Guidelines for Irrigation Scheduling with Skimmed Groundwater to Manage Root Zone Salinity –A Preliminary Framework

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ABSTRACT

In irrigated agricultural areas in semi-arid zones, where the canal water supplies are generally not sufficient to meet the crop water requirement, the necessity of pumped water application arises. If these irrigated agricultural areas are having shallow watertables, the salts are being added to the root zone: (i) from the bottom due to groundwater contribution and (ii) from the top due to pumped water and canal water applications. Under such irrigated agricultural conditions, there is a need of adopting practical ways and means for irrigation applications so that the root zone salinity is managed throughout the cropping season within the acceptable limits for good crop productivity. In this context, a set of guidelines for irrigation scheduling aimed at managing salinity in the root zone can provide such tools for irrigation applications.

However, for developing and implementing guidelines for irrigation scheduling with skimmed groundwater, there is a need to develop linkages between the net soil moisture depletion and the threshold levels of the root zone salinity at different stages of the crop growth under different soil moisture depletion levels. Therefore, after reviewing the literature available on the factors concerning the salinity in the root zone, a preliminary framework for irrigation scheduling with skimmed groundwater is presented. The monitoring and evaluation of this preliminary framework will help in developing guidelines for irrigation scheduling with skimmed groundwater. The methodology of developing such guidelines is formulated so that it can be generalized for uses in other similar aquifers in the Indus Basin of Pakistan.

INTRODUCTION

Brief Description of the project

The project is designed for the Mona Experimental Reclamation Project (MREP) and/or the Fordwah Eastern Sadiqia (South) Irrigation and Drainage Project (FESS) areas (Figure 1). The technology and management packages, under the project, comprise three inter-linked components: (i) the skimming well technologies, (ii) the pressurized and innovative irrigation application systems, and (iii) the root zone salinity management.

First component focuses on identifying and testing a limited number of promising skimming well technologies for skimming thin lenses of relatively-fresh groundwater from aquifers underlain by saline groundwater layers while controlling the saline groundwater upconing as a consequence of pumping. The options that considered while selecting the promising skimming well technologies include single-strainer/multi-strainers skimming wells, dugwells, scavenger well, and radial well, etc.

Under the second component, the in-country manufacturers will be encouraged and supported to develop low-cost pressurized irrigation application systems adaptable within the local setting of Pakistan. The options for low-cost pressurized irrigation application systems include sprinkler (raingun), drip/trickle, and bubbler, etc. Keeping in view the vastness of surface irrigation and the perceptions of the farmers with low discharge rates, the adoption of innovative irrigation application systems (like bed-and-furrow, furrow-ridge, bed-and-corrugation etc.) is also being viewed favorably.

The third component deals in developing and implementing guidelines for irrigation scheduling with skimmed groundwater to manage root zone salinity. The options for applying skimmed groundwater comprise the pressurized and innovative irrigation application systems.

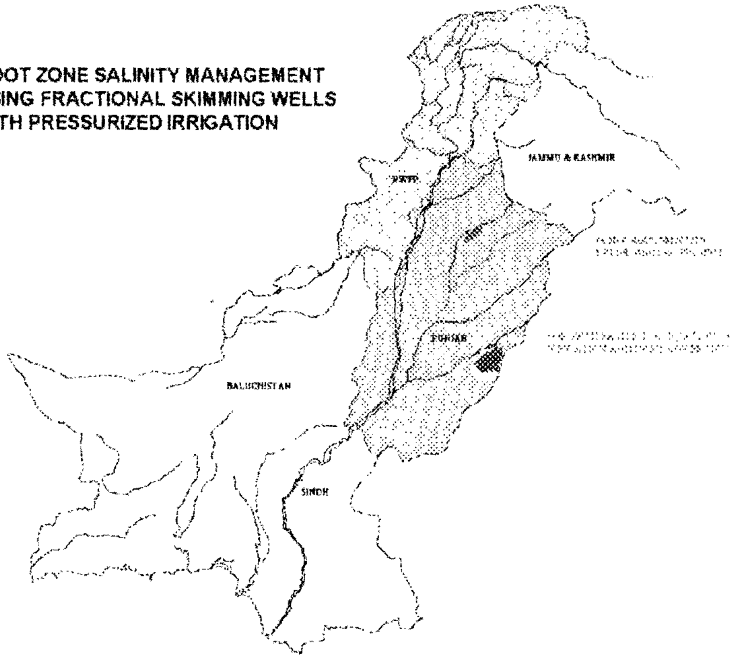

Figure 1. Location map of the project sites.

Specific conditions in the project areas

In the MREP area, there are 73 % farmers with small land holdings (less than 5 hectares), 18% with medium land holdings (5 to 10 hectares) and 9% with land holdings of more than 10 hectares (Kahlown et al., 1998). While in the FESS area, there are two farm types: the large farm with an average area of 11 hectares, and the small farm having average area of 3.5 hectares. The large and small farms cover 59% and 41% of the project area, respectively. By number, small farms constitute about 70% of the total number of farms in the area (WAPDA, 1997).

The cropping patterns, in the MREP area, include mainly rice-wheat and maize-wheat with sugarcane as a cash crop. Fodder crops also occupy a place in their cropping pattern. Citrus occupies an important position in the cropping pattern and considered as most profitable crop of the area (Kahlown et al., 1998). In the FESS area, the major crops are wheat, cotton, sugarcane, fodder and rice. The crops account for more than 94% of the cropped area, the rest is under maize, pulses and other minor crops (WAPDA, 1997).

At the small farms in the MREP area, the annual cropping intensity is 152%, which comprises 65 and 87% under *kharif* and *rabi* seasons, respectively. In *kharif*, rice, sugarcane, and maize occupy 26, 9, and 30% of the cropped area. While, wheat and fodder covers 72 and 15% of the cropped area in *rabi* season (Kahlown et al., 1998). Whereas in the FESS area, the annual cropping intensity is 129.3%, with 55.3% in *kharif* and 74% in *rabi*, counting sugarcane in both seasons (WAPDA, 1997).

The surface irrigation application method is the most prevalent form of irrigation practiced within the MREP and FESS project areas (WAPDA, 1997; and Kahlown et al., 1998). Over-irrigation is commonly practiced during *rouni* (pre-planting/soaking irrigation), 1st and 2nd irrigations, while under-irrigation is practiced during the last few irrigations (when soil surface conditions enhance the water advance behaviour).

Needs for irrigation scheduling with skimmed groundwater

In the MREP and FESS project areas, excluding the monsoon period, the canal water supplies are generally not sufficient to meet the crop water requirement. The watertable is shallow and therefore it also contributes to the evapotranspiration from the crops. But, when both the canal water supplies and the groundwater contribution due to capillary rise do not match the crop water requirement, the necessity of pumped water application arises. Thus, in the MREP and FESS project areas, the salts are being added to the root zone: (i) from the bottom due to groundwater contribution and (ii) from the top due to pumped water and canal water applications.

Different skimming well technologies are being used to extract relatively-fresh groundwater lenses from aquifers underlain by saline groundwater layers. However, the discharge rates from these skimming wells are too low to apply efficiently on surface irrigated croplands. Pressurized irrigation systems are highly advantageous over surface irrigation application systems while using these small discharges. These systems are handy in applying exact needed amount of water to the plants. The adoption of such systems also helps in providing technical assistance in managing root zone salinity under the agricultural lands with commonly grown crops, vegetables and orchards, as water can easily be measured before it enters the pressurized irrigation application system.

However, by introducing adequate interventions in design parameters and operational management strategies of skimming wells, higher discharges are also feasible. These higher discharges may induce minimum mixing of the saline groundwater layer either within the well or within the aquifer with the overlying relatively-fresh groundwater lenses. Therefore, the quality of this skimmed groundwater is expected to change with time while responding to recharge and discharge mechanisms. But, proper guidelines regarding the design parameters and operational management strategies of skimming wells can help in pumping a required quantity of groundwater of the desired quality. Where such systems exist, even surface irrigation can be practiced, or at least by using innovative irrigation application systems.

The soil moisture in the root zone is either utilized by the crops and/or evaporates from the soil surface, while leaving the salts behind. Resultantly, the salinity in the root zone is expected to increase with the application of such skimmed groundwater for irrigation purposes. Therefore, the use of skimmed groundwater will require unique but practical ways and means for irrigation applications so that the root zone salinity is managed at different crop growth stages throughout the cropping season within the acceptable limits for good crop productivity. In this context, a set of guidelines for irrigation scheduling aimed at managing salinity in the root zone can provide such tools for irrigation applications.

Irrigation scheduling is a procedure used to determine the time and depth of water application for each irrigation event. The time of water application is normally based on the depletion of stored soil water, whereas the depth of water application is usually equal to the value of soil water depletion, water application efficiency plus some additional water for leaching fraction, if required. Therefore, for irrigation scheduling with skimmed groundwater, knowledge of water and salt balances in the root zone is of crucial importance, as getting the salt balance right in the root zone is essential to both the short-term and long-term viability of an agricultural area. Thus, by knowing the salinity of the pumped water and the salt tolerance levels at different stages of the crop growth; the soil salinity and soil moisture in the root zone with depth; the evapotranspiration rates during various crop growth stages; and the groundwater capillary contributions in case of shallow watertables, the farmer can be given the guidelines for irrigation scheduling skimmed groundwater.

Basis for irrigation scheduling with skimmed groundwater

Guidelines for developing irrigation scheduling with skimmed groundwater could be defined as tools and yardsticks that play pivotal role in decision making regarding timing and amount of irrigation water applications aimed at managing root zone salinity and productivity of land and water. Such guidelines for irrigation scheduling could list the hours of pumping for each irrigation event that would satisfy crop water requirement, including an appropriate allowance for leaching in order to maintain the root zone salinity at acceptable levels for good crop productivity.

However, for developing and implementing guidelines for irrigation scheduling with skimmed groundwater, there is a need to develop linkages between the net soil moisture depletion and the threshold levels of the root zone salinity at different stages of the crop growth under different soil moisture depletion levels. Therefore, literature review is conducted before developing a preliminary framework for irrigation scheduling with skimmed groundwater under irrigated agricultural areas in semi-arid zones with (monsoon and winter) rainfalls and watertables having root zone within or beyond the capillary reach[1].

The building blocks of the framework that defines such linkages are identified as under:

- Irrigation with saline water;
- Salt tolerance of crops;
- Crop evapotranspiration under stress conditions;
- Groundwater capillary contribution;
- Management practices for root zone salinity control; and
- Monitoring and evaluation of management practices.

Irrigation with saline water

The aspect deals with the following information:

1. Quality of irrigation water;
2. Number of irrigations;
3. Soil texture;
4. Leaching fraction; and
5. Rainfall.

[1] If watertable having root zone within the capillary reach, then it is considered "shallow". On the other hand, the watertable is "deep" when the root zone is beyond the capillary reach.

Salt tolerance of crops

Plants differ widely in the their ability to grow and develop under saline and/or sodic conditions. The following parameters describes the impacts of soil and water salinity and/or sodicity on crop yield:

1. Soil salinity;
2. Soil sodicity; and
3. Quality of irrigation water.

Crop evapotranspiration under stress conditions

The estimation of crop evapotranspiration plays pivotal role in developing guidelines for irrigation scheduling with skimmed groundwater. The following stress conditions limit crop evapotranspiration and reduce root water uptake:

1. Soil water stress condition; and
2. Combined soil water and salinity stress condition.

Groundwater capillary contribution

In determining net soil moisture depletion, knowledge about the groundwater capillary contribution is also needed. However, the estimates of such contribution will depend on the following factors:

1. Soil texture;
2. Quality of groundwater; and
3. Root zone salinity resulting from capillary rise.

Management practices for root zone salinity control

The above stated knowledge, tools, and yardsticks are used in managing land, water, and crops to control salinity. However, for root zone salinity management, the following practices also become part of guidelines:

1. Irrigation management practices;
2. Rainfall management practices; and
3. Shallow watertable management practices.

Monitoring and evaluation of management practices

The estimation of water and salt balances are used to monitor and evaluate different management practices. The role of successful management for salinity control in the root zone should be to maintain the fluctuations in the water and salt balances within limits that neither allows excess drainage, nor reduces the crop growth.

LITERATURE REVIEW

In irrigated agricultural areas, particularly when relatively-fresh water is applied for irrigation, the salts continue to build up in root zone provided salts are not removed in equivalent amounts as are applied with irrigation water. When irrigated agricultural areas in semi-arid zones with rainfalls and watertables are irrigated with relatively-fresh water, the root zone salinity cycle can be divided into the following three periods:

- Salt builds up period: The root zone salinity builds up with each irrigation event.
- Salt redistribution period: The soil salinity redistributed in the root zone with winter rainfalls. The evaporation of the shallow watertable also redistributes the salinity in the root zone.
- Salt leaching period: During the monsoon, when in most places rainfall is in excess over the potential evapotranspiration, leaching occurs which moved the salts below the root zone. The *rouni* also provides leaching effect.

All these periods need different practices to manage root zone salinity.

Irrigation with saline water

The main factors, which control the extent to which salinity may develop in the root zone while irrigating with saline water under deep watertable conditions, include: (i) quality of irrigation water, (ii) number of irrigations, (iii) soil texture, (iv) leaching fraction, and (v) rainfall. The regression relationships between these factors and the salinity in the root zone, as mentioned by Gupta and Gupta (1997), are described hereafter. However, all the regression relationships of these factors with the salinity in the root zone are site-specific and crop-specific under the given management practices.

Quality of irrigation water

The salinity of the irrigation water (EC_i) and the electrical conductivity of the saturation extract of the soil[2] (EC_e) are related to each other. A regression relationship, which relates both the EC_e and EC_i, could be expressed as given below:

$$EC_e = a + b(EC_i) \qquad (1)$$

Where, a and b are regression coefficients. Gupta and Gupta (1997) stated that the regression coefficients of Equation (1) for different sites show large variations (Table 1). These variations were attributed to

Soil salinity is normally measured and expressed on the basis of the electrical conductivity of the saturation extract of the soil, as salt concentration in the soil changes with the change in soil moisture.

variations in the management conditions as well as to variations in number of irrigations, soil texture, and rainfall.

Table 1. Effect of quality of irrigation water on the salts accumulated in the root zone (Gupta and Gupta, 1997).

Sites	Sites categories	Regression coefficients	
		a	b
Agra	Experimental sites	1.59	1.02
Jobner	Farmers' fields	3.87	0.48
Pali	Farmers' fields	0.84	0.44

Number of irrigations

The soil salinity in the root zone achieved at the end of "salt builds up period" is related with the number of irrigations. A regression equation that takes into account the quality of irrigation water and the number of irrigations under field conditions, could be expressed as given below:

$$EC_e = a + b\left(EC_i\right) + c\,N \qquad (2)$$

Where, a, b and c are the regression coefficients and N is the number if irrigation. For medium texture soil and where number of irrigations is not more than 6, Gupta (1990) determined the values of the regression coefficients a, b, and c (in Equation 2) as –2.26, 0.90, and 1.24, respectively. However, similar type of regression relationships may be worked out for a particular soil and climatic region.

Soil texture

The rate of root zone salinity build up is faster in heavy (i.e., fine loam, clay loam, and silty clay loam) than light (i.e., sandy to loamy sand) textured soils. A regression relationship, which relates both the EC_e and EC_i under different soil textural classes, could be expressed similar to Equation (1).

Gupta and Gupta (1997) stated that the regression coefficient, b, varies from 0.36 for sandy to loamy sand soils but is 0.69 for fine loam, clay loam, and silty clay loam soils under the similar situations. The value of regression coefficient, a, may not vary much for heavy and light textured soils (i.e., from 2 to 2.2).

Leaching fraction

Leaching fraction, LF, is defined as the fraction of the irrigation water and/or rainfall that leaves the root zone (Singh, 1993; Somani and Totawar, 1993; and Tanji, 1995):

$$LF = \frac{D_d}{\left(D_{ir} + D_p\right)} = \frac{EC_i}{EC_d} \qquad (3)$$

Where, D_d is the deep percolation (mm), D_p is the rainfall (mm), D_{ir} is the depth of irrigation water to be applied (mm), and EC_d is the salinity of the water draining from the root zone as deep percolation.

However, Gupta and Gupta (1997) stated that the LF could also be easily known from the water application efficiency provided the water distribution efficiency is reasonably high. A relationship, which relates both the EC_e and EC_i under different leaching fractions with the water application efficiency, was presented as:

$$EC_e = K(EC_i) \tag{4}$$

The values of K are 2.0, 1.0, and 0.5 for low, medium and high leaching fraction, respectively. The qualitative terms low, medium and high leaching fractions are for 0.1, 0.3, and 0.5, respectively. It also means high (90%), medium (70%), and low (50%) water application efficiencies. For instance, an application efficiency of 70% means that the LF is around 0.30.

However, for the same amount of water applied, the leaching fractions will be more in light textured soils than in heavy textured soils. Therefore, the value of K could also be higher for the lower leaching fractions.

Rainfall

High rainfall leaches the salts accumulated in the root zone and reduces the number of irrigations. A regression relationship, which relates both the EC_e and EC_i under different intensities of rainfalls, could be expressed similar to Equation (1).

Gupta and Gupta (1997) found that with an additional 10 cm of rainfall under the wheat and mustard fields, the regression coefficient, b, is reduced by about 0.6 units for both the crops, which indicates the leaching of salts from the root zone after heavy rainfall (Table 2). The number of irrigations for wheat crop having low and high rainfall is 4 and 3, respectively, which means that high rainfall also reduces the number of irrigations.

Table 2. Effect of rainfall on the salts accumulated in the root zone and on the number of irrigation (Gupta and Gupta, 1997).

Crop	Rainfall (mm)	Number of irrigation	Regression coefficients	
			A	b
Wheat	17.1	4	2.44	1.29
Wheat	113.9	3	1.76	0.69
Mustard	18.2	3	2.76	1.11
Mustard	113.9	3	1.80	0.50

Salt tolerance of crops

Different crops have different salt tolerance. Plants differ widely in the their ability to grow and develop under saline and/or sodic conditions.

Soil salinity

In reviewing articles on impacts of salinity in the root zone on crop yield by Maas and Hoffman (1977) and Mass (1990), it is concluded that under optimum management conditions, the crop yields remain at potential levels until EC_e reached at threshold level, i.e., $EC_{e\ threshold}$:

$$Y_r = 100 \qquad\qquad 0 \le EC_e \le EC_{e\ threshold} \tag{5}$$

where Y_r is the percentage of the yield of the crop grown under saline conditions relative to that obtained under non-saline, but otherwise comparable, conditions.

It means that $EC_{e\ threshold}$ is the average root zone salinity at which yield starts to decline. If the average EC_e of the root zone increases above this critical threshold value, the yield decreases linearly in proportion to the increase in salinity. The rate of decrease in yield with the increase in salinity is usually expressed as a slope, b, having units of % reduction in yield per unit increase in EC_e beyond $EC_{e\ threshold}$. The salt tolerance of common agricultural crops is generally expressed as follows (after Maas and Hoffman, 1977; and Mass, 1990):

$$Y_r = 100 - b\left(EC_e - EC_{e\ threshold}\right)$$

$$EC_{e\ threshold} < EC_e < EC_{zero} \tag{6}$$

$$Y_r = 0 \qquad\qquad EC_e \ge EC_{zero} \tag{7}$$

Where EC_{zero} is the EC at or beyond which crop fails to give any yield. Table 3 lists the $EC_{e\ threshold}$ and slope b for common agricultural crops (adopted from Ayers and Westcot, 1985; and Rhoades, et al., 1992).

It is interesting to note that the values of $EC_{e\ threshold}$ and slope b parameters mentioned in Table 3 were determined primarily in research experiments where soil moisture at the 0.3 to 0.6 m depths (depending upon the crop) were maintained at levels close to field capacity[3]. Therefore, Table 3 does not help in predicting an accurate estimate of the expected yield, as the crop yield depends not only upon level of salinity but also upon many other cultural and environmental factors. Thus, the interaction between EC_e and soil, water, crop and climatic factors could modify the ability of the plant to tolerate salinity.

However, for the same average root zone salinity, crop production at or near to threshold levels could be possible, if the effective root zone is

[3] The field capacity was considered at about –3 m potential (-30 kPa).

somehow kept relatively salt free, as the crops adjust for their water requirement and draw more water from the salt free zone. And, the average root zone salinity can be managed at a pre-determined level within a wide range by controlling the LF. Mathematically (after Gupta and Gupta, 1997):

Table 3. Salt tolerance of common agricultural crops (Ayers and Westcot, 1985; Rhoades, et al., 1992).

Crop	$EC_{e\ threshold}$ ($dS.m^{-1}$)	b (% / $dS.m^{-1}$)
Vegetables		
Onion	1.2	16.0
Radishes	1.2-2.0	7.6-13.0
Spinach	2.0-3.2	7.7-16.0
Cauliflower	1.8	6.2
Potato	1.7	12.0
Carrots	1.0	14.0
Turnip	0.9	9.0
Tomato	0.9-2.5	9.0
Peas	1.5	14.0
Cereals		
Barley	8.0	5.0
Maize	1.7	12.0
Sorghum	6.8	16.0
Wheat	8.6	3.0
Fodder		
Alfalfa	2.0	7.3
Sugarcane	1.7	5.9
Citrus		
Grapefruit	1.8	16.0
Orange	1.7	16.0

$$LF = 1 - \frac{EC_{e\ threshold}}{S_i} \qquad (8)$$

Where, S_i is the salt initially present in the root zone. Table 4 provides crop tolerance to soil salinity for working out leaching fraction at some selected stations in India (adopted after Gupta and Gupta, 1997).

The yield of crops would be affected over time when salinity build-up in the total root zone proceeds upward. When some yield reduction is permissible, then $EC_{e\ threshold}$ in Equation (8) could be replaced by the salinity at which the desired yield reduction ($EC_{e\ yield\ reduction}$) would occur. The $EC_{e\ yield\ reduction}$ can be calculated by the by the data reported in Table 4 utilizing the following relationship (after Gupta and Gupta, 1997):

Table 4. **Crop tolerance to soil salinity for working out leaching fraction at some research sites in India (adopted after Gupta and Gupta, 1997).**

Sites	Soil type	Crop	$EC_{e\ threshold}$ ($dS.m^{-1}$)	b (% / $dS.m^{-1}$)
Sampla	Sandy loam	Wheat	4.0	29.0
		Barley	7.0	19.0
Karnal	Sandy loam	Sorghum	2.2	10.6
Agra	Sandy loam	Potato	4.4	16.1
		Tomato	1.3	6.5
		Wheat	8.2	19.8
		Alfalfa	3.5	12.5
Dharwar	Black clay	Wheat	2.3	20.5
Indore	Black clay	Maize	0.50	7.9
		Alfalfa	2.0	11.22

$$LF = \frac{EC_{e\ yield\ reduction}}{b} + EC_{e\ threshold} \quad (9)$$

It is known that outcome of the entire cropping season depends upon the initial crop stand. Therefore, most favorable conditions should be created during the germination and initial establishment stages. In case the salt tolerance of the crop at the germination stage is different than the average values given in Table 4, it is proper to use the threshold salinity levels at the germination stage.

Soil sodicity

Similar to soil salinity, some plants are more tolerant to soil sodicity than others. Excess exchangeable sodium percentage, high pH, lack of calcium, and the resulting poor physical properties are the main causes for reduction in yields due to soil sodicity (Gupta, et al., 1995). The critical exchangeable sodium percentage (ESP) values for 10, 25, and 50 percent yield reduction for some crops are presented in Table 5 (adopted from Mehrotra and Gangwar, 1964).

However, Gupta (1990) pointed out that these critical tolerance limits of ESP should be used on tentative basis because of the following reasons:

- Mehrotra and Gangwar (1964) did not maintained the complete control on soluble calcium. Tolerance of some crops, which were grown in later years after reclamation presumably with more calcium in the soil solution, may be under estimated; and

- ESP in the top 15cm soil profile was used as the criterion for tolerance. However, the effective depth of root zone in some crops may be different.

Table 5. Critical limits of soil ESP at three yield reduction levels of 10, 25 and 50 percent for different crops (Mehrotra and Gangwar, 1964)).

Crop	Critical limits of soil ESP for different yield reduction levels				
	Threshold	Slope	10%	25%	50%
Onion	9.8	2.2	14.3	22.5	32.3
Barley	8.5	3.5	29.5	42.0	52.2
Garlic	9.5	1.8	15.0	23.0	35.5
Peas	7.7	4.1	9.8	12.5	18.5
Wheat	16.4	2.1	22.5	33.3	46.0

Quality of irrigation water

Generally, where high sodium adsorption ratio (SAR) in irrigation water is accompanied with high EC, it is primarily the effect of salinity, which governs the plant growth. But where salinity is low and SAR and/or residual sodium carbonate (RSC) is high in irrigation water, plant growth is likely to be regulated more by the sodicity problem[4] (Gupta, 1990). Table 6 lists the salinity limits of irrigation waters at three yield reduction levels of 10, 25 and 50 percent for crops irrigated under natural field conditions on different types of soils at different places widely differing in agro-climatic conditions in India (adopted after Gupta and Yadav, 1986). The critical limits, as mentioned in Table 6, are obviously for EC_i but these will closely identify with EC_e when LF is close to 0.30 to 0.35 (Gupta, 1990). Therefore, these critical limits may decrease for lower leaching fractions and increase for higher leaching fractions.

Generally, when sprinkler uses saline water to grow the established crop, salt deposits on leaves may adversely affect some crops (Maas, 1985). Deciduous fruit trees are especially susceptible (Hoffman et al., 1980). Table 7 describes the relative susceptibility of crops to leaf injury from saline water applied with sprinkler irrigation application system during the daytime irrigation (after Maas, 1990; and Rhoades et al., 1992). Susceptibility of plants to leaf injury from saline sprinkled water depends on leaf characteristics affecting rate of absorption and is not generally correlated with tolerance to soil salinity. The degree of spray injury varies with weather conditions, especially the water deficit of the atmosphere. Visible symptoms may appear suddenly following irrigations when the weather is hot and dry. Increased frequency of sprinkling, in addition to

[4] Such information will be more valuable under the Indus Basin of Pakistan conditions where 70% of tubewells pump sodic water, and the application of this pumped sodic water has already resulted in high degree of sodicity in the irrigated agricultural soils (Qureshi and Barrett-Lennard, 1998).

increased temperature and evaporation, leads to increase the salt concentration in the leaves due to adsorption, and results in leaf damage. However, irrigation at night (or any other low evaporation period) minimizes the salt concentration in the leaves due to adsorption (Kruse, 1995).

Table 6. Critical limits of salinity of irrigation water for at three yield reduction levels of 10, 25 and 50 percent (Gupta and Yadev, 1986).

Crop	Soil texture	Location	Critical limits of EC_i for different yield reduction levels		
			10%	25%	50%
Onion	Sand	Bapatla	2.5	5.4	10.2
	Sandy loam	Agra	1.7	2.8	5.1
Barley	Sandy loam	Agra	7.6	16.2	
Maize	Sandy loam	Agra	2.7	5.5	10.3
	Black clay	Indore	1.2	3.1	9.5
Sorghum	Sandy loam	Agra	8.3	12.8	17.8
	Black clay	Dharwad	2.4	6.5	13.4
Wheat	Sand (dune)	Karnal	12.5	16.0	
	Sandy loam	Agra	9.0	12.9	17.6
	Sandy loam	Karnal	8.5	11.0	14.2
	Sandy loam	Hissar	7.4	10.2	13.1
	Loamy sand	Jodhpur	7.3	10.3	13.6
	Black clay	Dharwad	2.7	7.4	18.0
	Black clay	Indore	3.8	8.8	

Table 7. **Relative susceptibility of crops to leaf injury from saline sprinkled water (after Mass 1990; and Rhoades et al., 1992).**

Na or Cl concentration of irrigation water causing leaf injury ($dS.m^{-1}$)		
< 0.5	0.5 – 1.0	1.0 – 2.0
Citrus	Potato	Alfalfa
	Tomato	Barley
		Maize
		Sorghum

Crop evapotranspiration under stress conditions

The estimation of crop evapotranspiration plays pivotal role in developing guidelines for irrigation scheduling with skimmed groundwater. Both, the soil water and salinity stresses may reduce root water uptake and limit crop evapotranspiration.

Soil water stress condition

After irrigation and/or heavy rainfall, the soil drains from saturated soil moisture storage (θ_S) till the field capacity is reached. The soil moisture in the root zone decreases from the soil moisture storage at field capacity (θ_{FC}) as a result of evapotranspiration. The total soil moisture storage (TSMS) can be defined as the difference in soil moisture storage at the field capacity and wilting point. However, the TSMS is not available to fulfill the crop evaporative demand (CED). The proportion of TSMS that a crop can extract from the root zone without reduction in the actual evapotranspiration (AET) is the available soil moisture storage (ASMS). At ASMS, the soil moisture has a high potential, is relatively free to move and is easily taken up by the plant roots.

As the ASMS decreases, the potential level also decreases, and the soil moisture becomes more strongly bound by capillary and adsorption forces to the soil matrix, and is more difficult to extract. When the ASMS drops below the threshold level, the soil moisture can no longer be transported quickly enough towards the roots to respond to the CED and the crop begins to experience "water stress". Actually, the remaining soil moisture is held to the soil particles with greater force, lowering its potential level and making it more difficult for the plant to extract it. Eventually, the potential level reaches a point where the crop can no longer extract the remaining soil moisture. This point is known as wilting point. Therefore, the plants wilt permanently when wilting point is reached.

Therefore, the TSMS is the difference between the soil moisture at field capacity and wilting point, and the ASMS is the difference between the soil moisture at field capacity and threshold level (Allen et al., 1998):

$$\mathrm{TSMS} = \left(\theta_{FC} - \theta_{WP}\right) Z_r \qquad (10)$$

$$\text{ASMS} = (\theta_{FC} - \theta_{TH}) Z_r = p[\text{TSMS}] \quad (11)$$

where, TSMS is the total soil moisture storage in the root zone (mm), θ_{FC} is the soil moisture at field capacity ($m^3.m^{-3}$), θ_{WP} is the soil moisture at wilting point ($m^3.m^{-3}$), θ_{TH} is the soil moisture at threshold level ($m^3.m^{-3}$), Z_r is the (effective or total as the case may be) depth of root zone (mm), and p is the average fraction of TSMS that can be depleted from the root zone before reduction in AET occurs.

The magnitude of TSMS depends on the soil type and the depth of the root zone. Typical ranges for field capacity and wilting point are given in Table 8 for various soil types (Allen et al., 1998).

Table 8. Typical soil moisture characteristics for different soil types (Allen et al., 1998).

Soil Type (USDA soil texture classification)	θ_{FC} ($m^3.m^{-3}$)	θ_{WP} ($m^3.m^{-3}$)
Sand	0.07	0.05
Loamy sand	0.11	0.03
Sandy loam	0.18	0.06
Loam	0.20	0.07
Silt loam	0.22	0.09
Silt	0.28	0.12
Silt clay loam	0.30	0.17
Silty clay	0.30	0.17
Clay	0.32	0.20

Ranges of the maximum depth of root zone for various crops are listed in Table 9 (Allen et al., 1998). The values for p are also listed in Table 9 (Allen et al., 1998). The fraction p is a function of the crop evaporative demand (CED). A numerical approximation for adjusting p at different CED is given as under (Allen et al., 1998):

$$p = p\,(\text{from Table 9}) + 0.04\,(5 - \text{CED}) \quad (12)$$

where, the adjusted p is limited to $0.1 \le p \le 0.8$, and CED is in $mm.day^{-1}$. The value of p is also a function of the soil type. Generally, it can be stated that the p values listed in Table 9 can be reduced by 5-10% for clay, while for sand, they can be increased by 5-10% (Allen et al., 1998).

Soil moisture content in the root zone can also be expressed by root zone depletion, D_r, i.e., reduction in soil moisture relative to field capacity (Figure 2). At field capacity, D_r is zero. When soil moisture is extracted by evapotranspiration, the D_r increases and stress will be induced when D_r becomes equal to ASMS. After the root zone depletion exceeds ASMS, the root zone depletion is high enough to limit evapotranspiration to less than potential values and the crop evapotranspiration begins to decrease in proportion to the amount of soil moisture remaining in the root zone.

Therefore, for D_r > ASMS, the transpiration reduction factor, K_s, is given as (Allen et al., 1998):

Table 9. Ranges of the maximum depth of root zone[5] for various crops (Allen et al., 1998).

Crop	Maximum depth of root zone (m)	P (for EED ≈ 5 $mm.day^{-1}$)
Vegetables		
Onion	0.3-0.6	0.30
Radishes	0.3-0.5	0.30
Spinach	0.3-0.5	0.20
Cauliflower	0.4-0.7	0.45
Potato	0.4-0.6	0.35
Carrots	0.5-1.0	0.35
Turnip	0.5-1.0	0.50
Tomato	0.7-1.5	0.40
Peas	0.6-1.0	0.35
Cereals		
Barley	1.0-1.5	0.55
Maize	1.0-1.7	0.55
Sorghum	1.0-2.0	0.55
Wheat	1.0-1.5	0.55
Fodder		
Alfalfa	1.0-2.0	0.55
Sugarcane	1.2-2.0	0.65
Citrus		
At 20% canopy	0.8-1.1	0.50
At 50% canopy	1.1-1.5	0.50
At 70% canopy	1.2-1.5	0.50

$$K_s = \frac{TSMS - D_r}{TSMS - ASMS} = \frac{TSMS - D_r}{(1-p)TSMS} \qquad (13)$$

where, K_s is a dimensionless transpiration reduction factor (0-1), D_r is root zone depletion (mm), TSMS is the total soil moisture storage in the root zone (mm), and p is the average fraction of TSMS that can be depleted from the root zone before reduction in AET occurs.

[5] The larger values are for soils having no significant layering or other characteristics that can restrict rooting depth.

The estimation of K_s requires a daily water balance computation for the root zone. For soil moisture limiting conditions, $K_s < 1$. Where there is no soil moisture stress, $K_s = 1$. However, K_s describes the effect of water stress on crop transpiration rather than evaporation from soil surface. But, in situations where evaporation from soil surface is not a large component of AET, the following equation provides reasonable results (Allen et al., 1998):

$$AET = K_s K_c (CED) \tag{14}$$

where, K_c is the basal crop coefficient.

Combined soil water and salinity stress condition

Soil salinity can reduce AET by reducing root water uptake. The presence of salts in the soil increase osmotic potential and hence additional force is required for the crop to extract water from the soil.

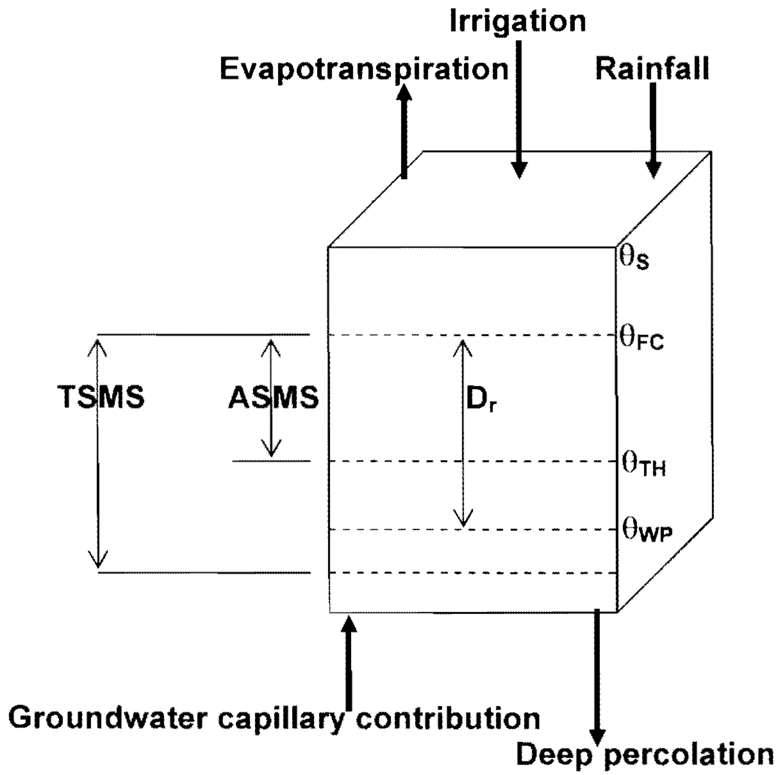

Figure 2. Representation of soil moisture components in the root zone.

Allen et al., (1998) presented an approximate function that predicts the reduction in AET caused by the stresses induced by soil salinity and soil water. The function was derived by combining crop yield-AET equation from Doorenbos and Kassam (1979) with crop yield-salinity equation from Ayers and Westcot, (1985). The resulting equation provides an approximation of the reduction in AET expected under various soil water and salinity stress conditions:

- When Dr < ASMS and $EC_e > EC_{e\ threshold}$

$$K_s = 1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\ threshold}\right) \qquad (15)$$

Where, K_y is a dimensionless yield response factor that describes the reduction in relative crop yield according to the reduction in AET caused by soil moisture stress, EC_e represents the average salinity in the root zone (dS.m^{-1}), $EC_{e\ threshold}$ is the threshold electrical conductivity of the saturation soil water extract where crop yields remain at potential levels (dS.m^{-1}), and b is the slope having units of % reduction in yield per unit increase in EC_e beyond $EC_{e\ threshold}$. The K_y values are crop-specific and may vary over the growing season. Table 10 provides values of K_y for common agricultural crops (adopted from Doorenbos and Kassam, 1979). However, the seasonal value for K_y is generally used to predict the reduction in AET, and Table 10 also gives the seasonal values of K_y for common agricultural crops.

Table 10. Yield response functions for common agricultural crops (Doorenbos and Kassam, 1979).

Crops	K_y (-)				
	Vegetative period	Flowering period	Yield formation period	Ripening period	Seasonal value
Vegetables					
Onion	0.45		0.80	0.30	1.1
Potato	0.45		0.70	0.20	1.1
Tomato	0.40	1.10	0.80	0.40	1.05
Peas	0.20	0.90	0.70	0.20	1.15
Cereals					
Maize	0.40	1.50	0.50	0.20	1.25
Sorghum	0.20	0.55	0.45	0.20	0.9
Wheat	0.20	0.60	0.50		1.15
Fodder					
Alfalfa	0.7-1.1				1.1
Sugarcane	0.75		0.50	0.10	1.2
Citrus					1.1-1.3

For many crops, the seasonal K_y is nearly 1. Therefore, for crops where K_y is unknown, its value may be considered equal to 1 (or equal to the K_y for a crop that has similar behaviour). The values of b for common agricultural crops are already mentioned in Table 3 and 4. It is clear from both of these tables that the values of b are site-specific, and therefore requires local calibration.

- When Dr > ASMS and $EC_e > EC_{e\ threshold}$

$$K_s = \left(1 - \frac{b}{K_y 100}\left(EC_e - EC_{e\ threshold}\right)\right)\left(\frac{TSMS - D_r}{(1-p)TSMS}\right) \qquad (16)$$

Where, EC_e represents the average salinity in the root zone.

Limitations in using Equation (15) and (16) are listed as under:

- It is assumed that "p" do not change with increasing salinity. This may or may not be a good assumption for some crops.
- Generally, the seasonal value for K_y is used to predict the reduction in AET, but the impact of salinity on plant growth, crop yield, and AET is a time-integrated process.
- Both of these equations are suggested as only approximate estimates of salinity impacts on AET, and represent general effects of salinity on AET as occurring over an extended period of time (weeks, months, seasons or years). These equations are not expected to be accurate for predicting AET for specific days.
- These equations may not be valid at high salinity, where the linear relationships between EC_e, crop yield and Ks may not hold.
- However, the use of these equations is generally considered valid when $EC_e < EC_{e\ threshold} + 50/b$.

Groundwater capillary contribution

In determining net soil moisture depletion, knowledge about the groundwater capillary contribution is needed. Due to capillary rise, groundwater evaporates at the land surface and/or utilized by the plants, leaving most of the salts behind in the root zone. The assessment of maximum groundwater capillary contribution can help to control the extent to which salinity may develop in the root zone. The main factor that affects the maximum groundwater capillary contribution is the depth to watertable. Other factors include: (i) the soil texture, (ii) the quality of groundwater, and (iii) the root zone salinity resulting from capillary rise (after Gupta and Gupta, 1997).

Soil texture and depth to watertable

Skaggs (1980) stated that the depth to watertable from 1.0m to 1.5m provided the maximum contribution from groundwater for a wide range of soil types. The shallower depth to watertable applies to sandy soils. Generally, the rate of maximum groundwater capillary flux decreases more steeply in a coarse than a fine textured soil with the increase in depth to watertable (Hoffman, 1995). Gupta and Gupta (1997) have given the following relationship to estimate the effect of soil texture on the maximum groundwater capillary flux that reaches the soil surface, q_{max} (mm.day^{-1}):

$$q_{max} = \frac{Aa}{d^n} \qquad (17)$$

where, d is the depth to watertable (mm), a (mm^{n+1}.day^{-1}) and n (-) are coefficients, and A is also a coefficient which depends on n. Some typical values of these coefficients for different soil textural classes are presented in Table 11 (adopted after Gupta and Gupta, 1997).

Table 11. Effect of soil texture on the maximum groundwater capillary flux that reaches the soil surface (Gupta and Gupta, 1997).

Soil texture	d (cm)	n (-)	a (cm^{n+1}.day^{-1})	A (-)	q_{max} (cm.day^{-1})
Sand	100	4	1.7×10^8	1.52	2.58
Fine sandy loam	100	3	3.2×10^5	1.76	0.56
Loam	100	2	1.7×10^3	2.46	0.42
Clay	100	2	1.1×10^3	2.46	0.27

With maximum contribution from the shallow groundwater, the salt tolerance of the crop and the availability of shallow groundwater limit total water use. In the cropped areas under shallow watertable conditions, the zone of salt build up in the root zone depends mainly upon the fraction of groundwater that reaches the soil surface. The rate of groundwater capillary flux that reaches the soil surface decreases with the increase in depth to watertable. Therefore, for maintaining favorable water and salt balance in the root zone, understanding and knowledge of the maximum groundwater capillary flux is most important.

Quality of groundwater and depth to watertable

Salinity in the root zone increases with decreasing depth to watertable. However, the salinity in the root zone increases with increasing salinity of the groundwater at the same depth to watertable.

Gupta and Gupta (1997) reported that the effect of groundwater quality on the salinity in the root zone was more pronounced at shallower than at deeper depths to watertables. When the depth to watertable is at or above 1.2m, the concentration of salts at the soil surface is significantly related to the quality of the groundwater.

Root zone salinity resulting from capillary rise

For the same amount of water applied through irrigation or drawn from the shallow watertable to meet the crop water requirement, the distribution of salts in the root zone in both the cases would be entirely different (Asghar, 1996). In case of water applied through irrigation, the salinity in the root zone increases with the increase in depth as the salts move downward resulting from leaching. Whereas, in case of water drawn from the shallow watertable, the salinity at or near the soil surface increases resulting from the upward movement of the salts from the groundwater due to capillary rise, and there is no leaching in this case.

Generally, the density of crop roots decreases with the depth, and the most active crop roots are concentrated in the top of the root zone (Salam and Wahid, 1993). Therefore, as a result of salt distribution patterns under irrigation and shallow watertable conditions, crops suffer more in the latter case than in the former case, even if the average salinity in the root zone is the same (Gupta and Gupta, 1997).

Management practices for root zone salinity control

Irrigation management practices

A summary of the factors affecting the selection of irrigation application systems for irrigating with saline water is presented in Table 12 (adopted from Kruse, 1995). However, management of different irrigation application systems also depends on the crops' characteristics, planting practices, and tillage practices. Timing of irrigation is another important factor when the management of different irrigation application systems includes salinity considerations too (Kruse, 1995).

Crops' characteristics: All crops do not tolerate salinity equally well at different growth stages. Therefore, management of different irrigation application systems often depends on the crops' characteristics. Sprinkler can apply small depths of water uniformly, keeping the seed bed adequately moist and salt-free. Therefore, sprinklers are sometimes used to geminate and establish salt-sensitive crops and surface irrigation is then used to grow the established crop (Robinson and Mayberry, 1976).

Planting practices: For the drip/trickle irrigation application systems, if emitters are located near individual plants of perennial crops, salts tend to move away from the roots and concentrate in intermediate soil areas (Kruse, 1995). To avoid problems with germination or salt stress on seedlings of annual crops, it is important to plant precisely where previous drip/trickle irrigation application systems has left low concentrations of salt. Planting seeds of furrow-irrigated crops on the sides of beds may keep seedlings out of the most saline soil zone (Gupta and Gupta, 1997).

Table 12. Factors affecting selection of irrigation application systems for irrigating with saline water (adopted from Kruse, 1995).

Systems	Crops	Salt distribution pattern	Leaching effectiveness
Surface	Most crops	Leaves salt in the root zone	Leaching requires more water than for methods with intermittent applications.
Furrow	Row crops	High in beds between furrows	Similar to above.
Corrugation	Close-growing crops	High in areas between corrugations unless entire field is inundated.	Similar to above
Sprinkler	Most crops	No salt concentrations in the root zone, if system designed and managed well	Uniform leaching, and can be used to leach salt accumulation left by other irrigation methods.
Drip/Trickle	High value crops	Salts concentrates at outer fringes of the soil profile wetted by each emitter.	Soil profile wetted by each emitter is well leached.

Tillage practices: Deep surface cultivation can redistribute salt in the soil profile. The practice should be evaluated on a small land area before cultivating the entire fields (Singh, 1993; and Gupta and Gupta, 1997). Minimum tillage practices allow furrow formed for one crop to remain undisturbed for the next. However, organic residue left on the soil surface by minimum tillage practices may present a problem for furrow irrigation (Tanji, 1995).

Timing of irrigation: The timing of irrigation needs special consideration while using saline water for irrigation, as soil water stress may occur more quickly and, add to the soil salinity stress, cause immediate crop damage. Proper timing of irrigation can help to avoid low levels of soil moisture that cause salts in the soil solution to become highly concentrated.

Frequent irrigation reduces soil water stress and soil salinity stress caused by the saline irrigation water. Frequent irrigation also keeps the salts moving through and away from the root zone. If irrigation is applied frequently, each irrigation must be light. Shainberg and Shalhevet (1984) reviewed the effect of the frequency of saline water application on yield, and concluded that higher frequencies result in higher yield. Irrigation intervals of several days to allow for internal drainage are unnecessary because large soil volumes are not saturated.

Light irrigation can seldom be applied as uniformly with surface irrigation application systems as with the sprinkler, drip/trickle irrigation application systems. Drip and trickle irrigation application systems help in maintaining suitable matric potential in the root zones of plants, even with saline water application (Kruse, 1995). If drip/trickle irrigation application systems cause high salt concentrations to accumulate near the soil surface, unexpected rainfall can move the salt down into the root zone. Irrigation should be scheduled during or after rainfall to leach the salts before they damage the crop (Somani, 1993).

Use of different quality waters: In many situations, the canal water supplies are either not assured or in short supply such that farmers are often forced to pump groundwater of varying quality for crop production. This calls for using the limited quantities of non-saline (canal) waters most judiciously in combination with poor quality waters. For the combined use of relatively-fresh water (saline and/or sodic) and freshwater (canal water), two options are available to the farmers: (i) blending of different quality water supplies, and (ii) cyclic use of different quality waters.

Though blending of saline water and canal water may not always be beneficial to crop production, as it does not reduce the total salt load (Gupta, 1990). However, it improves the stream size that would enhance the uniformity in irrigation by the surface irrigation application systems and allows for more area to be planted (Gupta and Minhas, 1993). The process, however, may lead to improvement in the quality of sodic waters. It seems that blending of canal water with the pumped groundwater of high RSC and low calcium concentration would result in under-saturation with respect to calcite. Consequently, the blended water on irrigation will have greater tendency to pick up calcium through dissolution of native calcite from soils. There is, however, no direct evidence available at present to support the above proposition.

However, the blending of sodic water (having high RSC and low calcium concentration) and canal water can dilute water to acceptable quality and can broaden the choice of crops. Therefore, it may be considered as an effective solution to the water quality problems if facilities for blending are available and the blending ratio is known. Thus, to achieve this, a prior information of the salinity threshold values of the crops to be grown in sequence and salt build up in the root zone with use of a given quality water during the cropping seasons is essential.

The strategy of cyclic use of different quality waters involves the use of canal water at the most sensitive growth stages/crops grown and saline water is used at other stages such that the effects of the resultant soil salinity build up can be minimized. In most of the crops, the germination and vegetative periods have been identified as the most sensitive stage to salinity. A failure at these stages will lead to poor crop stand and considerable reduction in yields (Rhoades, 1987).

Leaching practices: When watertable is deep, leaching of salts from the soils irrigated with saline water could be accomplished by ponding.

But, when watertable is shallow, care should be taken while applying such leaching practice. However, the timing of leaching does not appear to be critical provided crop tolerance is not exceeded for extended period of time. Where water is available only during a specific period, there is no alternative than to go in for leaching only at the time of water availability (Somani, 1993).

Ponding may be continuos or intermittent. Somani and Totawar (1993) described that half as much water was required with intermittent ponding as with continuos ponding for the same reduction in root zone salinity. Actually, intermittent ponding reduces bypass flow through macro pores because it creates the predominance of unsaturated flow in the root zone. Intermittent ponding also provides ample time for salts (adsorbed/absorbed) to dissolve in the soil water, and these dissolve salts, now, requires less water for the reduction of root zone salinity.

Rainfall management practices

As irrigation waters are applied to soils supporting crop growth, the crop removes much of the water and leaves a majority of the soluble salts behind. Maximum utilization of rainfall is the single most important practice for agricultural areas irrigated with the saline water. Actually, rainfall helps in the leaching of accumulated salts, because it is the best quality water available for leaching of soluble salts from the root zone. Therefore, every possible effort should be made to make effective use of rainfall (Somani, 1993).

Rainfall in many cases may be adequate to accomplish all the needed leaching. Where rainfall is not expected to be adequate, the initial leaching should be carried out with saline groundwater before the onset of monsoon. The monsoon will, then, help in leaching the salts further with high efficiency. Moreover, a pre-monsoon leaching coincides with the period when watertable is deep to facilitate leaching of salts to a greater depth while delaying upward rise of salts (Prathapar and Qureshi, 1999).

Shallow watertable management practices

Crop use of shallow groundwater: The amount of shallow groundwater available to a crop can be determined by knowing: (i) the depth to watertable, (ii) the quality of the groundwater, (iii) the depth of root zone, and (iv) the salt tolerance of the plants. The more closely the depth of root zone and crop salt tolerance match the depth to watertable and the quality of the groundwater, the more likely the plants are to extract groundwater (Kruse, 1995).

The reduction in crop yields with shallow watertables may be attributed to limited aeration and restricted root volumes, while reductions under deeper watertable depths might be due to limited groundwater capillary contribution to the roots (Tanji, 1995).

Management of soil salinity: The potential for increasing salinity in the root zone increases if significant quantities of saline groundwater are used (Hoffman and van Genuchten, 1983). Therefore, while maximizing the use of groundwater without a loss in productivity due to salinity, care should be taken to manage the root zone salinity below the salt tolerance level of the crop. Rhoades (1984) suggested that leaching should take place during a fallow period or early in the growing season, when crop's root system is shallow and the water demand is small and the watertable is relatively deeper to avoid raising the watertable to the extent that the crop is damaged.

Irrigation scheduling: Irrigation scheduling under shallow watertable conditions can be designed either for (i) the maximum contribution from the shallow groundwater, (ii) the little or no groundwater contribution, or (iii) the intermediate value of groundwater use. However, good irrigation management allows the crop to use shallow groundwater.

With maximum groundwater contributions, irrigation can best be scheduled using plant-based measures. The depth of irrigation water to apply is estimated from soil moisture measurements. The optimum time to irrigate is at the highest stress level that does not reduce yield. Irrigation at lower stress levels would result in more frequent irrigation, more deep percolation and less contribution to AET from the watertable. The time of first irrigation is critical for unrestricted plant growth and root development. Soil salinity measurements at the end of the previous irrigation season can be used to calculate the leaching required for re-establishing a favorable soil salinity profile for the next growing season. Rainfall plus *rouni* can provide necessary leaching. Most type of irrigation application systems allows this management (Kruse, 1995).

To obtain little or no groundwater contribution, management is somewhat simpler. Only irrigation and rainfall supplies the crop water requirement. Deep percolation is minimized. Daily irrigation application, to compensate water used by the crop, can do this most easily. The daily irrigation application also prevents significant contribution from the watertable. Periodic leaching during the season can prevent the buildup of salts in the root zone. An irrigation application system that can provide highly uniform applications is required. Sprinkler or drip/trickle irrigation systems are preferred (Kruse, 1995).

Lack of data on the plant's temporal extraction of groundwater presents an obstacle to obtaining an intermediate amount of groundwater use, which can achieved on a seasonal basis by eliminating the final irrigation of the season. Hutmacher et al., (1986) found that wheat grown in the presence of a shallow saline watertable did not suffer a reduction in yield when the last irrigation of the season was eliminated.

Monitoring and evaluation of management practices

The estimation of water and salt balances are used to monitor and evaluate different management practices. The water and salt balances are so closely related that it is not possible to separate them out (Gupta and Gupta, 1997).

Under irrigated agricultural areas where annual salinisation–desalinization cycles occur, the amount of salts stored in the root zone fluctuates continually. The goal of successful water and salt management for salinity control in the root zone should be to maintain this fluctuation within limits that neither allow excess drainage nor reduce the growth of the crops (Hoffman, 1995).

PRELIMINARY FRAMEWORK

A framework is defined as a set of inter-linked actions aimed at achieving desired objectives. The preliminary framework for irrigation scheduling with skimmed groundwater aimed at root zone salinity management comprises a set of inter-linked actions for which the following guidelines are provided:

- What is the basic set of information required?
- When to irrigate?
- How much to irrigate?
- How to irrigate?
- When to adjust?
- How much to adjust?
- How to adjust?

These guidelines could be defined as tools and yardsticks that play pivotal role in decision making regarding timing and amount of irrigation water applications aimed at managing root zone salinity and productivity of land and water without any adverse environmental effects.

What is the basic set of information required?

The following basic set of information identifies benchmark data to be utilized for implementing irrigation scheduling with skimmed groundwater aimed at root zone salinity management:

- Soil characteristics (texture, and soil moisture characteristics);
- Crop characteristics (effective and total depth of root zone, crop evapotranspiration behaviour at different growth stages, yield response functions; and salt tolerance characteristics); and
- Irrigation water quality.

When to irrigate?

The decision regarding the timing of irrigation depends upon the soil moisture depletion and soil salinity levels in the effective depth of root zone. The effect of root zone salinity is considered while keeping in mind the crop salts tolerance characteristics and yield response functions. The soil moisture depletion level in the effective root zone is an indicator for deciding the timing of irrigation. In the context of irrigation with skimmed groundwater, the management allowed deficit (MAD) for a predetermined salinity level is defined as the soil moisture depletion where root zone salinity is either equal or less than the crop salts tolerance. Figure 3 presents the flow diagram that can be used while deciding the timing of irrigation.

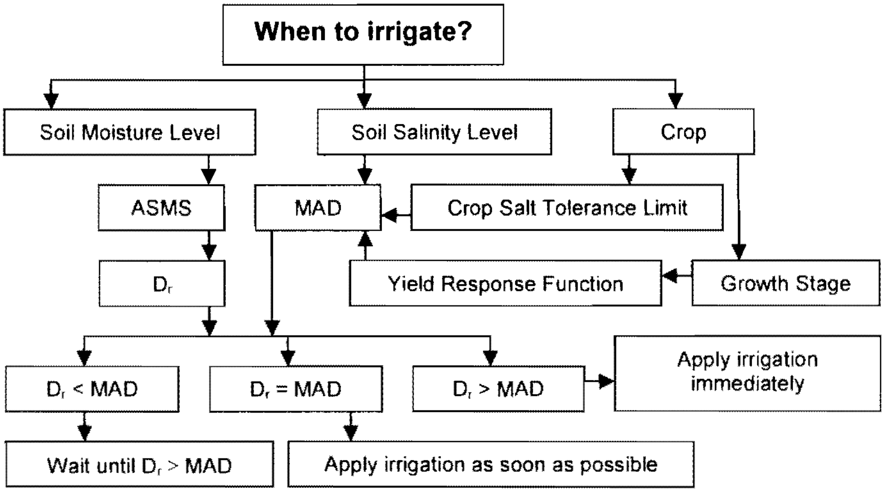

Figure 3. Flow diagram for deciding the timing of irrigation.

How much to irrigate?

Figure 4 presents the flow diagram for deciding the amount of irrigation water application. The decision regarding the amount of irrigation water, aimed at managing root zone salinity and productivity of land and water, is made by using two different strategies representing different watertable conditions.

Under shallow watertable conditions where the root zone falls within the groundwater capillary reach, the depth of irrigation water to be applied (D_{ir}) depends upon the net soil moisture depletion (D_r^*). Practically, the D_r^* is estimated by using tensiometers at different depths in the total root zone, as the soil moisture depletion level in the total root zone is an indicator for deciding the amount of irrigation. For the given application efficiency (AE), the D_{ir} is estimated as:

$$D_{ir} = \left(\frac{D_r^*}{AE} \right) \qquad (18)$$

Under deep watertable conditions where the root zone falls beyond the groundwater capillary reach, the D_{ir} depends upon the AET. Equation (14) is used to calculate daily AET. Where there is no soil moisture stress or soil salinity stress, the transpiration reduction factor, K_s, is equal to 1. When the soil moisture stress affecting the AET, then K_s is calculated by using Equation (13). However, under soil salinity stress, K_s is calculated either by using Equation (15) or Equation (16), depending upon the soil moisture and salinity stress conditions. The relationships between the AET and water stress, and the AET and the combined stresses of water and salinity are depicted in Figure 5 and 6, respectively. If n is the number of days between two irrigations, then for the given application efficiency (AE), the D_{ir} is estimated as:

$$D_{ir} = \left(\frac{\sum_{i=1}^{i=n} AET_i}{AE} \right) \qquad (19)$$

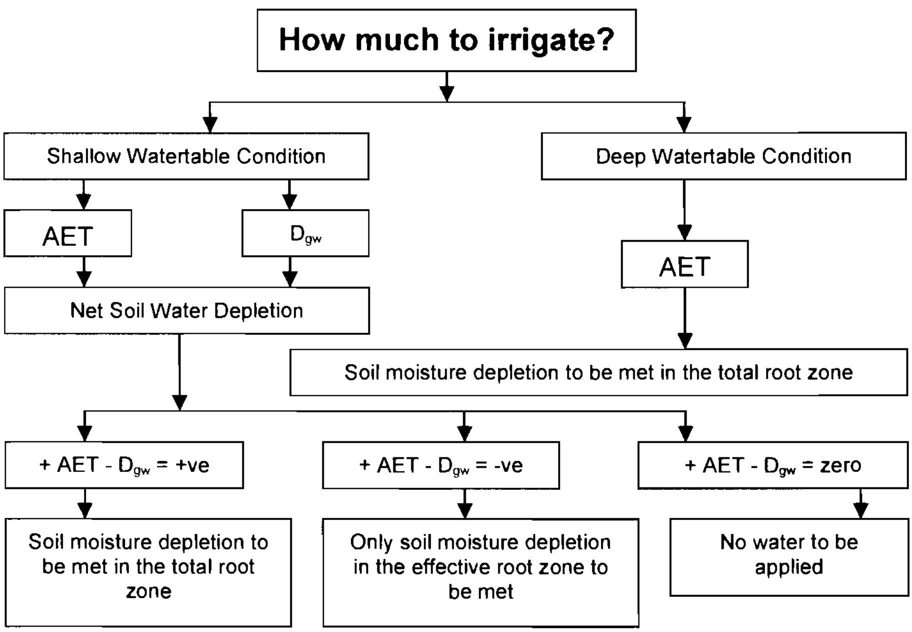

Figure 4. Flow diagram for deciding the amount of irrigation.

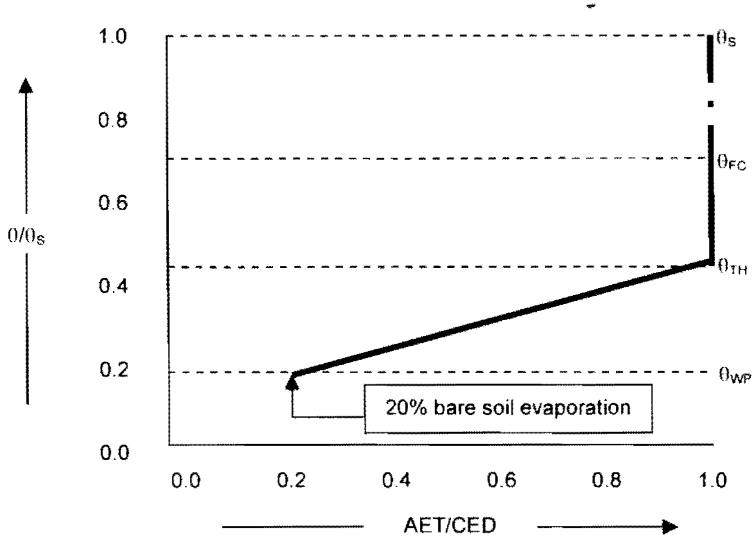

Figure 5. **The actual evapotranspiration behaviour under soil moisture stress.**

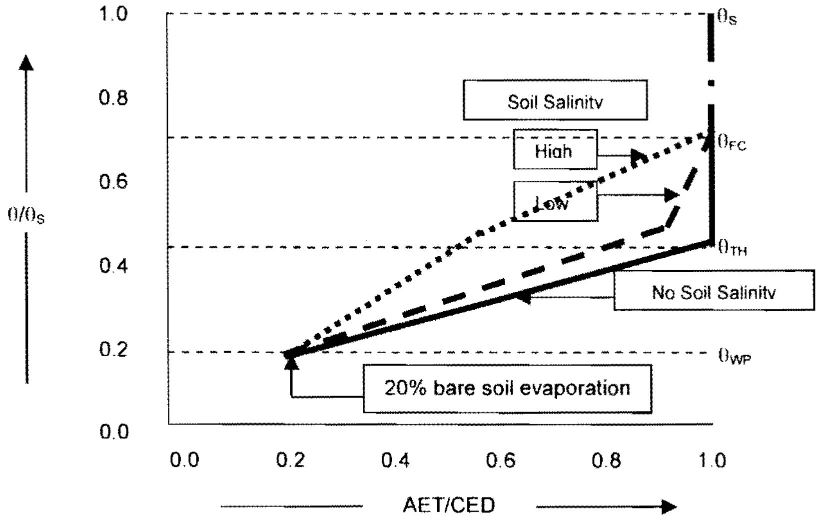

Figure 6. **The actual evapotranspiration behaviour under soil moisture and salinity stresses.**

How to irrigate?

Irrigation application systems play a vital role in increasing the irrigation performance of the irrigation scheduling practices. The following discussion relates that how different irrigation application systems apply the desired depth of water to the crop field aimed at managing root zone salinity and productivity of land and water without any adverse environmental effects.

Pressurized irrigation application systems

For the following reasons, the pressurized irrigation application system is preferred over surface irrigation:

- It helps to apply exact amount of water as determined by "how much to irrigation?", as there is no concern for a spatially varied flow due to soil surface conditions; and
- Light irrigation[6] is possible with these kind of irrigation application systems, where as it is difficult with surface irrigation.

However, the following constraints limit the scope of pressurized irrigation application systems:

- Initial capital cost is high;
- High operation and maintenance costs;
- Energy dependence;
- Skilled labour requirement;
- Traditionally non-familiar water application system;
- Requirement of silt-free water; and
- Field application constraints.

Innovative irrigation application systems

The innovative irrigation application systems provides the following opportunities:

- Relative to surface irrigation, the innovative irrigation application systems enhance capability of the farmer to control water applications;
- Relative to pressurized irrigation application systems, farmers[7]are more familiar with innovative irrigation application systems;
- Low initial, operation and maintenance costs;
- Less skilled labour requirement;
- Benefits derived by using silt-loaded water; and

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[6] Light irrigation is needed when there is a minimum crop water requirement. This is also a requirement when groundwater contribution meets the crop water requirement under shallow watertable condition to dilute the salinity in the effective root zone.

[7] Old generation of farmers (from Indian Punjab) used to use low discharges (6-14 lps) by using innovative irrigation application systems.

- Less energy requirements.

However, the following constraints may limit the scope of innovative irrigation application systems:

- Specialized machinery requirement; and
- Field application constraints.

Pressurized and surface irrigation application systems

The combined use of pressurized and surface irrigation application systems has the following benefits:

- The application of pressurized irrigation application system can help to geminate and establish salt-sensitive crops by applying small depths of water uniformly, and by keeping the seed bed adequately moist and salt-free; and
- Surface irrigation can help in growing the established crop, as when pressurized irrigation application system uses relatively-fresh water to grow the established crop, salt deposits on leaves may adversely affect some crops.

When to adjust?

The estimation of water and salt balances is used for assessing the need for any adjustments regarding the timing and amount of irrigation water applications aimed at managing root zone salinity and productivity of land and water. The monitoring and evaluation of this preliminary framework will also help in developing guidelines for irrigation scheduling with skimmed groundwater.

For the agricultural areas irrigated with canal water but also have shallow watertable with thin lenses of relatively-fresh groundwater overlying the native saline groundwater, the components of water and salt balances under the cropped lands, irrigated with canal and/or skimming groundwater, are summarized in Table 13.

Table 13. The components of water and salt balances under agricultural lands irrigated with skimming source pressurized irrigation application systems.

IN	OUT
Components of Water Balance	
• Canal water irrigation	• Evapotranspiration
• Rainfall	• Lateral groundwater contribution
• Groundwater capillary contribution	• Deep percolation
• Lateral groundwater contribution	
• Skimmed water irrigation	
Components of Salt Balance	
• Canal water irrigation	• Lateral groundwater contribution
• Groundwater capillary contribution	• Deep percolation
• Lateral groundwater contribution	• Precipitation
• Skimmed water irrigation	
• Fertilizer/Amendments	

Water balance

Irrigation (canal and/or skimmed water), rainfall, and groundwater capillary contribution add water to the root zone, and compensate the root zone depletion. Evapotranspiration and deep percolation remove soil moisture from the root zone and increases the root zone depletion.

The schematic representation of the different components of water balance in the root zone is depicted in Figure 7.

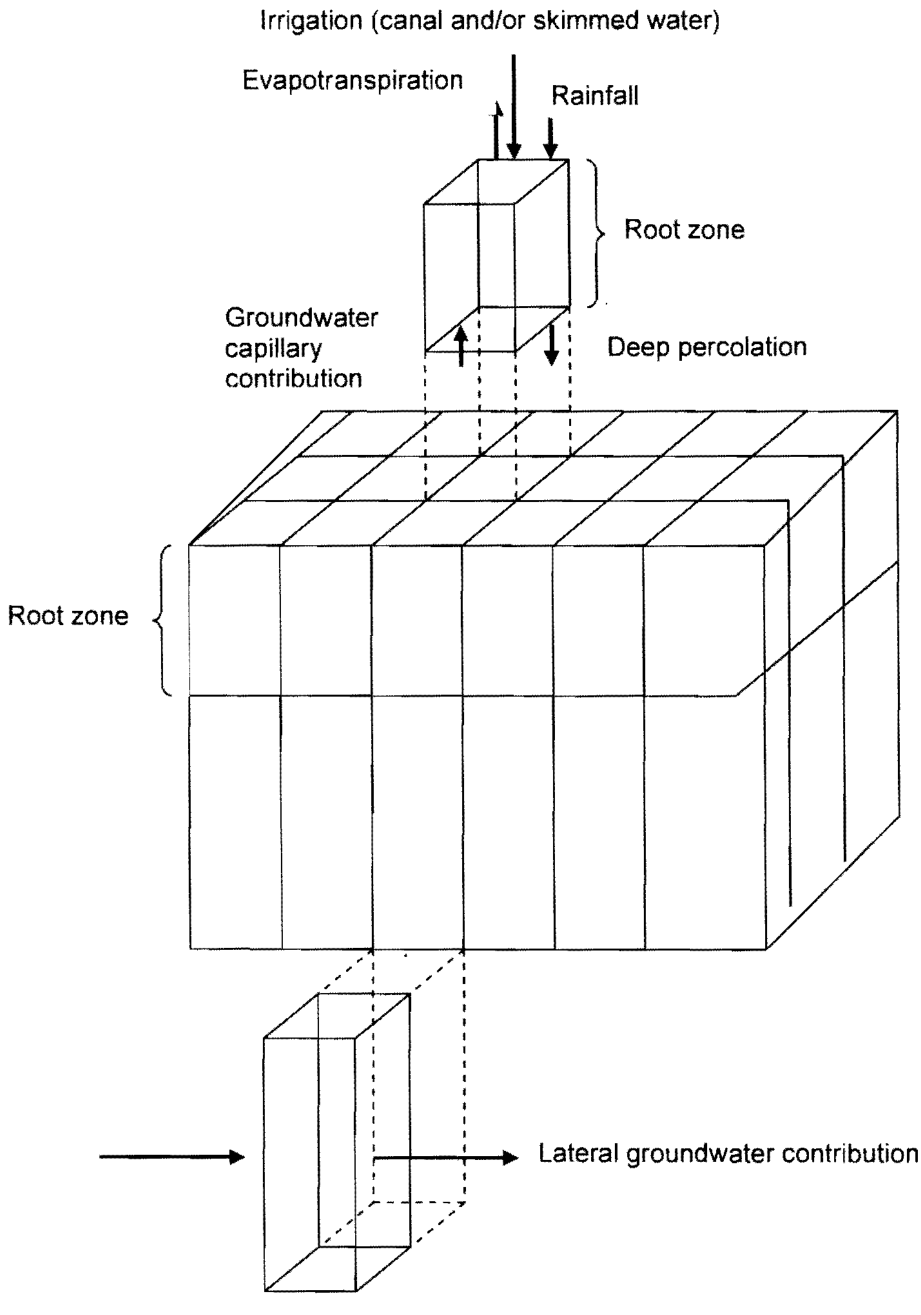

Figure 7. **Schematic presentation showing different components of salt and water balance under the irrigated agricultural areas.**

The water balance expressed in terms of root zone depletion is:

$$D_r = D_i + D_c + D_p + D_s + D_{gw} - D_d - AET \pm D_l \quad (20)$$

Where, D_r is the root zone depletion (mm), D_i is the initial soil moisture (or initial depletion) in the root zone (mm), D_c is the depth of canal water irrigation (mm), D_p is the rainfall (mm), D_s is the depth of skimmed water irrigation (mm), D_{gw} is the groundwater capillary contribution (mm), D_d is the deep percolation (mm), AET is the actual evapotranspiration (mm), and D_l is the net lateral groundwater contribution (mm).

To initiate the water balance in the root zone, D_i should be estimated. The initial depletion in the root zone can be estimated from the average soil moisture in the root zone (θ_i) by:

$$D_i = (\theta_{FC} - \theta_i) Z_r \quad (21)$$

If the amount of D_p is less than 0.2 times the CED, then it can usually be ignored in the water balance calculations as it is normally entirely evaporated. The D_c and D_s are the average irrigation (of canal and skimmed water, respectively) depth expressed for the entire field surface. The amount of D_{gw} depends upon the soil type, the depth to watertable, and the wetness of the root zone. The D_{gw} can normally be ignored when the watertable is more than 1.5m below the bottom of the root zone.

It is assumed that the water can be stored in the root zone until field capacity is reached. Although following irrigation or heavy rainfall, the soil moisture in the root zone might exceed field capacity, but the amount of water above field capacity is assumed to be lost the same day by D_d, following by AET for that day. As long as the soil moisture in the root zone is below field capacity, the soil will not drain ($D_d = 0$).

Salt balance

The salt storage in the root zone of irrigated areas can be worked out by various components of water balance (as already described in Table 13) by multiplying with their respective salt concentrations. The resulting salt storage or leaching from the root zone can be mathematically written as follows:

$$S_s = D_i S_i + D_c(EC_c) + D_s(EC_s) + D_{gw}(EC_{gw}) - D_d(EC_d) \pm D_l(EC_l) \quad (22)$$

where, S_s is the change in salt storage in the root zone, S_i is the salt initially present in the root zone, $D_c(EC_c)$ is the salt added through canal water irrigation, $D_s(EC_s)$ is the salt added by the application of skimmed water, $D_{gw}(EC_{gw})$ is the salt added by the groundwater capillary contribution, $D_d(EC_d)$ is the salt removed from the root zone as a result of deep percolation, $D_l(EC_l)$ is the addition/removal of salts due to net lateral groundwater contribution.

It should be remembered that irrigation may induce mineral dissolution (S_m), Salts may also be added directly to the root zone such as through application of amendments (S_a) and/or fertilizer (S_f). On the other hand, salts are removed from the root zone by crops (S_c). Salts may also be precipitated (S_p). However, if salts in the root zone are considered as conservative salts, S_m and S_p can be neglected. But still, it may not be possible to neglect S_a, S_f, and S_c without causing wide differences in the calculated and actual salt balance.

Moreover, unknown parameters in Equation (22) add another dimension to the complexity in the use of this equation. For example, D_{gw}, D_d, D_l, EC_{gw}, EC_d, and EC_l are not exactly known. Therefore, it is recommended to monitor the salt status of irrigated lands to work out the salt regime. It would not only help in diagnosing the problem, but also help in identifying factors that are responsible for salt accumulation in the root zone or those which would help to leach down the salts from the root zone. Therefore, while preparing the salt balance sheet, causes, rate and degree of accumulation or leaching should also be worked out.

The salt balance in the root zone is usually determined for short-term duration (monthly basis), medium-term duration (seasonal basis) and long-term duration (annual basis). The following salt balance situations may occur:

- Balance in favour of leaching (if S_s is negative)
- Stable salt balance (if S_s is zero)
- Balance in favour of salt accumulation (if S_s is positive)

In irrigated agriculture, time frame within which salt balance of the root zone is determined, could be very important not only from the point of view of saving water but also for the crop health. The time frame would normally depend upon how fast the salinity build-up occurs in the root zone. For salt sensitive crops irrigated with relatively-fresh water, salt balance at the each irrigation event may be important. For salt tolerant crops, it may be possible to allow build-up of salt in the root zone, and carry out leaching at appropriate time when water is available.

How to adjust?

While developing guidelines for irrigation scheduling with skimmed groundwater under the given management practices, there is a need of developing site-specific and crop-specific relationships between the salinity in the root zone and the factors affecting salinity in the root zone while irrigating with relatively-fresh water. These relationships develop linkages between the net soil moisture depletion and the threshold levels of the root zone salinity at different stages of the crop growth under different soil moisture depletion levels. These relationships would provide ample scope to manage salinity in the root zone at a pre-decided level.

Under shallow watertable condition

The relationships between the salinity in the effective root zone and following parameters will help in deciding "how to adjust?" for the given site-specific and crop-specific conditions:

- Depth to watertable;
- Groundwater capillary contribution;
- Quality of groundwater; and
- Soil texture.

Under deep watertable condition

The relationships between the salinity in the total root zone and following parameters will help in deciding "how to adjust?" for the given site-specific and crop-specific conditions:

- Quality of irrigation water;
- Number of irrigations;
- Soil texture;
- Leaching fraction; and
- Rainfall.

How much to adjust?

Based on the site-specific and crop-specific relationships, the adjustments will be quantified while developing guidelines for irrigation scheduling with skimmed groundwater. For instance, if MAD in the preliminary framework for irrigation scheduling with skimmed groundwater was taken equal to 50% soil moisture depletion. And, the monitoring and evaluation of the preliminary framework showed that it should be reduced to say 35% soil moisture depletion for managing salinity in the root zone and for enhancing the productivity of land and water under the given management practices.

In developing preliminary framework for irrigation scheduling with skimmed groundwater, the following information indicates that are we following irrigation scheduling practices right?

- What is the basic set of information required?
- When to irrigate?
- How much to irrigate?
- How to irrigate?

While the following information reflects that are we following right irrigation scheduling practices?

- When to adjust?
- How much to adjust?
- How to adjust?

Generally, it is concluded that the methodology of developing such guidelines is formulated so that it can be generalized for uses in other similar aquifers in the Indus Basin of Pakistan.

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