOILS

Soil Characteristics

The formation of sodic or saline-sodic soils is especially important because of additional problems of management and costs for chemical amendments, or organic matter, to prevent or correct the progression of the deterioration of the soil environment.

Unless a soil is sodium-affected and is being reclaimed, the onset of sodicity is gradual and not readily detected until significat changes have occurred that:

1) modify the infiltration and movement of water in soil;
2) inhibit germination of seed and emergence of plants;
3) disrupt tillage practices;
4) cause soil structural breakdown and degradation;
5) affect aeration in the root zone; and
6) create nutritional and toxic effects.

Factors which contribute to the response or problems of soils and plants in Na affected soils can be summarized as follows on the next page:

Infiltration of water | Germination of Seed and Emergence of Plants | Aeration | Nutrition

Porosity and Pore Size Distribution

Swelling, Dispersion and Movement of Clay

Clay Mineral Type | Ionic concentration of soil solution or water | Ion ratio Na/Ca, Na/Mg | Other; texture, organic matter, tillage, water appl.

Clay Minerals

Of the three particle size distribution groups -- sand, silt and clay -- that constitute the soil matrix, clays are the smallest and most reactive chemically. They are the site of cation and anion exchange and retention reactions.

Representative clays found in soils are:

Type	Platelet size	Surface area m^2/gm	Cation Exchange capacity me/100 gm
Montmorillonite 1)	small	800	125
Illite 2)	medium	150	80
Raolinite 3)	large	15	10

All are smectite minerals

Montmorillonite

Montmorillonite, a layered mineral, has swelling and shrinking characteristics in response to its exchangeable and solution environment. Grouping of several platelets into clusters to form aggregate units or tactoids are the basic units of soil aggregates and tend to give soil its pore size distribution, friability and structure.

Its internal and external surface area properties and Na ion properties result in a disproportionate concentration of Na ions on external surfaces, the site of platelet and particle size interactions. Consequently, as little as 10-15 percent of exchangeable sodium (XNa) will weaken soil structure, cause swelling, dispersion and clay movement. This has the affect of reducing infiltration of water, air exchange, and the hydraulic conductivity of the soil. As the zone of degradation increases in depth, tillage becomes more difficult. The soil may be slippery and soft when wet, but hard when dry; also, large cracks may develop on drying.

Illite

Illite is a non-expanding (slight) mineral with uneven platelet surfaces that tend to inhibit formation of strong and stable structures. It is considered to be adversely affected at lower XNa concentrations

Kaolinite

A non-expanding mineral of larger dimensions not as adversely affected by XNa.

Total Ionic Concentration

The concentration of salt in the soil solution, as previously noted, can affect the structural units of the soil aggregates through its effect on the hydrostatic pressure that is created when a separation of charge (ionic concentration) occurs in the regions of the clay platelets. As the soil solution concentration decreases, the tendency for swelling and dispersion increases. This is especially critical when the exchangeable sodium increases to higher concentrations. Therefore, replacing irrigation water of high SAR and EC with water of low SAR and EC causes infiltration problems.

Ion Ratios

The ratio of Na to Ca and Na to (Ca + Mg) in the exchange complex, and therefore in solution, is an important factor affecting the response of soils to water and the environment for plant germination and nutrition.

The monovalent sodium ion has a large hydration and consequently is easily dissociated, thereby making it osmotically active. Its bonding characteristics are much less than the Ca ion, which promotes platelet aggregation and soil stabilization. Magnesium is intermediate and in some cases has resulted in magnesium solonetz soil at large concentrations.

The interaction of total ionic concentration and ratio of Na/Ca are very important aspects of the sodic problem for soils in Pakistan.

Other factors

Other factors that produce the difference in response to the system properties already discussed include the organic matter content which acts as bonding materials for stabilizing structures. The amount of sand and silt also is a factor.

The manner in which water contacts the soil surface has been demonstrated to influence structure. Impact of rain drops, the force of water flowing over the soil surface, and the wetting and drying action all affect the pore system, infiltration and aeration.

Summary

Soils of the Rechna Doab, Bahawalnagar and Hasilpur areas appear to be responsive to the factors mentioned above. In some cases, these very fine sand to silty loam and loamy soils will have adequate, but not rapid, infiltration under ideal ion ratios and electrolyte concentrations. Since many of the soils have a prepondence of illite clay mineral, and the organic matter is low, poor infiltration and tillage characteristics are likely to develop as the ion ratio shifts to sodium and the electrolyte is less concentrated.

SODIFICATION OF SOILS

The formation of sodium-affected soils is a complex combination of various processes involved in the formation and evolution of soils. The general parent material, temperature, topography, moisture, biota and time are involved.

In the case of the Indus Basin, it is uncertain whether remnants of ancient marine seas exist in the groundwater zone to influence the quality of the groundwater, or whether the salt is derived principally from decomposition of parent materials. As long as the concentration of Ca > Mg > K > Na and Cl = SO_4 > HCO_3 + CO_3, the principal problem will relate to the impact that Ca + excessive salinity has on plant growth through restricting water availability to plants, or by specific ion toxicity. When the combination of cations and anions are such that through a combination of exchange reactions, precipitation, dissolution, and redox reactions, the concentration of Na dominates the soil solution, then either a combination of excessive salinity and sodium, or only excessive sodium, may occur.

The problems of salinity in general then can be thought of as involving excesses of either salts in general or Na in particular. The manifestation of these excesses of salt or sodium is different in the soil and crop and require different management practices.

The excesses of salts dominated by Ca and Mg in the root zone of crops results from decomposition of primary or secondary materials, the continual application of water containing salts, or accumulation of salts from the groundwater. Processes involved in this changing salinity environment include evaporation at the soil surface, plant transpiration and respiration, organisms and various physio-chemical reactions such as ion exchange, precipitation and dissolution. These same processes are involved in the formation of sodium-affected soils, except the composition of the soil solution is dominated by Na rather than Ca and Mg.

In simplified form, these processes involving components of interest can be expressed as

$$H_2O + CO_2 \text{ <---> } H_2CO_3 \text{ <----> } H^+ + HCO_3$$

that act on the primary minerals to produce the elements.

Primary Mineral	Example Mineral	Chemical formula	Released element
feldspars	Osthoclase anorthite albite	$KAlSi_2 O_6$ $Ca Al_2 Si_2 O_8$ $Na Al Si_2 O_8$	K, Na,Ca
amphibole	hornblende	$(Na Ca)_2 (Mg, Fe, Al)_5$ $(Si, Al)_8$ 22 $(OH)_2$	Ca,Mg,Na
apatite	apatite	Ca10 $(F,OH, Cl)_2$ $(PO4)_6$	Ca, P, Cl
pyroxenes	enstatite diposide angite	$Mg Si O_3$ $Ca, Mg Si_2 O_6$ Ca (Mg, Fe, Al) $(Si, Al)_2 O_6$	Mg, Ca Fe

Further dissolution, concentration, spatial changes and temporal fluctuations result in the more common solid plase minerals normally considered in agricultural production. These are mainly

$Ca^{++} + HCO_3 + OH$ -----> <----- $Ca\ CO_3 + H_2O$ calcite

$Ca^{++} + SO_4 + 2H_2O$ -----> <----- $CaSO_4\ 2H_2O$ gypsum

$Mg^{++} + Ca^{++} + H_2CO_3 + CO_2$ -----> $Ca\ Mg\ (CO_3)_2 + Ca$ dolomite

However, of particular interest is the evolution of the soil environment from one where Ca + Mg dominates the soil solution composition to one were Na is the dominating cation.

Several conditions and processes have been identified that lead to such results. One or more may be involved in a given environment.

1) Action of dissolved CO_2 on silicate minerals as previously mentioned. Calcium, Mg, Na and K are released and if and, when evaporation occurs, CO_2 is lost from $Ca\ HCO_3$ and $Mg\ HCO_3$ to form $Ca\ CO_3$ and $Mg\ CO_3$. Similarly, $Na\ HCO_3$ is converted to $Na_2\ CO_3$.

2) Action of Na Cl or $Na_2\ SO_4$ on $Ca\ CO_3$.

$Ca\ CO_3 + 2\ Na\ Cl$ ------> <----- $Ca\ Cl_2 + Na_2\ CO_3$

$Ca\ CO_3 + Na_2\ SO_4$ ------> <------ $Ca\ SO_4 + Na_2\ CO_3$

3) Replacement of exchangeable sodium.

by H - ions or Ca-ions-

Na_2-Clay + H_2CO_3 -------> <------ H_2 - Clay + $Na_2\ CO_3$

Na_2-Clay + $CaCO_3$ -------> <------- Ca Clay + $Na_2\ CO_3$

Na Clay + Ca $(HCO_3)_2$ -------> <------- Ca Clay + 2 Na HCO_3

4) Reduction of $Na_2 SO_4$.

Under low redox potential, $Na_2 SO_4$ may be reduced to $Na_2 S$. Carbonated water then reacts with $Na_2 S$.

$$Na_2 S + H_2CO_3 \rightleftharpoons H_2S + Na_2 CO_3$$

This occurs in reducing environments such as exist in waterlogged soils and may be a source of $Na_2 CO_3$ in the regions of interest.

5) Decay of plant material.

The precipitation of less soluble calcium compounds (in contrast to the corresponding sodium compounds) and the exchange processes that occur in the root zone must not be underestimated when evaluating the formation of saline-sodic soils in the Rechna Doab and Hasilpur areas. The impact of solubility difference is well illustrated by the Gibbs model and the Hardie - Eugster model for salinization of waters by evaporation.

Gibbs and Hardie - Eugster Models

In the Gibbs model of chemistry (Figure 1) of world surface waters, the water of the major rivers of Pakistan are similar to others where the chemistry reflects the dominance of rock source (canal water, Table 1). The Na/ (Na + Ca) = 0.12 and TDS = 120 mg/l puts the water at the central apex. The Bamundir branch drain, Table 2, indicates the processes of evaporation and crystallization.

These shifts in evaporation toward increasing Na and decreasing Ca are futher illustrated by the simplified Hardie - Eugster (Figure 2) model for evaporation salinization of water. As applied to the canal water, upon concentrating, the HCO_3 exceeds Ca so that after calcite, sepsolite (Mg Si_2 O6 $(OH)_2$ forms. Since Mg > HCO_3, Mg, Na, Cl and SO_4 will be the principal remaining salts. However, in the case of the soil system, the model does not include ion exchange, production of CO_2 by plant roots, and organisms and additional inputs of capillary rise from the water table.

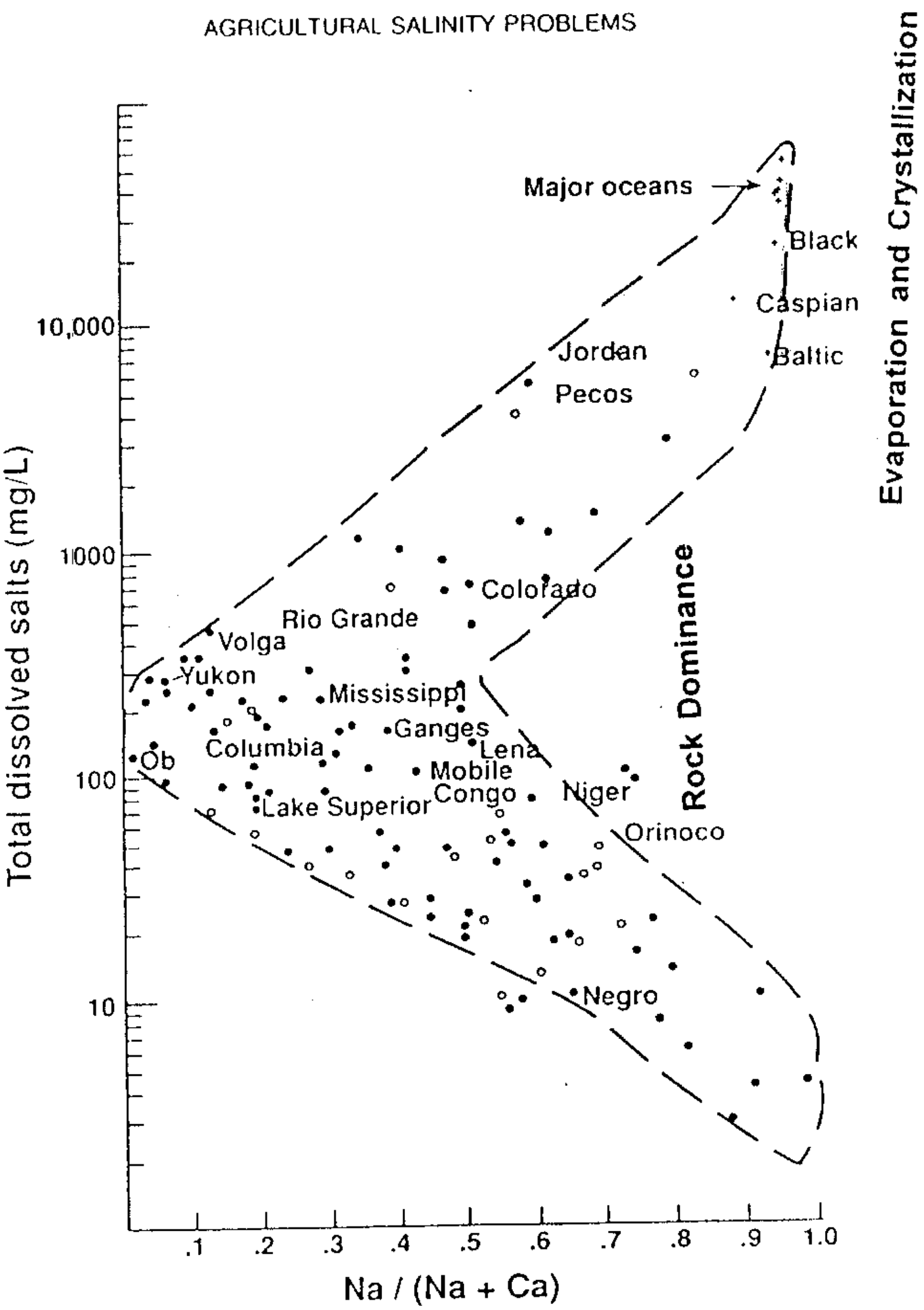

Figure 1. Chemical Characteristics of World Waters (Gibbs 1970)

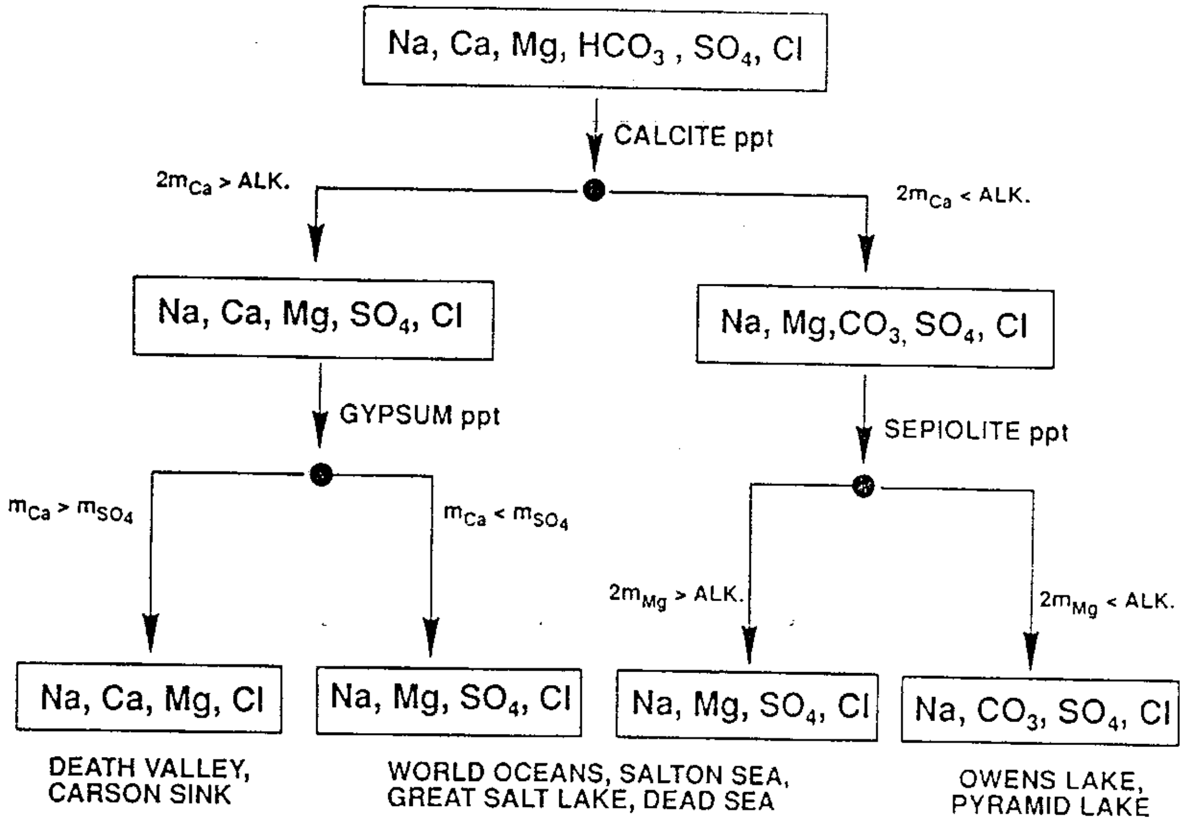

Figure 2. Hardie-Eugster Model for Evaporative Salinization of Waters (Drever 1982)

Table 1. Canal water from the Rechna Doab area and the Hasilpur area.

Ca	Mg	Na	CO_3	HCO_3	Cl	SO_4	EC	SAR
<----------			meq/l	----------		----->	dS/m	
Canal - Rechna Doab								
1.25	0.45	0.17	0	1.4	0.3	0.2	0.18	0.2
Canal - Hasilpur								
0.70	0.9	0.2	0	1.2	0.4	0.3	0.19	0.2

Table 2. Canal surface drain, and sump water at SIB9 sump.

Ca	Mg	Na	CO_3	HCO_3	Cl	SO_4	EC	SAR
<----------		meq/l		----------	----->	dS/m		
Sump (Ave) pH = 7.7								
3.25	3.25	27.6	0	12.5	10	11.9	3.23	15
Samundri Br. Drain. pH = 9.3								
1.55	1.15	24	3.2	8.8	5	10.2	2.53	20
Canal pH = 7.8								
1.9	0.4	0.43	0	2.3	0.3	0.2	0.27	0.4

Tubewell Water

The waters of this group may be characterized as $Na_2 SO_4$, $NaHCO_3$ waters having a range in salinity from EC = 0.4 to 4.00 dS/m. The chloride concentration is low, ranging from 0.6 to 6.8 meq/l. The sulfate ranges from 1.0 to 32.2 meq/l and bicarbonate from 2.1 to 11.4 meq/l. The sodium concentration is generally moderate to high, but ranges from 0.9 to 39.2. Calcium and magnesium (Mg) are low with a range of 0.7 to 9.0 for Ca and 0.1 to 8.6 meq/l for Mg. In many cases, the sodium adsorption ratio, a measure of sodium hazard, is high. Because the total ion concentration is also high, these waters could be used without immediate water penetration problems. However, the exchange complex will shift to sodium dominance. Then, if water of lower concentration (such as canal water) is applied, or rainfall occurs, the soil will disperse and low infiltration develop.

If the ratio of Mg/Ca increases, nutritional problems may develop. The alkalinity as represented by the bicarbonate/carbonate ions causes higher pH values and infers the potential progression to formation of sodic soil. Through ion exchange of Ca for Na, the Ca ion will precipitate with carbonates to form lime. If the sulfate concentration in lime is large enough, gypsum will also precipitate. The Gibbs and Hardie - Eugster models are illustrative of changes resulting from evaporative drying and concentrating.

Many of these waters, if used on soils in the Hasilpur area, will quickly create sodium problems unless amendments are used to control the progression to exchangeable sodium.

WAPDA guidelines for water use

	Useable	Marginal	Hazardous
EC dS/m	0-1.5	1.5-2.7	>2.7
RSC meq/l	0-2.5	2.5-5.0	>5.0
SAR	0-10	10-18	>18

RSC = Residual Na carbonate.

It is worth noting that some of these waters are probably saturated with respect to lime, so that lime would precipitate in the soil, thereby removing Ca from solution.

Movement from a shallow water table, creates conditions for the formation of Na HCO3, and Na2 CO3 and sodic soils.

Comparisons

A comparison between the situation that exists in the Rechna Doab, Hasilpur, and Bahawalnagar areas might suggest quite different conditions prevail and, consequently, the changes that occur in the two areas will diverge. To be more specific, problems of having excess salt can be found in both regions. However, the occurrence of saline-sodic and sodic soils would appear to be more prevalent in the Rechna Doab region than the other two areas. Why should there be differences? If one examines the soils, it is evident that similar types of textural classes exist in both regions. The fine sandy loams and silty loam soils are quite suitable for rapid upward movement of capillary water with salt if a water table is present. The existence of restricting layers in the subsoil prevents rapid leaching of salts. In addition, the process of upward movement of water is more efficient for transporting salt than the reverse process of leaching. In the different areas, the composition of drainage, while showing some difference, is nevertheless quite similar in terms of the direction in which the saline condition is likely to progress. The drainage waters from soils where salts have accumulated previously and are now being leached, generally have EC values in excess of 1500 dS/m, SAR's in most cases exceed 10, and there are significant increases in HCO_3 concentration. Shallow well water tends to show a presence of HCO_3, even though the concentration of $Na < Ca + Mg$. A shift is occurring towards a higher total concentration of salts, with Na increasing at a faster rate than Ca + Mg with sulfates and chlorides also increasing. Reference to the earlier comments on the sequence of precipitation provides some explanation.

Another factor is the composition of the applied water from the rivers. They are essentially $CaHCO_3$ waters which, as noted, shift to sulfate and chloride solutions in the arid soil environment. The cropping patterns are somewhat different, partially reflecting perhaps a more favourable climate/soil for one cash crop over another. However, the basic staple crops are similar.

Thus, in summary, given similar major factors that drive the system, it may seem difficult to explain the more evident occurrence of saline-sodic soils in the Rechna Doab region. A closer examination however reveals similarities greater than differences. At this stage, progression to a saline-sodic condition is more advanced in the Rechna Doab than the Bahawalnagar - Hasilpur regions, but that both systems will proceed in the same direction without intervention.

APPLYING THE SALT BALANCE APPROACH

Collection of data in various regions of the irrigation and drainage project provides an opportunity to estimate the salt balance (ion balance) that is occurring on a local (field) scale, project scale and regional scale.

The salt balance approach considers the inputs, outputs and change in storage of the entity of interest to assess accumulation in the zone, or outflow from the zone. Both kinds of information are useful for different reasons. Undertaking a salt balance will involve also doing a water balance.

The simplest expression can be given in terms of water depths.

$$Ds = Dr + Dg + Di - De - Dt - Dd$$

Ds	=	depth stored in zone
Dr	=	depth rainfall
Dg	=	depth entering from groundwater
Di	=	depth applied (irrigation)
De	=	depth evaporated
Dt	=	depth transpired
Dd	=	depth drained

Change in storage, Ds, can be measured.
Rainfall can be measured or estimated.
Irrigation can be measured (calculated).
De + Dt (evapotranspiration) can be estimated using available models.

So, a net value for Dg + Dd can be assessed, or Dd may be estimated from tile outflow.

The corresponding salt balance

$$Ss = DrCr + DgCg + DiCi + Sm + Sf - DdCd - Sp - Sc$$

Ss	=	salt stored in (root) zone
Cr	=	concentration of salt in rainfall
Cg	=	concentration of salt in groundwater
Ci	=	concentration of salt in irrigation water
Sm	=	salt derived from mineral dissolution
Sf	=	salt derived from fertilizer
Cd	=	salt concentration of drainage water
Sp	=	salt precipitated
Sc	=	salt removed by crop

Assume as a first approximation that the major sources and sinks of salt are irrigation water and drainage water; then, assuming that the change in Ss = O (steady state)

$$DdCd = DiCi$$

and replacing concentration with EC and rearranging

$$LF = \frac{Dd}{Di} = \frac{ECi}{ECd} \text{ or } \frac{Cli}{Cld}$$

The leaching fraction (LF) is thus defined. Various estimate can be made for Sm, Sp, Sc and Sf (farmer).

Obviously, it is dangerous to draw conclusions if steady state has not been reached, even for trends. However, nothing ventured nothing gained.

A comparison should be made on the ratios of constituents that do not undergo significant precipitation-dissolution reactions with those that are expected. The obvious choice for comparison is Cl since its interaction is mainly related to an ion exclusion interaction which will be ignored at first. The other choice is EC replacing total concentration. The calculation is made for the average value of constituents in the water from the sump, the canal water and the Samundri Branch drain.

Table 4. Salt Balance Estimate

	Ca	Mg	Na	CO_3	HCO_3	Cl	SO_4	EC
	--------------meq/l				---------------------- dS/m			
Sump	3.25	3.25	27.59	-	12.5	10	11.9	3.2(Avg)
Canal	1.57	0.42	0.30	-	1.85	0.3	0.2	0.23
Drain	1.55	1.15	24.0	3.2	8.8	5.0	10.2	2.53
Canal Sump	0.48	0.12	0.01		0.06	0.03	0.01	0.07
Canal Drain	1.01	0.36	0.01		0.21	0.06	0.02	0.09

Data from sump SIB9

If the Hoffman guidelines are applied to this situation, an estimated mean root zone salinity for this water (canal-sump) and a leaching fraction (LF) of 0.05 should be about EC = 1.5. If it is assumed that the EC at the bottom of the root zone is about twice the mean root zone salinity, then the drainage water EC = 3.0 dS/m. This value approximates those of SIB9 sump water. The corresponding LF derived from canal/sump Cl = 0.03 and EC = 0.07 (see Table 4). For this canal water, the range in LF is minimum to adequate. The LF calculated from salt flow could be quite appropriate. A comparison with an estimated water balance would be useful.

In addition to not knowing whether steady state exists, it is well understood that the other constituents will be subject to dissolution and precipitation reactions, biological processes, etc. Nevertheless, it is interesting to note that the LF for Ca and Mg, the two constituents that are most likely to precipitate or dissolve and undergo exchange (preference to Na), is estimated to be much larger than that from EC and Cl and much less for Na, SO_4 and HCO_3. Consideration should be given to the dissolution of silicates. Thus, a dilemma.

However, it is unlikely that Ca or Mg will preferentially leach compared with Cl. The same can be argued for Na in the opposite sense. The large absolute value for Na in the sump water would suggest stored sources of soluble Na salts from prior accumulations now being removed or in other words, steady state has not yet been reached. It is also possible that some Ca is dissolving in response to the effect of high concentrations of Na salts on the dissolution of $CaCO_3$. That dissolution could enhance the out flow of Na due to ion exchange initially. But the behavior of the Cl implies that excessive water application is not occurring.

The bicarbonate increases because of biological activities in the root zone and atmosphere inputs. However, it is evident from a closer, if only cursory, assessment of the sump water, that these waters are close to or saturated with respect to calcite. This chemical constraint limits the outflow of Ca and therefore gives the appearance of a larger leaching fraction which in reality does not occur.

Interestingly, at this point, an examination of tubewell waters in the Hasilpur region demonstrate similar possible constraints with respect to calcite and may also involve gypsum.

A chemical computer program would be useful in more precisely speciating the soil and drainage waters and identifying major processes involved in the salt storage and salt flow out of the profile.

Probably, a combination of processes and reactions are occurring. Because of salinization in other regions, excess sodium salts are being removed that are not derived from the applied water. Some dissolution of Ca and Mg, and exchange of Na for Ca, may occur. As better assessment of the salt outflow is made, it will become evident whether subsurface flow of salt into or out of the region is occurring that might delay reaching a quasi steady state. The Branch drain water is obviously a bad water and its use or release to the region would degrade the system waters unless amended. The relationship of the drain water constituents to the processes occurring in the region drained by the sump drainage system may be more tenuous, rendering the salt balance calculation even more questionable.

Again, it must be emphasized here, that this example may not be a good one, but the concept is, and could be applied in various regions.

SUMMARY COMMENTS

1. The canal-river waters of Pakistan are of excellent quality providing a wide range in options for crop and soil selection.

   As one progresses from the source to the lower reaches of the river, the quality may be degraded by return flows from drains, subsurface flows, and industrial inputs. Therefore, care should be take to monitor the rivers at selected locations on a regular basis for more common major constituents. A thorough geochemical analysis should be done at a few selected sites annually, or seasonally, or when major changes in water quality might be expected due to exceptional weather events or drastic changes in river management. This information is necessary for the protection of the water system, the public health, and the protection of the food production system.

   However, in situations where salts are allowed to accumulate in soils and shallow water tables, the development and use of these waters will cause saline-sodic soil conditions.

2. The soils of Pakistan are good productive soils with potential for high continuous food output.

   However, the soils are also of the type that are easily degraded if not properly managed. They are not highly structured soils and the structure they possess is fragile and, therefore, not as resilient to abuse. Hence, it will be found that water penetration (infiltration) problems will exist and be aggravated by compaction and adverse water quality. Proper management of the available good water will result in successful production for many years, but excessive use of poor quality waters will degrade the soils and lower agricultural production.

3. Additional measurements at selected sites of soil water pressure, water content and hydraulic conductivity should be made in the subsurface drainage project and the irrigation management area. These data from both areas can then be used to develop or improve current models for estimating water balance, determining and guiding better use of water, better distribution, better application, and better drainage requirements. The data collection and analyses should simultaneously involve modelling just as the reverse is true.

4. Chemical model (s)

Plans should be initiated to implement the use of chemical models involving more detail than electrical conductivity. Recognizing the great expense and time involved in measuring and monitoring chemical species, adequate models, once assessed relative to the system to be described, can reduce the need for intensive monitoring. They also can provide better insight into the direction that the system is moving in terms of sustainability.

This comment applies to several scales in terms of size. Although a chemical model for root zone salinity may require more detail, less detailed models may be adequate for describing local, or regional, flows. Larger scale models are now in use and more are under development.

5. The potential for development of saline-sodic soils using the ground waters and drainage waters does indeed exist and, in fact, has already occured in the Rechna Doab, Fordwah Eastern Sadiqia, and Hasilpur areas. These types of soil problems result from insufficient leaching of accumulated salts, development of shallow water tables with extensive evaporation, use of poor quality ground water, and the failure to develop management schemes to deal with these adversities. Often the farmer is not aware of the sodium problem or its potential until it has degraded the soil. In the case of salinity only, he has visual evidence in advance of, or in addition to, a reduction in crop production.

6. Collection of EM 38 soil salinity data over a broad area on a temporal basis provides the opportunity to analyze it spatially and temporally using geostatistical and time series methods as the data collection occurs before and during operation of the drainage system trials.

The additional collection of water quality of tile drain effluent to evaluate the changes in salt balance at the local (farm) and regional scales would also be useful. That coupled with selected soil profile salt balance assessments would render model application both useful and productive. Water balance is already being assessed. Adding the salt balance component would seem prudent and attainable with only a limited extension of resources.

7. Geostatistical methods with or without GIS might extract valuable information from several data sets. More thorough appraisal of the data sets and objectives to be achieved might be worthwhile. Examples to be mentioned include:

1) Tubewell water quality in the Rechna Doab and its relationship to the drainage and salinity problems. Other areas may also be amenable to these analyses.

2) Application to water table data collected in the subsurface drainage project.

3) Spatial data collected in the Hasilpur area.

Can tubewell quality be related to subsurface characteristics, such as old buried channels?

8 In like manner, time series analyses could be used to evaluate temporal data such as water quality parameters from rivers, tubewells, drain effluents, etc. Such analyses would help identify trends and make predictions of future problems.

9. Salt balance evaluations in several regions on both local and regional scales will provide useful information on trends occurring in the system. It would also provide information on the salt flows and where they occur. For example, how much of the salt load is derived from evapotranspiration and from dissolution of solid phases?

10. The problem of water penetration in some Pakistan soils could become both more severe and extensive in the future if the practice of cyclic use of low salt, low sodium canal water, with more saline sodium waters gains acceptance. This condition rapidly developed in California when soils previously irrigated with more saline well water was replaced with canal water of low salinity.

The practice of cycling the use of waters of two different qualities, usually one being of poorer quality, is gaining favor as a means of expanding crop acreage, or reducing the volume of drainage water, that must be discarded.

The impact of such a practice is most critical at the soil surface where water enters and where the forces of rainfall or traffic are most severe. On a microscale, the solution environment in which the colloidal clay component of the soil resides strongly influences the pore structure through which the water must pass. The proportion of exchangeable sodium to calcium and magnesium is significant because the monovalent sodium ion does not support and strengthen the bonding of soil particles together the way the divalent calcium ion can. The weakly bonded Na ion contributes to water penetration problems by causing swelling and dispersion of some types of soil clay minerals. The forces of hydrostatic pressure indirectly caused by the Na ion are the reason for the disintegration. Howevewr, the total electrolyte (or salt) concentration of the solution also is significant in this process because it tends to prevent this disintegration of the soil pore system. Consequently, the concentration of sodium and total salinity of an irrigation water are factors that need attention when managing the cyclic use, or blending, of waters.

The dangers of practicing cycling or blending of waters is now evident. Waters that are more saline, even with higher SAR (sodium) do not adversely reduce the infiltration because the salt concentration is large enough to prevent the exchangeable Na from creating a condition of elevated hydrostatic pressure to breakdown the structure. However, if the soil is then irrigated with water of low salt content, the exchangeable Na previously accumulated, will create a pressure sufficient to break the bonding of the particles, reducing the pore structure and decreasing the infiltration of water into the soil.

The rate and degree with which a soil responds to these changes in the ratio of Na to Ca varies. Water may stand for longer periods on the surface and not penetrate as deeply in equal time periods. Although the degraded structure is reversible, it may require time, the addition of amendments or organic matter, or some form of tillage to reestablish good structure. The process of wetting and drying is also involved.

While there may be good reasons for cycling or blending of waters, the associated management practices are more crucial for the long-term sustainability of the system.

FIELD NOTES FOR LOWER RECHNA DOAB

Stop # 1. Surface salinity is evident. The govt. had installed ample tubewells to lower the water table. Then the govt. built sugar mills in area and sugarcane expanded as did the increase in the water use by that crop.

Variation in quality of water associated with the public (and private?) tubewells is related to the intersection of old buried channels that conduct water from canals to various regions farther away.

As well failed, the water table rose and now the land is being salted from water table. Soil appeared to be saline non-sodic.

Stop # 2. Area smaller empty canal some 200 yds. Field over-saline but surrounded by sugarcane, mango and some wheat. Also there was alfalfa and mustard.

Stop # 3. Very near the road, some alfalfa and wheat. Further look disclosed a very salt/sodic condition - pH 8.8 - 90 - 10 at surface and 15 cm 8.6. - Govt. tubewell was saline; helped a little, but not much, as focus was lowering water table (WT).

Gr H2O at 1-2 feet. - Used to farm 40 years ago until WT rose.

When area was good, only 40% of area farmed in winter, but over 60 % summer. But with new varieties, expanded growing area and more water has raised WT.

now WT 1 1/2 m - sandy loam - Sodic/saline - area kikar babe - Noted 1/2 mile away sugarcane - Tubewell abandoned.

Stop # 4. Some Eucalyptus growing. This vast salt affected area like a broad river flood zone through the landscape - a continuation of the previous site. Attemps being made to reclaim with wheat - some sugarcane.

The large salted area appears to be a natural flow zone across which a surface drain was constructed and when it overflows, water came down the natural drain.

Stop # 5. On road to Faisalabad a large salted area with $Na_2\ CO_3$. Mango trees look alright.

At village vast flood plain from high cut and seepage from distributary.

<u>Northeast of Faisalabad</u>

Stop # I. Along road sandy loam soil, saline patch surrounded by crops, wheat, mustard and sugarcane.

<u>History</u>. 10 years ago, cultivated. WT rose. Farmers abandoned. Then area tiled - water table controlled. Field now being placed for onion and tobacco pH 8.5 surface.

Stop # II. At tile drain pump to surface drain. Some salinity - pump not operating, because WT below drains. Pumping lowered WT.

Stop# III. Surface saline - sodic pH 7-9. Elevation lower than previous stop so was wet- now WT dropped to 20 ft. Farmer reclaiming - with canal H2O and no gypsum except where water stands. .
Sugarcane, wheat, sparse mustard. There is evidence of excessive sodium. use gypsum and/or green manure for CO_2 production.

Stop # IV. Further east of III
very large salted area - low lying - flooded in 1977. before that very productive - after flooding people abandoned - now WT at 20-40 ft so can reclaim - soil saline sodic surface pH 10, while below is less than pH 9 - Proceeded to surface drain and drove along drain. Eucalyptus trees grove 25' x 5" dia about 10 years reclaiming. Drain poorly maintained.

Stop # V. native vegetation - large bushes - loam soil surface pH = 9 lower 8.5 - 9.0 - probably mostly saline not bad sodic - sugarcane 500 yards away. Could use tubewell water to begin reclamation. Because saline sodic

Stop # VI. to west - field planted to wheat but sparse - loam soil large crack-salt leached but sodium remains - probably saline sodic at surface but saline below - Attempted to grow sugarcane - not as salt tolerant as wheat - nearby field has good growth of mustard, alfalfa.

Area was productive - then WT came to surface - soil salted and farmers abandoned. Then came tile drain.

Field trip III

Stop I. The first stop near the small canal - field sandy loam surface but the next field soil removed from surface and piled along border. Soil at depth more loam. Forage crop nearby looks good. Farm at tailend-no canal water, watertable was high due to canal seepage. Salt accumulated-used tubewell (brackish) now watertable lower and outlet from canal secured. WT at 20'. Eucalyptus trees 4 years old. 35 feet high by 12 inches dia. Soil surface pH=8.6 - 8.8 - somewhat sodic. Subsoil saline-some cracking. Area tile drained 2 km away. More land will be reclaimed - now native vegetation. Bare areas with some surface salt, area not leached.

Stop II SE-7
At drain sump. Sump not working. Surface drain nearby poorly maintained. Farmer planted fields but sump pump failed, for 3 months not working, so field not being reclaimed. WT at 3 feet. Area to southeast waterlogged. Soil loam to clay loam - cracking upon drying.

STOP III SIB-9 Water quality being pumped from pipe drains is = 3 dS/m - Area of 800 ac. - 300 ac in research 8 years old, collectors 10" lateral with 200 spacing. Better description in organization report. Demonstration project nearby to test the use of drainage water in rotation scheme of maize, wheat; flat beds, raised beds, T1=canal W, T2 = subsurface drains T3 surface drain with 50% available water depletion. T4=subsurface drain, Ts= surface drain, 25% depletion with 0.2 LF.

Another test rotation experiment - Rice wheat rotation - T1= drain water, T2=canal water; T3=soil applied gypsum to RSC; T4= fertigation with H_2SO_4 to RSC, T5= farm manure 25 Mg/ha annual. Experiments indicate flat better than raised beds; that canal and drain water can be used when amendments used.

STOP IV near branch canal - High water table; soils silt loam and saline/sodic, pH -> 9. Patchy wheat crop where there is no surface salt; trees look stressed.

Field trip IV - visit to Faisalabad University - noted experiment on water table depth and water use by crops. Using tensiometers and suction cups.

Field trip IV. Region between the two canals-soils contain more silt.

Stop # I Surface soil severely saline pH 8.4 - 8.5 WT high - seepage from canals. WT position depending on water level in canals. When canal full, WT rises and when empty WT declines. Thus, water transmission is good enough to affect WT's over very large saline area.

Stop # II Area where ground water has good quality, no sodium problem. WT at 12 feet. Irrigating for 12 years from tubewell. Wheat crops good - 1000 kg/acre.