IN THE NAME OF ALLAH
THE COMPASSIONATE, THE MERCIFUL

DEDICATED
TO MY LATE
PARENTS

USE OF BRACKISH WATER FOR SUSTAINED CROP PRODUCTION WHILE MAINTAINING SOIL HEALTH

BY

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To

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We, the Supervisory Committee, certify that the contents and form of thesis submitted by Mr. Nazir Hussain have been found satisfactory and recommend that it be processed by External Examiners for the award of Ph.D. Degree.

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INTRODUCTION

Water is a basic necessity for sustaining life in the universe. Functions of water in plants are manifold and diversified. Among the versatile functions just a few are; maintenance of turgidity, opening and closing of leaf stomata, uptake and translocation of nutrients and metabolites, synthesis of proteins and other related products, sequestration of excessive salts and toxic materials into vacuoles and out of tissues and serving as a medium for all biochemical and bio-energy reactions.

Water exists on this earth mainly in the form of seawater, terrestrial water, rain-water and groundwater and in total covers almost three fourth of this planet. A major portion (97%) of it occurs as seawater which is brackish and cannot be used for agricultural purposes except for a few special plants of little economic importance. Therefore, rains are the only source of fresh water. If rains are well distributed and sufficient to meet crop needs like humid and sub-humid regions, no expenditure is incurred on construction of dams, diversions and canals. Contrarily, secanty rains do not fulfill the requirements of agriculture crops in arid and semi-arid regions. Geographically, Pakistan is situated mostly in arid regions. Frequency and intensity of rains are the other factors to be considered but unluckily in Pakistan, these are not favourable too. Most of the rains are received in monsoon season (July, August), often devastating agriculture through floods, leaving rest of the year dry. Hence, rainwater alone could never meet water requirements of crops and needs alternative arrangements of artificial irrigation. This situation necessitated irrigated agriculture, for which world's largest canal system was built up. Inspite of the volume and length of canal system, it failed to cope with the demands of cultivated crops and soils. According to reports, a little expansion in irrigated agriculture with canal water is possible because suitable waters have already been fully developed (Anonymous, 1974).

An increasing population at the rate of three percent per year in Pakistan demands an increase in cropping intensity, elevations in per acre yield and horizontal spread in arable land. Canal water supplies at the farm are always lower than the actual needs. It has been estimated that the water supplies are short by 30% even for the existing cropping intensity. This shortage is about 35% in winter and 25% in summer seasons (Badruddin, 1983). So, there is a little scope of increasing crop intensity or bringing more acres of land under plough with the existing surface water supplies. Thus, water has always been and will remain a scarce input in crop husbandry under agroclimatic conditions of Pakistan. This unpleasant situation necessarily demands an exploration of other water resources and groundwater is the only substitute available at present. According to the estimates (Ahmad, 1993), about 2 billion acre-feet of groundwater is stored in the alluvial deposits of Pakistan. The country would have been very fortunate if the quality of this groundwater was suitable for sustained yields and maintenance of soil health. But with respect to quality, groundwater in the 40% area within the canal command has a salt concentration > 1000 ppm (Ahmad, 1993). According to another survey, two third of this water is not usable directly and requires special management practices or prior amelioration (Hussain et al., 1991). Hence, the poor quality of groundwater is the major reason for lower pumpage.

Brackish water has been regarded as the main cause of accelerated salinity in Pakistan. It is urgently needed that cost effective and site specific technology for safe use of brackish waters be generated. The existing technology for use of groundwater involves the use of costly inputs like gypsum, manures, acids and other reclaimants. Other techniques conventionally under use are leaching fractions or blending of ground and canal waters. Application of leaching factions often fail to produce desired results when the water has high SAR because of impairment in the physical properties of the soil. Blending is also not very useful practice because it does not decrease the total salt load of poor quality water and plant have to spend metabolic energy in extracting pure water from the blend (Minhas et al., 1989). Moreover, it is not easily practicable under the existing canal water supply system. The cyclic use of saline and canal water proposed by Rhoades (1983) fits under this situation. Under this strategy, saline water is substituted for the good quality water when irrigating a relatively salt tolerant crop in rotation. His work proved that soil salinity developing in the root zone from continuous use of brackish water did not occur in cyclic use because saline water was used for a limited time. Whatever salts accumulated in the soil profile from brackish water were diluted during subsequent cropping period when a low salinity water (canal) was used.

The present studies were planned to work out a low cost practicable technology so that brackish groundwater may safely be used for sustained crop production without affecting the soil health adversely. For this purpose, cyclic use of canal and brackish water was compared with the existing practices like mixing and application of amendments. The efficiency of this technique was ascertained in summer, winter and whole of the year (seasonal and yearly). Major crops like wheat, rice and fodder were included into study so as to suit the crop rotations of rice zone (rice-wheat) and central agroclimatic zones (wheat-summer fodder) of the Punjab Province. Production of these crops is not possible with canal water only due to its scarcity. Supplementation with groundwater is a must. The cyclic use strategy can fit the prevailing conditions of the areas. However, some other management techniques like crop establishment with canal water, burrying-in the rice straw and incorporation of sesbania were also investigated. Studies being reported here were carried out with the following objectives:-

1) To devise low-cost and readily practicable technology for use of brackish groundwater which assures sustained yields and does not impair soil properties adversely.
2) The generated techniques should be equally effective as are the conventional one but economically more beneficial.
3) Prevailing conditions of the present farming systems are not significantly disturbed with the evolved techniques.
4) Farmers have not to incur extra money.
5) Agricultural environment is not polluted appreciably when the technologies are put into practice.

CHAPTER II

REVIEW OF LITERATURE

CHAPTER-II

REVIEW OF LITERATURE

Agriculturists in arid regions were forced to use brackish groundwaters in the past due to scarcity of surface water and demand to bring more areas under plough. But with the progressive increase in groundwater use diverse problems sprouted. To overcome various practical problems faced by the users, research on the use of brackish water was initiated and stepped up with the passage of time by the scientists. Commendable work on this aspect has been carried out in Pakistan and the world uptil now and a voluminous information generated.

2.1 Groundwater Resources

In the last decade, cropped area increased at a slower rate than the population growth in Pakistan. The gap in demand and production was quite clear which might widen further with the passage of time (Malik, 1990). One of the biggest constraints to crop production was, the limited supply of irrigation water (Malik *et al.*, 1984). Water resource, present as well as future, was inadequate to meet the needs of the cultivated area already under irrigation. This is evident from the cropping intensity which is about 100 % for the country, whereas climate and manpower can enable to produce at least two crops a year (Mian, 1992). According to another estimate, present water supplies were about 30 % short on annual basis even for the present cropping intensity (Baddruddin, 1983).

Available terrestrial water has already been fully diverted into canals and distributories. Canal withdrawls for Punjab Province in the year 1990-91 were 56.899 MAF while in 1994-95, these were 52.705 MAF (Anonymous, 1995) indicating a net decrease. Hence groundwater has to be pumped to increase the water supply. Cropping intensity could be enhanced by 2 to 3 times if 2 billion acre feet of ground water stored in alluvial deposits was not left untapped. Safe pumpage of 40 million acre feet would have not only increased cropping intensity but also new lands could be brought under plough (Ahmad, 1993). The water requirement of the country was 114.44 MAF in the year 1990-91 which increased to 120.32 MAF in 1994-95 and would go to 126.40 MAF in 2000-01

(Mohtadullah *et al.*, 1993). The estimated deficit would be 40.3 MAF at the end of 20th century (Mohtadullah, 1997).

Efforts were made to make up this deficiency through installation of tubewells in public as well as private sector. It was estimated that 43.79 MAF of groundwater was being pumped by 0.32 m tubewells upto the year 1991 (Anonymous, 1995). There was a need to pump more water under scientific management.

2.2 Irrigation Water Classification

Standards to be adopted for classification of irrigation waters is a very difficult task. If strict standards are imposed, a vast reservoir of groundwater may obviously be eliminated and if somewhat liberal standards are fixed, potential hazards may operate to affect soil as well as crop health. Many authors do not agree to use word suitability of waters. According to them, no water is unsuitable for all situations but only selection of a set of conditions like type of soil, crops to be grown and management practices are important (Rhoades, 1984, Khan, 1977 and Hussain, 1978). Clay mineralogy (clay types and content), climatology (temperature, rainfall intensity and frequency) and drainage are of prime importance to make decision on use of a water. Live with bad waters should be the strategy in the light of limited water resources. Management practices like frequent irrigation, use of extra water for leaching, deep tillage, addition of amendments and organic matter may be helpful (Rhoades, 1968, Jilani *et al.,* 1990 and Sharma, 1989).

2.2.1 Parameters for Classification

Even the parameters used for assigning categories to waters are not uniform every where. SAR has been claimed the best single predictor of effects on soils and crops followed by TDS (Hussain *et al.,* 1977). The prediction did not improve when RSC was included in the model. Problem of RSC is related with low salinity (Chauhan *et al.,* 1990). U.S. Salinity Laboratory (Richards, 1954) used only EC and SAR and constructed a diagram for prediction the effect of irrigation water. However, the approach is not adaptable universally and all the three factors; TDS, SAR and RSC were considered necessary to be included in classification criteria, as any of these singly did not suffice the purpose (Qayyum and Sabir, 1976 a & b). Gupta (1990) claimed that use of this diagram for classification of water is obsolete due to its various limitations e.g. C_1 and C_2

waters never have high (S_3) or very high (S_4) sodium. Secondly, C_1 class water may create permeability problem.

Alkalinity is another important hazard and related to quantity of cations (Ca^{2+} + Mg^{2+}) and anions (CO_3^{2-} and HCO_3^{1-}). To assess the possible increase in soil pH, the parameter of RSC was suggested (Eaton, 1950). He calculated it as (CO_3^{2-} + HCO_3^{1-}) - (Ca^{2+} + Mg^{2+}). But, practically in many cases it is being calculated as (HCO_3^{1-}) - (Ca^{2+} + Mg^{2+}) when CO_3^{2-} are absent. Since bicarbonates could precipitate Mg^{2+} to a minimum extent, Gupta (1984) suggested that RSC should be simply determined as (HCO_3^{1-}) - (Ca^{2+}) and called it as RSBC (Residual sodium bicarbonate). This parameter should be determined in waters having EC less than 3 dS m^{-1}. The permissible limit of RSBC fixed was 10.0 me L^{-1} provided SAR value was less than 10.

For classification of waters having EC more than 5 dS m^{-1} and Mg^{2+}/Ca^{2+} ratio higher than 1, another term SCAR (Sodium to calcium adsorption ratio) was suggested (Gupta and Abichandani, 1970) which proved useful for the Indian soils for the specific conditions and can simply be applied elsewhere in similar cases. The SAR can simply be calculated as Na^{1+}/Ca^{2+} and corresponds highly with the observed values of soil ESP (exchangeable sodium percentage).

Ayers and Westcot (1976) recommended another parameter "adjusted SAR" (adj. SAR) to measure true sodicity hazard of irrigation water, as it has more close relationship with soil ESP. The limits for this computed characteristic of water are; less than 6.0, 6.0 to 9.0 and more than 9.0 imposing no problem, increasing problem and severe problem, respectively (Westcot and Ayers, 1975).

Besides the major constituents of irrigation water and deciding parameter computed there of, some minor elements are also of specific importance occasionally. Occurrence of chloride ions in irrigation water beyond limits is toxic to plants, although have no deterimental effect on soil properties. Chloride ions are more harmful than sulphates, especially for sensitive plants e.g. citrus root stock. It has been reported that chloride content less than 4 me L^{-1} caused no toxicity, 4-10 increased the problem and more than 10 has the severe problem for citrus (Ayers and Westcot, 1985). Doneen (1963) introduced the term potential salinity of irrigation and suggested its determination as shown below.

Potential Salinity = Cl^{1-} + 1/2 SO_4^{2-}. Recommended permissible limits are; 5-20, 3-15 and 3-7 me L^{-1} for soils of good, medium and low permeability, respectively.

Nitrate ions are another constituent which are beneficial in lower quantities usually 2 to 5 me L^{-1} and help partly in the substitution of nitrogen fertilizers. However, excessive amounts, nearly greater than 10 me L^{-1} tend to cause specific ion toxicity on plant growth (Gupta, 1990). Boron is the characteristic element toxic to plants slightly above the optimum concentration. It is not present in many irrigation waters and safe upto 1 mg L^{-1} of B but injury may develop on more sensitive plants when exceeds 3 mg L^{-1} (Gupta, 1990). In contrast, the safe limits recommended for sensitive and tolerant crops by U.S. Salinity Laboratory Staff (Richard, 1954) were 0.3 and 2.0 mg B L^{-1}, respectively.

2.2.2 Standards for classification

Variable standards have been adopted for categorization of waters in different parts of the world and by different organizations in Pakistan. These are mainly due to specific set of conditions, i.e. pertaining to soil, climate and management, e.g. under optimum management conditions and farm management, following limits were formulated by Hussain (1978) after field investigations.

Table 2.1 Limits of water quality standards (Hussain, 1978)

Class of water		TDS (ppm)	SAR	RSC
Good	a)	upto 1000	upto 10	upto 2.5
	b)	upto 750	upto 7	upto 2.5
Marginal	a)	1000-2000	10-15	2.5-5.0
	b)	750-1500	7-12	2.5-5.0
Hazardous	a)	> 2000	> 15	> 5.0
	b)	> 1500	> 12	> 5.0

a = optimum conditions
b = farmer conditions

Criteria standardized under another situation are as under (Qayyum and Sabir, 1975)

Water Quality	TDS (ppm)	SAR	RSC
Safe	upto 1000	upto 10	upto 2.5
Marginal	1000-1500	10-18	2.5-5.0
Hazardous	> 1500	> 18	> 5.0

Irrigation water of salts upto 860 ppm (EC_{iw} 1.23 dS m^{-1}), SAR upto 7.5 & RSC 1.25 me L^{-1} did not raise the ECe or SAR of normal soils under prevailing management conditions (Yunus, 1977). However, under good management, EC_{iw} upto 1.5 dS m^{-1}, SAR 10 and RSC 2.5 was safe. Even RSC between 2.6 to 4.0 was not hazardous on mod. coarse and medium textured soils (Hussain, 1979).

2.2.3 Equations and Models for Prediction of Water Hazard

Various prediction curves, equations and models have been developed by scientists recently and being used widely alongwith computer programmes for predicting hazards of different nature attached with brackish water.

2.2.3.1 Salination

Irrigation water is a major source of secondary salinity. The degree to which salination will occur depends upon the composition of irrigation water itself and the balance between the quality supplied to the soil surface and removed from the lower boundary of the profile. Salination of a given profile might occur if $EC_{dw} \times D_{dw} < EC_{iw} \times D_{iw}$ where EC and D indicate Electrical Conductivity and depth of irrigation water (iw) and drainage water (dw). The rate of salination in this situation can be expressed as the increase (ΔEC_e) in the form of equation-1 (Kamphorst and Bolt, 1978).

$$\Delta EC_e = \frac{(EC_{iw} \times D_{iw}) - (EC_{dw} \times D_{dw})}{D\ soil \times SP \times BD/100} \quad \ldots. \quad (1)$$

in which D soil is the depth of the profile under consideration (cm), SP is the average moisture content of the saturated paste (%) and BD is average bulk density of the profile (Mg m^{-3}).

Under stagnant high ground water level or impermeable sub-soil layer, $D_{dw}=0$ and equation-1 will be changed to

$$\Delta EC_e = \frac{EC_{iw} \text{ x } D_{iw}}{\text{D soil x SP x BD/100}} \qquad \text{.....(2)}$$

Concentration of drainage water removed neither can be measured easily nor it can be controlled under natural conditions but as first approximation, it is soil solution at moisture content just above field capacity (FC). Hence $EC_{dw} = EC_{fc}$•Salination will gradually come to steady state. So when $\Delta EC_e = 0$, soil salinity will reach a constant level according to :

$$EC_e = \frac{FC}{SP} \text{ x } EC_{fc} \qquad \frac{FC}{SP} \text{ x } \frac{D_{iw}}{D_{dw}} EC_{iw} \qquad \text{......(3)}$$

(Kamphorst and Bolt, 1978).

Net effect of saline water in refined terms could be calculated giving allowance to all the soil, water and environmental factors. For this purpose, salt balance (SB) is to be taken into account.

Salt balance helps in maintenance of productivity of an irrigation tract and avoiding a built-up of soluble salts in the soil. Wilcox and Resch (1963) calculated salt balance (SB) values for irrigation projects or specific soils as:

$$SB = V_{dw} C_{dw} - V_{iw} C_{iw} \qquad .....(4)$$

where V designates volume, C concentration and dw and iw indicate drainage water and irrigation water, respectively. A positive value was suggested necessary to avoid salt accumulation and reduction in crop productivity. Several scientists have modified the salt balance equation to account for other factors and processes. Carter (1975) expanded the eq. 4 to give.

$$S_p + S_i + S_r + S_d + S_f = S_{dw} + S_c + S_{ppt} \qquad .....(5)$$

where:

S_p = Salts in rainfall falling upon the area.

S_i = Salts in irrigation water diverted to the area

S_r = Residual soil salts

S_d = Salts dissolved from and/or weathering of soil minerals

S_f = Salts applied as fertilizer

S_{dw} = Salts in drainage water leaving the area

S_c = Salts removed in the harvested crop

S_{ppt} = Salts precipitated.

Number of irrigations with saline water depends upon the rainfall during crop growth. Normally equilibrium salinity levels are obtained with four to five irrigations. Salinity will become steady when the slope of regression exceeds 0.5. When leaching fractions are restricted, the salinity levels will continue to rise linearly with every irrigation. A multi-linear regression equation was developed by Gupta (1985) for sandy loam soil which is

$$EC_e = -2.26 + 0.904\ EC_{iw} + 0.235\ n$$

n = number of irrigations

The average EC_e within the crop rootzone resulting from long term irrigation with a water of EC_{iw} can be predicted from

$$EC_e = Fc \,.\, EC_{iw} \qquad .....(6)$$

(Rhoades, 1984)

where Fc is the relating concentration factor appropriate for leaching requirement (LR). Fc can be calculated as;

$$Fc = \frac{\text{Maximum permissible salinity } EC'_e}{EC_{iw}} \qquad .....(7)$$

The value of EC'_e used in equation-7 will be that given in crop tolerance tables of Maas (1986).

Leaching requirement (LR) can be calculated as;

$$LR = \frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}} \qquad \text{(Richard, 1954)} \qquad .....(8)$$

Total amount of irrigation water for the growth of a crop can be calculated from

$$D_{iw} + D_{rw} = D_{dw} + D_{cw} \qquad .....(9)$$

where $_{rw}$ is rain water and $_{cw}$ is consumptive use of crop (evapotranspiration). Rain water may alter the effects of saline water and often predicted values of soil EC_e using different equations do not match the absolute ones. Therefore, as an average of a long time, the conductivity of irrigation water used should be a weighted average for the conductivities of rain water (EC_{rw}) and irrigation water (EC_{iw}) i.e.

$$EC\,(_{rw\,+\,iw}) = \frac{D_{rw}\,EC_{rw} + D_{iw}\,EC_{iw}}{D_{rw} + D_{iw}} \qquad .....(10)$$

where D indicates the depth of waters (Richard, 1954).

According to Van Schilfaarde and Hoffman (1977), the equation-7 over estimated the LR 3 to 4 times. A ratio for LR calculation proposed by them was,

$$LR = EC_{iw} \Big/ \frac{EC_{dw}}{Q_{fc}/Q_s} \qquad .....(11)$$

where Q_{fc} and Q_s are volumetric water content at field capacity and saturation, respectively.

The EC_{dw} was also predicted using following equations and found to be very close to the observed ones (Muhammad *et al.*, 1977).

$$EC_{dw} = \frac{EC_{iw}}{LF} \qquad \text{(assuming no precipitation or solubilization of soil minerals)}$$

$$EC_{dw} = \frac{Cl_{dw}}{Cl_{iw}} \times EC_{iw} \qquad \text{(Accounting for precipitation or solution of soil minerals)}$$

For any succession of crops, the maximum fraction of saline water that must be used could be determined by

$$LF = 1 - \frac{\alpha a}{\alpha b} \qquad .....(12)$$

where α values refer to the allowable EC of the drainage (saline) water for the first crop, a and second crop, b (Bernstein, 1966).

Predicting yields of different crops after achieving steady-state under brackish water irrigation is another challenge. Relative crop yields (Y) can be estimated using Maas and Hoffman (1977) equation.

$$Y = 100\text{-}B\,(EC_e\text{-}A) \qquad .....(13)$$

In which A = The salinity threshold in dS m^{-1}

B = Percent yield decrease per unit salinity increase.

Soil EC_e can be predicted using various equations already discussed or simply from the equation as under.

$$EC_e = 1.5\ EC_{iw} \qquad .....(14)$$

(Gupta, 1990)

2.2.3.2 Sodication

Aside from salination, the actual composition of the soil solution following brackish water irrigation is also very important. Increases in total quantity of Na^{1+} on the exchange complex beyond the permissible limits is called sodication. The average concentration of an ion (say Na) in the profile at field capacity may be estimated by

$$C_o = 1.5 \times \frac{D_{iw}}{D_{dw}} \times C_{iw} \qquad .....(15)$$

(Kamphorst and Bolt, 1978)

in which C_o is the concentration of an ion species in the soil solution and C_{iw} is its concentration in irrigation water.

A good agreement between the Gapon's empirical approach and thermodynamic approach was observed by Poonia and Pal (1979) for four soils varying in texture and CEC. It was indicated that specific exchange sites for Na^{1+} were absent but there was a little more preference for Ca^{2+} over Mg^{2+}. Independent verification of Gapon equation at low to moderate ESP values was provided by U.S. Salinity Lab. Staff (Richards 1954), who tested the linear regression between exchangeable sodium ratio (ESR or (NaX + Mgx), and sodium adsorption ratio (SAR). This relationship was

$$\mathrm{ESR} = -0.0126 + 0.01475\ \mathrm{SAR} \qquad .....(16)$$

The relationship between ESP (exchangeable sodium percentage) and soil SAR was found to be

$$\mathrm{ESP} = \frac{100\ (-0.0126 + 0.01475\ \mathrm{SAR})}{1 + (-0.0126 + 0.01475\ \mathrm{SAR})} \qquad .....(17)$$

ESP of four soil profiles collected from different locations and irrigated with different quality waters, was found nearly the same as obtained by following equation involving EC as well as SAR, namely.

$$ESP = 14.2 + 0.23\ EC + 0.18\ SAR \qquad \text{.....(17a)}$$

(Paliwal and Maliwal, 1971)

Although, under prevailing conditions of steady state, Na^{1+} and other cations in solution as well as exchange phase are at equilibrium with that present in sodic irrigation water and exchange equations hold good to predict Na^{1+} hazard but extent of development of exchangeable Na^{1+} in soils depends primarily on SAR, pH_c, leaching fraction (LF) and mineralogy of the soils. Bower *et al.*(1968) included some of these factors in an empirical model developed by them for prediction of SAR of drainage water SAR_{dw} from SAR_{iw}

$$SAR_{dw} = \frac{1}{\sqrt{LF}} SAR_{iw} [1 + (8.4 - pH_c)] \qquad \text{.....(18)}$$

Where pH_c is the calculated pH of water in equilibrium with soil lime. The model of Bower was refined by Rhoades (1968) when he included another component known as weathering coefficient (Y) indicative of the changes that occur in SAR of the water applied to soil by the process of soil mineral weathering and the model become as

$$SAR_{dw} = \frac{Y^{1+2LF}}{\sqrt{LF}} SARi_{iw} [1 + (8.4 - pH_c)] \qquad .....(19)$$

Sharma (1980) tested this model on alluvial soils of Karnal using Y value of 0.75 for waters of $pH_c = 7.50$ and Y value of 0.80 for water of $pH_c >$ 7.50. Good agreement between the observed and predicated SAR_{dw} was observed. However, calculated SAR_{dw} were slightly higher than observed ones in upper 10cm soil depth. Muhammad *et al.*, 1983) in pot study used different equations for prediction of SAR_{dw}. They found that depending upon the chemical composition of irrigation water, use of LF and pH_c terms worked well but, when LF was calculated as EC_{iw}/EC_{dw}, the predication was the best.

Gupta (1987) reported that SAR of the irrigated soils (Y) is highly correlated with the product of SAR_{iw} (X_1) and salt concentration factor ($X_2 = (EC_e/EC_{iw})^{1/2} = 1 / (LF)^2$, according to the following equation.

$$Y = X_1 . X_2 \qquad .....(20)$$

The high value of the coefficient of correlation ($r = 0.99$) indicated that processes such as precipitation, dissolution and mineral weathering did not play a significant role under the prevailing conditions. This showed that as irrigation water after entering the soil becomes more concentrated, the SAR value increased in proportion to the square root of the concentration factor.

In a detailed assessment of validity of SAR, distinction between practical SAR (SAR_p) not corrected for ion complexes and 'True' SAR (SAR_t) corrected for ion pair complexes, was made by Sposito and Mattigod (1977). The relationship found after analyzing 105 water samples was;

$$SAR_t = 0.08 + 1.115\ SAR_p\ (r^2 = 0.99) \qquad .....(21)$$

The valid generalization made was

$$SAR_t > SAR_p$$

Efforts were made to correlate SAR of water directly to ESP of soil. In this regard, Rhoades (1972) added some useful refinements, who presented two equations relating pH_c and SAR_{iw} to equilibrium soil ESP likely to develop upon irrigation with that water.

$$ESP_s = SAR_{iw}\ [(1 + 8.4 - pH_c)]^2 \qquad .....(22)$$

It is used to predict surface-soil ESP.

$$\mathrm{ESP} = \left[\frac{Y^{1+2LF}}{(LF)^{1/2}}\right]^{3} \mathrm{SAR}_{iw}\,[1 + (8.4 - \mathrm{pH}_c)]^2 \qquad \text{.....(23)}$$

Where Y = empirically determined mineral weathering coefficient.

It is used to estimate ESP that will develop in deeper soil profile near the bottom of the root zone. The first equation is the more practical of the two.

Pal *et al.* (1984) formulated a model based on simple and easily determinable parameters to predict the distribution of soluble and exchangeable Na^{1+} in a soil profile, using Gapon equation for Na^{1+} - Ca^{2+} + Mg^{2+} exchange and tested validity of different models under irrigation with high SAR waters. One of these models is as under.

$$\frac{Y_1 + X}{Y_2 + X} = K_G \; \frac{(W_oC_1 + W_1\,C_1' \pm X)/FC}{[(W_oC_2 + W_1\,C_2' \pm X)/2\ FC)]^{1/2}} \qquad \text{....(24)}$$

Y_1 = Initial adsorbed Na^{1+} (me 100 g^{-1} soil)

Y_2 = Initial adsorbed Ca^{2+} + Mg^{2+} (me 100 g^{-1} soil)

X = The amount of cation which goes on or comes from the exchange complex from or to solution (me 100 g^{-1} soil).

W_o = Initial moisture content (% by weight).

W_1 = Amount of solution received by a soil layer (me 100 g^{-1} soil).

C_1 = Concentration of Na^{1+} in initial solution in a soil layer (me L^{-1}).

C_2 = Concentration of Ca^{2+} + Mg^{2+} in initial solution in a soil layer (me L^{-1}).

C_1 = Concentration of Na^{1+} in incoming solution (me L^{-1})

C_2 = Concentration of Ca^{+2} + Mg^{2+} in incoming solution (me L^{-1}).

FC = Field capacity (% by weight)

K_G = Gapon selectivity coefficient.

Assumptions to the model placed were;

1. Only that amount of irrigation water entered into a layer which moistered layer to field capacity.
2. Complete mixing of original and incoming solution.
3. Instantaneous exchange equilibrium between the cations in solution and those on the adsorbed phase.
4. No precipitation, hydrolysis or dissolution of minerals in soil.

The agreement between observed and predicted values of ESP after the second, third, fourth and fifth irrigation was fair.

The waters from arid and semi-arid regions, nearly saturated with respect of $CaCO_3$ and a few contains high concentrations of SO_4^{2-}. These could precipitate in the soil on concentration. Wilcox (1948) pointed out that Ca^{2+} and HCO_3^{1-} would precipitate as $CaCO_3$ in the soil. Oster and Rhoades (1976) proposed a second order regression line ($r = 0.8$) for predicting precipitation of Ca^{2+} as function of $(Ca^{2+})\,(SO_4^{2-})$ product in irrigation water. The equation was applied to 30 water types when (HCO_3^{1-}) was less than Ca^{2+}.

$$\text{Relative } Ca^{2+} \text{ ppt} = -0.001\,[(Ca^{2+})\,(SO_4^{2-}) \pm 0.13\,(Ca^{2+})\,(SO_4^{2-})] + 44.3 \qquad .....(25)$$

Concentrations were in me L^{-1}.

It was noticed that for concentration product of 100, 50% of Ca^{2+} would precipitate which would increase to 75 and 80% at concentration product of 300 and 550, respectively.

Langelier (1936) devised an index to predict precipitation and termed it as the Saturation Index (SI). The extent of $CaCO_3$ precipitation or dissolution can be calculated as;

$$SI = PH_a - pH_c \qquad .....(26)$$

where pH_a is actual pH of a water and pH_c is the theoretical pH that the water would have at equilibrium with soil $CaCO_3$. Positive values of the index indicate that $CaCO_3$ will precipitate from the water whereas negative values indicate water will dissolve $CaCO_3$. Langelier equation for calculating pH_c from water analysis is as given below.

$$pH_c \quad = \quad (pk'_2 - pk'_c) + P(Ca^{2+}) + p(Alk) \qquad .....(27)$$

where pCa^{2+} and p Alk are negative logrithum of molar concentration of Ca^{2+} and equivalent concentration of titrable base $(CO_3^{2-} + HCO_3^{1-})$, respectively. The $p\,K'_2$ and pK'_c are the negative logrithum of second dissolution constants of H_2CO_3 and solubility product constant of $CaCO_3$, respectively, both corrected for ionic strength. Pratt *et al.* (1960) and Bower *et al.* (1965) suggested modification of Langelier equation by replacing pH_a by 8.4 (pH of highly buffered soil) and pAlk by $p(HCO_3^{1-})$ because they found that fraction of applied HCO_3^{1-} was more close to the actual precipitation. The above two equations thus became

$$SI \quad = \quad 8.4 - pH_c \qquad .....(28)$$

$$pH_c \quad = \quad (pK'_2 - pK'_c) + p(Ca^{2+}) + p(HCO_3^{1-}) \qquad .....(29)$$

Later, Bower *et al.* (1968) suggested that both Ca^{2+} and Mg^{2+} should be included in $p(Ca^{2+})$ term. Ayers and Westcott (1976) used pH_c to determine adj. SAR.

$$\text{adj. SAR} \quad = \quad \text{SAR} \, [(1 + (8.4 - pH_c)] \qquad .....(30)$$

Adjusted values were supposed to be very close to equilibrium ESP of irrigated soil. Calculations of pH_c can be made using tables prepared by Wilcox (1966).

In all these calculations, a soil source of calcium from soil lime ($CaCO_3$) or other minerals such as silicates was assumed and no precipitation of magnesium was considered which could be used to predict more correctly potential infiltration problem due to relatively high sodium (or low calcium) in irrigation water supplies (Suarez, 1981). Comparison of SAR and adj. SAR values had shown that SAR values fall within ± 10 percent of the values obtained through adj. SAR (Ayers and westcot, 1976).

2.2.4 The Quality of Groundwater in Pakistan

Quality of canal water is excellent in Pakistan, as salinity/sodicity level in river waters are far below the limits considered hazardous for irrigation. Salt concentration of river waters varies from 105 to 345 mg L^{-1} whereas SAR and RSC are from 0 to 4.37 (m mol $L^{-1})^{1/2}$ and 0 to 1.2 me L^{-1}, respectively (Ibrahim and Hussain, 1988). But unluckily, quality of groundwater is generally, in contrast to it. Groundwater in 60% of area within the canal command has a salt concentration less than 1000 ppm (EC_{iw} 1.43 dS m^{-1}) at depth of 100-400 feet. In about 15% area salts varied from 1000-2000 ppm (EC_{iw} 1.43 to 2.86 dS m^{-1}), 5% of this has 2000-3000 ppm (EC_{iw} 2.86 to 4.28 dS m^{-1}) salts and 20% area was with salts above 3000 ppm (EC_{iw} 4.28 dSm^{-1}) (Ahmad, 1993).

It was assessed that average salt concentration was 1252 ppm (EC_{iw} 1.79 dS m^{-1}) while SAR and RSC were 8.39 (m mol $L^{-1})^{1/2}$ and 3.42 me L^{-1} in Punjab groundwaters respectively. Thirty percent of these waters were categorized as C_3 S_1 (high salinity, low sodium) while 20% as C_2 S_1 (medium salinity and low sodium) under USDA classification system (Richard, 1954). Remaining 50 % occupied other classes. Two third of these waters were not usable without scientific management (Hussain *et al.*, 1991). Groundwaters of Sindh Province were characterized in C_1S_1, C_3S_1, C_3S_2, C_4S_1, C_4S_2, C_4S_3, and C_4S_4, majority occupying C_3S_1 and C_3S_2 classes. Quality is deteriorating from the upper to lower Sindh and worst in Karachi area (Choudhary, 1977). Waters of NWFP Province were classified in C_2S_1, C_3S_1 and C_4S_1 categories indicating only salinity problem. In some of tested samples, Mg^{2+} was found even more than Ca^{+2} (Hamid *et al.*, 1977 and Sarier *et al.*, 1981). Boron content mostly varied from 0.39 to 0.96 ppm showing good to permissible limits (Muhammad *et al.*, 1966).

Quality of groundwater has also been found to be season dependent. The EC, SAR and RSC were significantly higher in summer than that during winter, most probably due to concentration effect. The water table was deeper during premonsoon part (Khan *et al.*, 1991). Variation also existed in the quality of groundwater in specified areas under specific conditions. Survey of area in between Rakh and Jhang canal upto river Chenab revealed that salt content increased away from both the canals, average being >3000 ppm (EC_{iw} 4.28 dS m^{-1}) in shallow as well as deep water. Its quality improved towards the river (Akhtar *et al.*, 1986). Another study of Faisalabad district classified the groundwater as 23.8 % fit, 7.6 % marginally fit and 68.6 % unfit for irrigation (Shah *et al.*, 1994). Bhatti *et al.*, (1992) also noticed almost similar pattern of quality of Faisalabad groundwater, deep water away from canals being adjudged as mostly unfit. The EC and SAR of Pindi Bhattian groundwater was generally noticed within permissible limits (EC_{iw} 0.22 to 2.5 dS m^{-1} and SAR<10) whereas RSC was fairly high except a few sites (Lone *et al.*, 1992). Adopting somewhat liberal standards of WAPDA (Section 2.2.2), quality of SCARP tubewell waters of the Indus Plain was claimed to be good, 63 % waters being regarded as usable (Yunus, 1977). A study of hydro-salinity system of Punjab Province was undertaken for 8 years. It was noticed that 79.5 % salts were contributed by the tubewells while 11.3 % by canals and 9.2 % due to dry period capillary rise. There was a net addition of 0.63 t ha^{-1} annually which was calculated to be 0.04 % of the total received through various sources (Awan et al., 1992).

2.3. Effects of Brackish Water

2.3.1 Soil Properties

Irrigation with poor quality water tend to disturb physical and chemical properties slowly at first, consequently crop yields start declining. Management of soil is as important as the quality of water itself. Hazardous waters in the absence of proper management could increase EC_e and SAR of normal soils. Continuous cultivation of low delta crops without organic matter addition did not permit proper leaching of salts and favoured salination. (Hussain, 1977). Soil EC_e

may increase upto 300% in one year only with irrigations of water of EC 4.0 dS m^{-1} and SAR of 3.97 mainly due to reduced infiltration rate (Baumhardt *et al.*, 1992). However, saline waters (EC 1.05 to 2.8 dS m^{-1} and SAR 2.8 to 4.6) increased infiltration rate of loam soil (Chaudhary *et al.*, 1986). Irrigation water having salts of 2700 mg L^{-1} (3.87 dS m^{-1}) converted normal soil into saline-sodic up to a depth of 30 cm (Bhatti, 1986). Hydraulic conductivity of normal soil decreased due to clay dispersion as a result of increased ESP (Lal and Singh , 1973, Yousaf and Rhoades, 1988 and Yasin *et al.*, 1990). Clay dispersion positively correlated with SAR and RSC and negatively with EC of water in the above studies. Soil structure deteriorated (Yousaf, 1992) when electrolytes of low concentration (0, 2.5. 5.0 m mol L^{-1}) or high pH (8.0 and 9.0) were applied.

Clay and clay + silt content of soil are directly correlated with salt accumulation (Singh and Narain, 1979, Timer, 1989 and Chaudhry and Rafiq, 1983). Soil EC_e, pH and ESP were elevated to 3.5 and 2.6, 8.6 and 8.7, 18.4 and 21.4, respectively when waters of TDS 2240 and 1120 mg L^{-1} (3.2 and 1.6 dS m^{-1}) and SAR 12 and 2.5 were used (Alawi *et al.*,1980). Depending upon leaching fractions and time of application, soil EC_e and ESP increased gradually with increasing EC, SAR and RSC of irrigation waters (Haider *et al.*, 1975, Yasin *et al.*, 1988, Khandewal *et al.*, 1990 and Ali *et al.*,1991).

Kinds of anions contained in irrigation water are important too. Very high concentration of bicarbonates in low salinity water or more quantities of chlorides in high salinity waters increased soil EC_e and pH (Gupta *et al.*, 1989). Similarly, waters with high SAR (> 20) [m mol $L^{-1}]^{1/2}$ caused increased soil pH, EC_e and SAR (Qayyum, 1973) and were regarded more harmful for crops than waters with higher salinities (1.89 to 3.68 dS m^{-1}) [Haider *et al.*, 1973]. A proportional increase in soil SAR was noticed when SAR of irrigation water increased from 5.93 to 23.58 (Haider and Hussain, 1976). When high Mg^{2+} water was used, Mg^{2+} accumulated in soil (Ghafoor *et al.*, 1992).

2.3.2. Crops

High salinity waters EC (7.5 to 10.0 dS m^{-1}) have bad effect on germination and growth of plants (Gupta *et al.*, 1989) and reduced root development as well as evapotranspiration (ET) (Minhas *et al.*, 1989). The reduced ET was attributed to less water absorption caused by osmotic stress (Akbar, 1975). Crop genotypes respond differently to saline irrigation and thus a separate account of various crops is presented.

2.3.2.1 Wheat

Wheat yield is relatively less affected by saline irrigation rather initially upto EC_{iw} of 2.4 dS m^{-1}, it increased (Khattak *et al.*, 1973). Under steady-state 7,5,13% decrease in grain yield of wheat was recorded when EC of water was 1.5, 2.0 and 2.85 dS m^{-1} (Chaudhary *et al.*, 1986) as result of reduced tillering, plant height, root length and water use efficiency (Holloway and Alstan, 1992 and Zahid *et al.*, 1986). Statistical relationships indicated that 50% reduction in grain yield occurred at EC_{iw} of 12-16 dS m^{-1}. The corresponding salinity hazards of water were designated as low, medium, high and very high at respective values of less than 8, 8-12, 12-16 and more than 16 dS m^{-1} for Agra region of India (Pal and Tripathi, 1979). The critical limits of EC_{iw} for yield reduction of 10, 25 and 50% ranged from 2.7 to 9.0, 7.4 to 13.0 and 13.1 to 18.0. Lower values for sandy soils and higher values for loamy soils (Gupta and Yadav, 1986). The ESP limits for similar yield decreases were 22, 33 and 46 (Gupta, 1990). Biomass and grain yield of wheat decreased with high Mg^{2+} water (Ca^{2+}: Mg^{2+} 1:4 and 1:6) when used on saline-sodic soil. High Mg^{2+} water tended to decrease nutrient (N,P,K and Mg^{2+}) absorption. The absorption was improved when FYM was applied.

Increase of EC_{iw} from 1.0 to 2.0 dS m^{-1} or RSC of water from 2.5 to 5.0 me L^{-1}, decreased wheat yield but uptake of Na^{1+} by grain and straw was enhanced (Yasin *et al.*, 1987). Decreased grain and straw yield as well as K^{1+} concentration of wheat leaves was recorded with increasing sodicity (ESP 20 to 60). Wheat variety Pak-81 performed better than Rawal (Yasin, 1991).

Variety Lyalpur-73 performed comparatively better at EC_e of 7.5 and 15.0 dS m^{-1} followed by Chenab-79 and V5444 (Ehsan *et al.*, 1986). Number of tillers, plant height and yield of wheat decreased significantly at EC_e 16 and 24 dS m^{-1}. Performance of SA-42, Sandal and Punjab-76 was lower than LU-41 and PARI-73 (Zahid *et al.*, 1986).

2.3.2.2 Rice

Rice has been found highly tolerant while wheat was moderately to exchangeable Na^{1+} (Abrol and Bhumbla, 1979). Early stages of this crop were more sensitive to EC and SAR of soil and irrigation water than later stages (Jamil, 1972). Seedling emergence of rice cultivars was delayed and negatively affected to a great extent with increasing water salinity (EC 12 dS m^{-1} onwards). Height of rice seedlings was significantly reduced (Ahmad *et al.*, 1990). Plant height, tillers, number of grains per panicle and straw and paddy yields decreased significantly as salinity/sodicity of soil increased (1.9, 6 and 12 dS m^{-1} or ESP 9, 30 and 64). The effects were more marked when both factors combined. No grain formation occurred at EC 12 dS m^{-1} with ESP 64 (Javid *et al.*, 1988). Water with SAR 20 (m mol $L^{-1})^{1/2}$ did not prove useful for rice production even if amended with gypsum (Hussain, 1982). Varieties/lines IR-6, V 44935 and V 44677 were more tolerant to salinity (Khan *et al.*, 1988). The tillering and grain and straw yield decreased while a positive correlation existed between paddy yield and K percentage in rice straw when grown on saline soils with EC 5.8 to 12.0 dS m^{-1} (Muhammad *et al.*, 1991). Brackish water irrigation changed the nutrient requirements of rice and responded to Zn, Fe, Mn and B application which was not recorded under canal water irrigation (Tahir *et al.*, 1992). Critical limits of EC_{iw} for yield reductions of 10, 25 and 50% were found to be 1.8, 4.0 and 7.5 dS m^{-1} when rice was grown in heavy textured soil (Gupta and Yadav (1986) while ESP limits for the same yield decreases were 38, 54 and 72, respectively (Gupta, 1990).

2.3.2.3 Cotton

Growth development and biomass of cotton was not affected significantly in the first year of brackish irrigation but later germination and stand was reduced. The K^{1+}:Na^{1+} ratio in leaf tissues changed and yield decreased with water of EC 9 and 12 dS m^{-1} (Ralston *et al.*, 1986). Substitution of water with EC 4 dS m^{-1} after crop establishment did not affect the cotton yield significantly while sole use of this water caused a substantial loss (Rhoades *et al.*, 1988).

2.3.2.4 Sorghum

An increase in water EC reduced development of roots, especially in deeper layers. Evapotranspiration (ET) was curtailed and sorghum plants spent more and more metabolic energy in alleviating the adverse effect of excessive uptake of ions, otherwise this energy had been utilized in biomass production. Resultantly, dry matter decreased by 18, 32 and 68% at water EC of 2.5, 4.7 and 6.4 dS m^{-1}, respectively (Minhas *et al.*, 1989). High SAR and RSC of waters also played a similar role (Yasin *et al.*, 1985) due to increased soil EC and ESP which could partially be controlled by providing leaching fractions (Yasin *et al.*, 1988).

The SAR more than 10 (m mol $L^{-1})^{1/2}$ proved detrimental (Haider and Hussain, 1976). The critical limits of EC_{iw} for yield reduction of 10, 25 and 50% were reported as 8.3, 12.8 and 17.8 dS m^{-1} in loam soil and 2.4, 6.5 and 13.4 for heavy textured soils (Gupta and Yadav, 1986).

2.3.2.5 Maize

Maize is more sensitive to irrigation water and the soil EC at early growth stage but can withstand relatively higher salinity at later stages. Dry matter yield decreased with increasing EC_{iw} (Sherazi *et al.*, (1971) which became significant at water EC of 2.16 dS m^{-1} (Shakir *et al.*, (1990). However water with TSS 1500 ppm (EC_{iw} 2.14 dS m^{-1}) and SAR 20 was safe and did not affect germination significantly (Qayyum, 1973). The SAR 15 and 20 decreased maize fodder yield while gypsum application had a positive effect (Ali *et al.*, 1991). Comparable yields to canal water were obtained by passing sodic water through gypsum stone placed in the water channel (Muhammad *et al.*, 1975). The critical limits of EC_{iw} for yield reduction of 10, 25 and 50% were 2.7, 5.5 and 10.3 dS m^{-1} for sandy loam soil and 1.2, 3.1 and 9.5 dS m^{-1}, respectively for clay soils (Gupta and Yadav, 1986).

2.3.2.6 Legumes

Germination of lentil was not affected up to 40% sea water concentration (EC_{iw} 25.5 dS m^{-1}) but decreased sharply with > 50% sea water (EC_{iw} 29.0 dS m^{-1}) and completely inhibited above 70% sea water i.e. EC_{iw} 40 dS m^{-1} (Bukhtiar and Shakra, 1990).

All the tested gram varieties could not survive at EC_{iw} above 4 dS m^{-1} in studies of Khandewal *et al.*, (1990). Under a different set of conditions, chickpea was found more susceptible to NaCl than $NaHCO_3$ salts in irrigation water, as increasing RSC up to 10 me L^{-1}, at fixed EC and SAR increased the yield (Sharma *et al.*, 1989). Yield of berseem declined significantly with increasing RSC from Nil to 15 me L^{-1} (Chauhan *et al.*, 1989). Water SAR exceeding 10 decreased berseem fodder considerably (Haider and Hussain, 1976).

2.3.2.7 Sugarcane

Under optimum management conditions, irrigation for 3 years with water having salinity up to 2000 ppm and SAR less than 4 did not affect medium textured soil and sugarcane growth. Higher SAR was more harmful than with higher EC_{iw} (Ali *et al.*, 1978). Sugarcane crop due to its growth period in hot and dry season, is adversely affected when irrigated with saline water compared to other kharif crops grown in rainy season (Rehman *et al.*, 1978).

2.4 Amelioration of Brackish Water Effects.

2.4.1 Leaching Fractions (LF)

Excessive salts may accumulate if only consumptive requirements of crops are met with brackish water. The extra quantity of water over consumptive use is called leaching fraction (LF) and applied to check accumulation of salts. The LF will depend upon the quality of brackish water and tolerance of crop to be grown. Irrigation with water having salts up to 2600 ppm (EC_{iw} 3.71 dS m^{-1}) and SAR 10 did not affect adversely the soil and crop yields when 30-40% extra water (LF = 0.3 - 0.4) was provided (Haider and Hussain, 1978). Beneficial effects of LF in keeping salt build-up low and obtaining sustained yields of wheat, alfalfa, maize and sorghum when irrigated with brackish water, have also been recorded (Muhammad *et al.*, 1977, Khalid *et al.*, 1972 and Yasin *et al.*, 1987). But it has also been observed that leaching fractions did not materially help to leach down the salts when EC_{iw} was 3.87 dS m^{-1} and SAR_{iw} was 12.78 (Bhatti, 1986).

Short but heavy monsoon rains in summer in Pakistan and other countries may cause significant leaching of salts after saline irrigation. Rainfall amounting to 35-45 cm largely reduced initial high salt concentration which occurred during irrigation with saline water. Rains converted 40 cm of the soil surface non-saline. It was generalized that depth of soil from which the soluble salts (80 percent) may be leached during monsoon season, corresponded roughly with total rainfall during the season (Gupta and Abichandni, 1970). Five years salt balance studies of soils irrigated with saline water (EC_{iw} 2.7 to 12 dS m^{-1}) in four different crop sequences, have shown the salt concentration increased during irrigation cycle, whereas monsoon rains prevented salt accumulation in surface layer of soil. Only 23-27% of added Na^{1+} and Cl^{1-} salts accumulated in the soil while rest got leached down during crop season itself. The LF was conducive to lower EC_e and ESP of soils thereby resulting higher yields of crops (Jain, 1981).

2.4.2 Gypsum Bed and Gypsum Stone Lining

The SAR and RSC of tubewell waters was brought down by construction of gypsum bed using different sizes (5 to 20 kg) of gypsum stone. The rate of dissolution of gypsum stones was found proportional to the square root of velocity of flowing water and inversely proportional to the size of the stone in the bed (Ahmad *et al.*, 1979). The RSC of sodic water decreased from 5.57 to 0.75 me L^{-1} after passing through the gypsum bed of mixed fragments. The concentration of carbonate and bicarbonate remained unchanged, showing no precipitation of $CaCO_3$ in gypsum bed (Pal and Poonia, 1979). Similarly RSC also decreased by 2-3 me L^{-1} by passing the saline-sodic water through gypsum stone lined water course 138 m long. An increase in soluble $Ca^{2+} + Mg^{2+}$ was observed too (Ghafoor *et al.*, 1987). Soil infiltration rate was significantly higher when water was applied after passing through gypsum lined channel as compared to pure tubewell water of marginal quality (EC_{iw} 1.14 dS m^{-1}, SAR 5 and RSC 5 me L^{-1}. The EC_{iw}, SAR and RSC were 1.48 dS m^{-1}, 6.8 and 0, respectively after passing through gypsum stone bed (Chaudhry and Hamid, 1984).

2.4.3 Inorganic and Organic Amendments

Adverse effects of sodic waters can be minimized by soil application of inorganic and organic amendments. Total volume of leaching water through 30 cm soil column increased when fine grade gypsum was mixed in soil (Ghafoor *et al.*, 1988). Good ameliorative effects of gypsum were noticed when its quantities were worked out on water requirement basis of the total consumptive use of irrigation water for different crops. It was possible to keep soil SAR at a desired level but EC_e increased over a period of time for which leaching fractions were also to be included (Saleem *et al.*, 1992).

If gypsum is applied equivalent to 100% G.R. of soil, ESP can be controlled and crops can be grown successfully (Sharma *et al.*, 1989). Soil-application of gypsum was slightly superior to that dissolved in water but with non-significant differences, both succeeding in controlling ESP build up under irrigation of water having RSC 14 me L^{-1} (Poonia *et al.*, 1990). Gypsum is a less soluble salt but its solubility increased four and a half times in the presence of Na^{1+} saturated resin compared to pure water. In the soil system, the dissolved quantity of gypsum increased linearly with increasing ESP (Abrol *et al.*, 1979).

An increase in EC_e, pH and ESP of soil due to saline-sodic water use was managed by the addition of gypsum and H_2SO_4 (Alawi *et al.*, 1980). Similarly, gypsum, FYM, sulphur and H_2SO_4 indicated great improvement in soil properties and resultantly wheat and cotton yields were also increased (Bhatti, 1986). High soil infiltration rate was maintained with irrigation water of RSC 2.07 to 7.18 me L^{-1}, provided that the gypsum requirement of soil was met (Hussain and Haider, 1979). However, gypsum requirement of both the soil and water was to be fulfilled under another set of conditions to achieve similar results (Haider and Hussain, 1978). Useful effects of gypsum were also noticed in other studies (Hanif and Jabbar, 1974, Haider and Farooqi, 1972 and Chaudhary and Rafiq, 1985). Soil lime could be solubilized and $Ca^{2+} + Mg^{2+}$ contents increased when HC1 was applied along with irrigation water (Ahmad *et al.*, 1985). Soil conditioners induced aggregation and promoted hydraulic conductivity of soil (Yousaf, 1991).

Crop production was favoured with soil application of farm yard manure (Jilani *et al.*, 1990) and helped a lot in mitigating the adverse effects of poor quality water (Chaudhary and Rana, 1975). Infiltration rate of water increased with organic matter whereas very little water passed in its absence (Ahmad, 1978). Higher EC of leachate was recorded indicating removal of more salts in the presence of organic matter (Maqsud, 1982). Appreciable leaching of

Cl^{1-} and Na^{1+} was observed when guar (*Gyamopsis tetragonolopa*) was used as amendment. Soil Ca^{2+} + Mg^{2+} content increased through incorporation of alfalfa which confirmed dissolution of $CaCO_3$ by the evolution of CO_2. Soil structure was improved and ESP of soil was decreased (Haq and Dabin, 1981).

2.4.4. Conjunctive use of Canal and Brackish Water.

Water supplied at farm-gate and cropping intensity can be increased if canal and brackish water are used conjunctively. With the utilization of surface and groundwater resources, the present crop intensity can be almost doubled in Pakistan (Ahmad, 1987). Use of saline and flood water has been proposed for desert lands development (Bakhsh and Hussain, 1975). Occasional irrigations with highly saline sodic water were regarded safe for wheat yield and soil properties (Qureshi *et al.*, 1977 and Aslam *et al.*, 1977). Mixing of brackish and canal water was also found to be useful to maintain soil properties (Bhatti, 1986).

2.4.5. Cyclic use of Canal and Brackish Water

When brackish water is used for irrigating a relatively salt tolerant crop and canal/good quality water for the subsequent crop, it is called as cyclic use. This strategy was proposed by Rhoades (1983). Work in USA indicated that brackish and good quality water can be used in a cyclic manner without significant reduction in yields of wheat, sugarbeets, cantaloupe, cotton and alfalfa while salt accumulation in soil remained within permissible limits for these crops (Rhoades *et al.*, 1988). Accumulated salts in surface and sub-surface with brackish water irrigation leached into down layers to a greater extent during the subsequent cycles of good quality water (Sen and Bandyopadhya, 1979). It was possible to use only saline water for crop production except crop establishment which could be obtained with good quality water (Dinar *et al.*, 1986).

Saline water used for a single season for wheat and barley caused minimum yield loss (Ralston *et al.*, 1986). Under the prevailing management conditions in Pakistan, supply of tubewell water (EC up to 3.0 dS m^{-1}, SAR up to 12 and RSC zero) in Rabi and canal water during Kharif produced no adverse effects on normal soils. The LF and manuring proved favourable for maintenance of soil properties (Yunus, 1977). Soil EC$_e$ and SAR was significantly increased up to 90 cm soil depth where tubewell water of EC 2.6 dSm^{-1}, SAR 9 and RSC 2.8 me L^{-1} was used continuously. Only slight increase in these parameters was observed where tubewell and canal water were used in cycles for each crop or mixed. Sorghum fodder and wheat grain yield rather increased in these treatments compared to brackish water alone. Thus harmful effects of brackish water were controlled even on long term basis (Chaudhary *et al.,* 1990). Successful management strategy under rice-wheat and cotton-wheat crop rotations was irrigating rice and cotton with brackish water and wheat with canal water. No significant crop yield reductions were observed and salts in soil remained lower than continuous use of brackish water or mixture of both (Hussain *et al.,* 1990, 1991 a,b,c,d).

2.4.6 Agronomic Practices

Management of brackish water primarily aims at improvement of soil-water availability to crops. Matric potential is manipulated by adequate and timely irrigation, so that water is not rendered physiologically unavailable.

2.4.6.1 Method of Irrigation

Surface irrigation methods have an overall lower efficiency, resulting in aggravation of soil salinity and alkalinity. Precise levelling helps in uniform application and allows less depth of application, which means less additions of salts. Furrow irrigation permits only wetting of ridges and helps in better germination of seeds, particularly of crops salt tolerant at later growth stages (Gupta, 1990). Application of saline water (EC = 11 dS m^{-1}) through sprinkler, reduced wheat yield by only 3 % while water of EC 6 dS m^{-1} was safe for pearl millet. The salt accumulation was 30 to 40 % less in sprinkler irrigation compared with surface application (Agarwal *et al.*, 1982). Drip irrigation has given good results even when using relatively more saline waters. High salt concentration which would built-up with conventional irrigation was avoided. To obtain similar yields, drip irrigation required 50 % less water than furrow irrigation (Gupta, 1990). Mean EC_e was found as 6.0 dS m^{-1} under sprinkler irrigation with saline water against 5.0 dS m^{-1} under drip irrigation while respective yield decrements were 60 and 30%,respectively (Pasternak, 1984).

2.4.6.2 Frequency and Depth of Irrigation

Salinity of soil-water changes continuously after irrigation. More frequent irrigation with decreased depth of water were supposed to maintain better water availability in the upper part of the root zone if the total amount of water applied was almost the same as in case of less frequent but more deep irrigations. Frequent irrigation favoured plant height and ears in barley (Patel and Dastane, 1969). Thin and frequent irrigation with saline water gave higher wheat yield.

Frequency of 10 days gave 31 q ha^{-1} wheat grains compared to 27, 23.6 and 21 q ha^{-1} with 15, 20 and 25 days frequency, respectively (Sharma *et al.*, 1977). Daily irrigation stored 68% of applied water in the top 30cm depth compared to 59% in two days frequency. The respective loss of water below 60 cm was zero and 7.1% (Gupta and Tyagi, 1984).

2.4.6.3 Cropping System

Adoption of suitable crop rotation, cropping system and fallowing, helps in economical and sustained yields. Two rotations, fallow-wheat-green manuring-wheat-millet-barley, and fallow-wheat-millet-barley-green manuring-wheat were found suitable under saline water irrigation (Mehta *et al.*, 1973). Yields of wheat after fallow, legume, sesamum or millet were not significantly different showing that crop rotation would be governed by net profit. Guar-wheat crop rotation proved to be the most economical for saline water areas of Rajasthan (Jain *et al.*, 1976). Saline waters could be used more rationally by growing two different crops simultaneously in strips. The irrigation of main crop helped to the unirrigated inter-crop and thus both the crops played a complementary role to save water and accumulation of salts. Inter-crop of unirrigated gram or mustard could be raised successfully with wheat, being irrigated through saline water (Goyal, 1984).

In some situations or in some years rainfall may be unduly low and far below the average. Fallowing of the lands in such event for one season or more in arid or semi-arid regions, may be a beneficial practice in regenerating the brackish water irrigated soils. Soils irrigated with waters below EC 5 dS m^{-1} may be double cropped whereas those with higher salinity may be used in rotation with a fallow period for natural amelioration (Dhir and Bhattia, 1975). The huge salinity build-up during the irrigation cycle is taken care of by one above yearly rainfall or two subnormal rainy seasons. (Dhir, 1977). Soil EC_e and ESP increased during brackish water irrigation, can be brought down by monsoon rains especially at surface layer (Jain, 1981). Natural rainfall or intermittent ponding proves preferably more effective because the leaching occurs predominantly in unsaturated soil at a slow rate which allows greater exchange by dilution of salts between regions of varying velocities (Biggar and Nielson, 1962).

2.4.6.4. Planting Practices

Placement of seeds, higher seed rate, deep tillage, sowing inside shallow furrows or double-row raised or sloping beds and heavy presowing irrigation, are cultural and planting practices, most appropriate under brackish water use (Brovic *et al.*, 1982 and Khan, 1977). Sowing of Barley by ridge and furrow method at high seed rate in saline, water-logged soil gave a yield of 22.2 q ha^{-1} as compared to 17.1 q ha^{-1} by flat sowing with lower seed rate. In this method, the crop was sown near the bottom of the furrow on both sides of the ridge. The salts moved on the top of the ridge resulting in lower salt concentration near the bottom of the ridge (Nalamwar and Dastane, 1966). Orientation of ridges in the north-east to south-west direction on saline soil induced desalination on the north-west slope as a result of salt movement of south -west slope receiving greater intensity and duration of solar radiation. The ridges were 25 cm high, constructed with a base angle of 60° and spaced 60 cm apart. EC_e of 15.5 was, thus, reduced to 6.7 dS m^{-1} on the north-west slope (Bains and Singh, 1966).

The chemical, physical and agro-physical treatments of seeds and seedlings induced salt tolerance (Storgonov, 1964). One of the main causes for the poor germination or stand of the crop in sodic conditions of soil is the disruption in the permeability of roots due to which it fails to control balanced ion absorption. Calcium ions have been reported to maintain membrane integrity (Mangel and Kirkby, 1979 , Clarkson and Hanson, 1980). Seed treatment with calcium salts increased salt tolerance of wheat (Chaudhuri and Wiebe, 1968). Wheat seed soaking in 3% $NaSO_4$ solution gave highest yield under irrigation with saline water (Puntaamkar *et al.*, 1971) but no good response was obtained when seed soaking of wheat and barley was carried out in other salt solutions (Manchanda and Bhandari, 1976). However, pre-soaking in low salinity tubewell water, usually resulted in higher grain yield than seeds presoaked in NaCl or Na_2SO_4 solution.

2.4.6.5. Manures and Fertilizers

Manures and fertilizers enhance the suitability of brackish water for irrigation. Dressing of FYM and fertilizers showed beneficial effect on wheat and millet, grown under saline water irrigation, up to a moderate level of salinity and SAR (Maliwal and Paliwal, 1971a, 1972). Similar was the response of maize and barley (Paliwal and Maliwal, 1971; Maliwal and Paliwal, 1971b). Plant height, panicles, straw and paddy yields increased with combined applications of poultry manure and fertilizer under brackish ground water irrigation (Hussain *et al.*, 1991e). Wheat yield also increased by the addition of 5 to 20 t ha^{-1} of dung in a sandy clay loam soil irrigated with HCO_3^{1-} dominant water. However, response of fertilizer decreased as the level of EC and SAR of water increased (Lal and Singh,

1972) and there was no response of wheat and barley at EC 6.3 dS m^{-1} or SAR 32 (Sharma and Lal, 1975). Application of N beyond 90 kg ha^{-1} did not increase grain and stover yield of maize to any appreciable extent under saline water (Verma *et al.*, 1971). Application of Zn (20 kg ha^{-1}) increased wheat yield from 28.6 to 33.1 q ha^{-1} on normal soil irrigated with saline sodic water (Lal *et al.*, 1980).

Green manuring is also one of the useful practices in the management of saline water and therefore, it should find an important place in crop rotation. Sesbania grew well and provided complete cover to the soil compared to other green manure crops even with highly saline water irrigation. Wheat yield increased from 15.7 to 20.8 q ha^{-1} after ploughing under sesbania green manure when irrigation water had EC 10.5 dS m^{-1} (Gupta, 1985).

2.5. Use of Brackish water for reclamation purposes

Reclamation of salt affected soil requires a lot of water for leaching of salts. If brackish groundwater is used for this purpose, huge quantities of good quality water can be saved for crop production from normal soil. For solubilizing gypsum and lime in soils, saline water would be very much helpful. A saline-sodic soil with ECe of 25 dS m^{-1} and ESP 60 % was reclaimed when simply irrigated and leached with saline water due to solubilization of substantial quantities of natural gypsum and lime in the soil profile. High permeability during leaching of soil was maintained (Jury *et al.*, 1979). The SAR, ESP and pH of a saline-sodic soil reduced to safe limits by addition of organic matter and gypsum and subsequent leaching with saline-sodic water. Leaching with distilled water failed to reclaim the soil (Khan *et al.*, 1990). Combination of sub-soiling, gypsum and leaching with brackish groundwater (EC 1.8 dS m^{-1}, SAR 9.8 and RSC 7.2 me L^{-1} proved effective in reclaiming the "Khurrianwala" and "Gandhra" soil series (Muhammad *et al.*, 1990).

Growing salt tolerant grasses/green manures with saline water and incorporation into the salt affected soils is another way of using brackish water for reclamation. Sudan grass, Rhodes grass, Bermuda grass, Sesbania, Leptochloa, Sorghum and Bajra napier hybrid etc. were the potential biotic materials which were grown with saline or sodic waters (EC_{iw} 0.55 to 3.2 dS m^{-1}). Incorporation of these into sodic soils improved physical and chemical properties (Alawi *et al.*, 1980, Ahmad *et al.*, 1992, Ahmad *et al.*, 1984 and Ahmad *et al.*, 1990). Growing grasses was helpful in an increase of organic matter content, improvement of infiltration rate & saturated hydraulic conductivity and reduction in EC_e, pH, SAR and ESP of a salt affected soil (Akhtar *et al.*, 1990).

Leptochloa fusca is a versatile halophytic, primary colonizer, C_4, easily propagatable, perennial, thermophilic, nutritive and palatable forage plant species which can be grown with poor quality water on soils ranging in pH 3.0 to 11.0, may be saline, sodic or saline-sodic or waterlogged. It depletes salts from root zone and provides better root environment for the growth of other plants (Abdullah *et al.*, 1989, Siddique *et al.*, 1990, Abdullah *et al.*, 1990). After the improvement brought by the growth of grasses, subsequent crops of rice and wheat yielded satisfactorily. Subsequent to rice-wheat cycle of 5 years, less tolerant fodders such as teosinte, maize and alfalfa could also be grown (Kumar, 1990). It was observed that 89% of total salts was added by poor quality water applied to grow Leptochloa and 96% of total output leached down below 2m soil layer. The role of roots of this plant in affecting physical and chemical properties, especially hydraulic properties,was very important (Akhtar *et al.*, 1990).

CHAPTER III

MATERIALS

AND

METHODS

CHAPTER-III

MATERIALS AND METHODS

Research studies reported in this manuscript were conducted at Soil Salinity Research Institute, Pindi Bhattian, District Hafizabad, Pakistan with the official approval of Director, Advanced Studies, University of Agriculture, Faisalabad. The studies comprised of one field and two lysimeter experiments. Details of each experiment are described separately. Various strategies on the use of brackish water for crop production were investigated. Lysimeter experiments were planned to investigate a long list of treatments while selected techniques were verified under field conditions.

3.1 Experimental Soil:

Bulk soil was collected from the surface (0-15 cm) of two different fields for study 1 and 2. Study 3 was carried out in the field (Rasulpur soil series). Chemical analysis of soil was completed by obtaining representative samples (Table 3.1). The physical

Table 3.1 **Analysis of experimental soil (s)**

Characteristics	Unit	Study-1	Study-2	Study-3	
				0-15 cm	15-30 cm
Moisture Saturation	%	35.20	36.80	35.80	29.60
Electrical Conductivity(EC_e)	dS m^{-1}	1.99	1.44	1.64	1.69
pH_s	-	8.10	8.40	8.00	8.20
Calcium + Magnesium	me L^{-1}	6.55	4.10	7.00	5.20
Sodium	me L^{-1}	12.45	10.30	9.20	11.60
Carbonates	me L^{-1}	Nil	Nil	Traces	Nil
Bicarbonates	me L^{-1}	2.50	7.00	3.60	5.20
Chlorides	me L^{-1}	2.00	2.00	4.60	5.00
Sulphates	me L^{-1}	14.40	5.40	8.20	6.70
Sodium Adsorption Ratio	(mmol $L^{-1})^{1/2}$	6.90	7.19	4.92	7.19
Bulk Density	Mg m^{-3}	1.41	1.43	1.65	-
Particle Density	Mg m^{-3}	2.45	2.40	2.45	2.50
Hydraulic Conductivity	cm hr^{-1}	2.37	1.77	1.86	1.63
Degree of dispersion	%	28.00	28.50	26.70	25.90
Sand	%	65.09	63.20	64.30	73.81
Silt	%	3.60	12.55	13.50	9.60
Clay	%	21.31	24.25	22.20	16.59
Textural Class	-	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy loam

properties were determined from the undisturbed soil core drawn simultaneously (Table 3.1). Values of EC_e and Sodium Adsorption Ratio indicated that the soil of study 1 & 2 had no salinity/sodicity problem. Soils had a medium texture (sandy-clay loam) and good hydraulic conductivity. Similarly, soil of study 3 was non-saline, non-sodic with good hydraulic conductivity. Texture was medium (sandy clay loam) in surface 0-15 cm soil depth and light (sandy loam) in 15-30 cm.

3.2 Study 1: Managing brackish water for sustained rice and wheat production.

This study was conducted in lysimeters on rice-wheat rotation for two years.

3.2.1 Treatments

Treatments of this experiment were:

T_1 = Canal water alone for all the crops in the rotation.

T_2 = Brackish water alone for all the crops in the rotation.

T_3 = Blending of canal and brackish water (1:1) for all the crops in the rotation.

T_4 = Alternate irrigation each of canal and brackish water for all the crops in the rotation.

T_5 = Rice irrigated with brackish water and wheat with canal water (Seasonal cycle).

T_6 = First two crops irrigated with brackish water and subsequent two with canal water (Yearly cycle).

T_7 = Crop establishment with canal water (first two irrigations) in yearly cycle (T_6)

T_8 = Brackish water (T_2) + rice straw (@ 10 t ha^{-1}) incorporated into the soil at harvest of each rice crop.

T_9 = Brackish water (T_2) + gypsum calculated by Eaton's formula on gypsum requirement basis of water used and added to the soil after the harvest of each crop.

T_{10} = Brackish water (T_2) + H_2SO_4 added to the soil (with each irrigation) equivalent to neutralize CO_3^{2-} + HCO_3^{1-} of water used.

T_{11} = Yearly cycle (T_6) + green manure (Sesbania) @ 10 t ha^{-1} before rice transplantation.

3.2.2 Methodology

Soil in bulk was brought to the green-house and packed in cement lysimeters without grinding and sieving. Dimensions of lysimeters were 1 x 0.3 m. Uniform packing of soil columns (90 cm) were achieved through alternate wet (distilled water) and dry cycles. Occasional wet and dry cycles were followed until well developed soil columns were obtained. Experiment was started after obtaining a bulk density of 1.5 Mgm^{-3} (nearer to the original one). The lysimeters were arranged according to Completely Randomized Design (CRD) with three repeats and irrigation treatments were imposed during growth of crops. The experiment was started with rice transplantation and followed by wheat. Other details regarding crops are mentioned in section 3.6.1.

Two crops of rice as well as wheat were raised. Soil samples (0-15 cm) were obtained for analysis of chemical and physical properties at harvest of rice and wheat. Whole of the lysimeters were sampled at the end of the experiment (4th crop). Lysimeters were open for leaching at the bottom as well as to rainfall throughout the experimental period. Rainfall data were recorded separately (App. 15).

3.3 Study 2: Sustainable wheat and fodder productivity with brackish water.

This study was also undertaken in lysimeters on wheat-sorghum (fodder)-wheat-maize (fodder) rotation for two years. The study was initiated from wheat in winter season in contrast to study-1 which was started in summer.

3.3.1 Treatments

T_1 = Canal water alone for all the crops in the rotation.

T_2 = Brackish water alone for all the crops in the rotation.

T_3 = Blending of canal and brackish water (1:1) for all the crops in the rotation.

T_4 = Alternate irrigation each of canal and brackish water for all the crops in the rotation.

T_5 = Wheat irrigated with brackish water and summer fodders (sorghum and maize) with canal water.

T_6 = First two crops irrigated with brackish water and subsequent two with canal water (Yearly cycle).

T_7 = Crop establishment with canal water (first two irrigations) in yearly cycle (T_6)

T_8 = Brackish water (T_2) + Farm yard manure @ 20 t ha^{-1} after wheat harvest.

T_9 = Brackish water (T_2) + gypsum calculated by Eaton's formula on gypsum requirement basis of water used and added to the soil after the harvest of each crop.

T_{10} = Brackish water (T_2) + H_2SO_4 added to the soil with each irrigation equivalent to neutralize CO_3^{2-} + HCO_3^{1-} of water used.

T_{11} = Yearly cycle (T_6) + green manure (Sesbania) @ 10' t ha^{-1} after harvest of wheat.

3.3.2. Methodology

Almost same methodology as described under study-1 was adopted with change of crop rotation to wheat-sorghum (fodder)-wheat-maize(fodder). Various irrigation treatments alongwith amendments (where needed) were applied as detailed above. The farm yard manure (FYM) applied in T_8 was well decomposed and collected from mixed animals. It had 0.6, 0.4 and 1.3 % N, P and K which were counted in fertilizer calculations for this treatment.

3.4 Study 3: Soil health care during groundwater irrigation of rice-wheat system.

A field experiment on rice-wheat rotation was conducted at the Farm of Soil Salinity Research Institute, Pindi Bhattian, District Hafizabad, Pakistan. This study continued for three years.

3.4.1 Treatments

This experiment was carried out with the following selected treatments from lysimeter experiments.

T_1 = Canal water irrigation to rice and wheat.

T_2 = Tubewell water irrigation to rice and wheat.

T_3 = Seasonal Cyclic use: Tubewell water for rice and canal water for wheat.

T_4 = Seasonal Cyclic use + Sesbania (green manure @ 10 t ha^{-1}) before rice transplanting.

T_5 = Tubewell water (T_2) + Gypsum (calculated by Eaton's formula on the basis of delta of water for crops and added before sowing of each crop).

T_6 = Tubewell water + H_2SO_4 equivalent to CO_3^{2-} + HCO_3^{1-} of water (applied with each irrigation).

3.4.2 Methodology

Field was prepared by ploughing and puddling as required for low land rice. Sesbania was incorporated 30 days before starting tillage operations in the plots of T_4. All treatments were arranged in accordance with Randomised Complete Block Design (RCBD) comprising of 4 replications and sub-plot size of 8 x 3 m^2. Recommended cultural practices and fertilizer applications were followed as described in the later section on crops.

3.5 IRRIGATION WATERS:

3.5.1 Quality of water:

Canal as well as brackish water were used to irrigate different crops.