TR - 22

LEACHING REQUIREMENT OF AGRICULTURAL LAND AND STUDY OF MOVEMENT OF SALTS

SATISH CHANDRA
DIRECTOR

STUDY GROUP

B. SONI
G.C. MISHRA

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247 667 (U.P.) INDIA

1986-87

CONTENTS

Page No

LIST OF FIGURES

LIST OF TABLES

SUMMARY

One of the major problems associated with irrigated agriculture land is accumulation of salt in the soil which results in low productivity if proper water management practices are not adopted. Irrigation water contains salts from 0.1 to 4 metric tons/1000m^3 and are generally applied to soils at annual application rates of 10,000 to 15,000 m^3/ha. The concentration of soluble salts in soils increases as the applied water is removed by evaporation and transpiration. Evapotranspiration creates a suction force that produces an upward flow of water and salt into the root zone from lower soil depth. To prevent harmful accumulation of salts in soils, an additional amount of water, over and above that required to meet crop evapotranspiration needs, must be passed through the root zone for leaching of salts.

A model has been formulated using Green and Ampt equation for estimation of infiltration volume from different soil layers. The soil system was divided into 4 layers of thickness 50 cm each having some initial salt concentration and soil moisture. When irrigation water having low salt concentration is applied to soil system for leaching, the solute movement from 1st layer to 2nd layer, 2nd layer to 3drd layer, likewise have been determined using salt balance approach. The time required to fill the different layers have been estimated from the initation of the infiltration. The variation of salt concentration with time and depth have been estimated and presented.

Break-through curves have been presented for different layers. It is found that when soil is near saturation and when one pore volume of water passes through the top soil of 50 cm thickness, the solute concentration predicted by the present model is 0.54. For an ideal break-through curve, 50 per cent displacement of salts take place at one pore volume. Thus the salt prediction by the present model is satisfactory. It has been said that 1.2 to 2.0 times the pore volume replacement of the soil solution should remove about 80 per cent of the original salt content. From this study, it is found that when water twice the pore volume is passed through the 50 cm of the top soil, 76 percent of salt is removed.

For a silty loam soil, it is found that for wheat crop when 50 cm of irrigation water having salt concentration 1.00 mm ho/cm passes through the soil having initial solute concentration 13.00 mm ho/cm, the salt upto 106 cm depth has been leached out.

1.0 INTRODUCTION

One of the major problems associated with irrigated agriculture land is accumulation of salt in the soil which results in low productivity if proper water management practices are not adopted. The primary sources of soluble salts in agricultural soils are i) irrigation water, ii) salt deposits present in soil parent materials when the soils were brought into production, iii) agricultural drainage waters (both surface and subsurface) draining from upper-lying to lower-lying lands, and iv) shallow water tables. The secondary sources of salts include: i) fertilizers, agricultural amendments, poultry manures applied to soils, and ii) weathering soil minerals.

Irrigation water may contain from 0.1 to 4 metric tons of salts/1000 m^3 and are generally applied to soils at annual application rates of 10,000 to 15,000 m^3/ha (Rhoades, 1974). Thus from 0.1 to 60 metric tons of salts per hectare may be added to irrigated soils annually. These salts are added to those already present in soils. While it may possible to eliminate the salts from the other major salts sources, it is not yet economically possible to eliminate salt from irrigation water.

The concentration of soluble salts in soils increases as the applied water is removed by evaporation and transpiration. Evapotranspiration creates a suction force that may produce an upward flow of water and salt into the root zone from lower soil depth. This is the process where shallow saline water table exist. The main factors responsible for creating salinity problems are i) salt content of irrigation water, ii) the soil, iii) ground water, iv) water table depth, v) climatic conditions, and vi) water management practices.

Since soluble salts are transported in soils in the water phase, their distribution and removal are controllable by water management. The only economical means of controlling salt salinity is to apply a flow of low salt water through the root zone and to maintain a net downward flux. When water containing a low salt content, different from the soil solution, is passed through the soil, the concentration and composition of salts in the drainage water will gradually change according to the processes that occur in the soil i.e. dispersion, mixing of the solution, physical absorbtion, ion exchange.

To prevent harmful accumulation of salts in soils, an additional amount of water, over and above that required to meet crop evapotranspiration needs, must be passed through the root zone while irrigating. This additional amount of water added to the soil to keep a favourable salt balance and termed as Leaching Requirement (L_r). It is defined as fraction of the applied water (irrigation + rainfall) leached below the root zone to prevent any loss in crop productivity from an excess accumulation of soluble salts. The concept is most useful when applied to steady state water flow rates or to total depth of water used for irrigation and leaching over a long period of time. Any non-uniformity in water application, in addition, to the L_r must be considered in the design and management of irrigation drainage system to meet the drainage requirement.

An estimation of leaching requirement has been made from a salt balance model approach. The model has been applied to a soil profile, divided into different layers, having some initial salt concentration and soil moisture. When irrigation water having low salt concentration, is applied for leaching, the solute movement from first layer to second layer, second layer to third layer, likewise, have been determined. In the present study, Green and Ampt infiltration equation has been used for estimation of volume of water infiltrated from different layers. The time required to fill the 1st layer, 2nd layer, 3rd layer and 4th layer have been estimated from the initation of the infiltration. The salt concentration at each layers, before and after it is filled with water have been determined.

2.0 REVIEW

Leaching is an essential part of the reclamation process i.e. the process of reclaiming of salts. The amount of water required for leaching purposes depends upon the initial salinity of the soil and the final salinity level desired. Bower and Fireman (1957) at U.S. Salinity Laboratory observed that under ponding condition, 50 percent of the salt in the root zone can be removed by leaching with 15 cm of water for each 30 cm of the root zone affected whereas about 80 percent can be removed with 30 cm water per 30 cm depth of soil. To remove 90 percent of salt, 60 cm of water must be used for 30 cm depth of soil to be leached. Thus if average salinity in 90 cm depth of the soil is 40 mm hos/cm and it is desired to reduced it to 8 mm hos/cm i.e. by 80 percent, then 90 cm of water must be applied.

Russian workers have made interesting contribution to the study of leaching process in solonchak-like soils. Early empirical equations for determining the leaching requirements for reaclaiming saline soils were of the following types:

$$M = FC - m + n\,(FC) \qquad \ldots \quad (2.1)$$

where,

M = Amount of water needed in m^3/ha,

FC = Field capacity in m^3/ha,

m = Water reserve in the soil prior to leaching in m^3/ha, and

n = Coefficient varying from 0.5 to 2.0 depending on the salanity and texture of the soil

Kovda (1961) included two other factors, viz texture of the soil and ground water characteristics, besides the salinity in determing the quantity of water required for leaching and gave the equation:

$$y = n_1 . n_2 . n_3 . x\ (400) \pm 100 \qquad \ldots (2.2)$$

where,

y = depth (mm) of leaching water,

x = mean salt content (%) in 2 m soil profile,

n_1 = coefficient for soil texture (sand 0.5; loam 1.0; clay 2),

n_2 = water table depth (less than 2 m = 3; 2 - 5 m = 1.5; 7 - 10 m = 1.0), and

n_3 = ground-water salinity (weak = 1; strong = 2; very strong = 3)

The above formula do not take into account the type of salinity found in the soils. An equation which takes into account the kind of salts to be leached out is further developed:

$$M = K \log \left(\frac{S_1}{S_2}\right)^a \qquad \ldots (2.3)$$

where,

M = Amount of water needed in M^3/ha,

K = Coefficient of variation,

S_1 = Soil salinity in percent or tonnes/ha

S_2 = Tolerable soil salinity in the same units, and

a = Coefficient for type of salinity ($Cl = 0.90 - 0.95$; $SO_4 - Cl = 1.0$; $SO_4 - CO_3 = 1.1 - 1.2$)

The relationship between leaching requirement and soil salinity was found not be linear but logarithmic in nature, particularly when the total salt content rises above 2 percent. Thus the following facts emerge regarding the leaching requirements of purely saline soils. The leaching requirement will be high in the same proportion as :

i) The initial moisture content of the soil is in relation to its field capacity;

ii) The texture of the soil becomes more clayey;

iii) The total salinity in the soil increases;

iv) The proportion of chlorides in the total salts in the soil goes up, and

v) The ground-waters become shallower and more mineralized.

For saline-alkali soils the quantity of water needed for leaching is also related to the kind of amendment used.

Hill (1961) has pointed out that the soil solution varies from the surface to the lower limit of the root zone and also varies with the time since soil has been irrigated. The minimum average concentration of the soil solutions at all horizons in the root zone shortly after irrigation should be about equal to the arithmetic average of the concentration of the irrigation water and of the water percolated from the root zone. This average has been taken as an index of the effective concentration (C_s) of the soil solution i.e.

$$C_s = \frac{C_a + C_p}{2}$$

or $$C_p = 2\,C_s - C_a \qquad \dots (2.4)$$

where,

C_a = Salt concentration of the applied irrigation water, and

C_p = Salt concentration from the percolated water from the root zone

However for salt balance, the quantity of salt carried away by the percolated water below the root zone should be equal to the quantity of the same salt in the water applied to the surface of the land.

If P = Volume of percolated water,

C_a = Salt concentration of irrigation water,

C_p = Salt concentration of the water draining out of the root zone,

D_a = Quantity of water applied to the land, in depth per unit area, and

D_o = Consumptive use requirement of the crop

Then by defnition

$$D_a C_a = P\, C_P$$

$$\text{or} \quad \frac{P}{D_a} = \frac{C_a}{C_P} \qquad \ldots (2.5)$$

Assuming $P = (D_a - D_o)$

Then

$$D_a C_a = D_a C_P - D_o C_P$$

$$\frac{D_a}{D_o} = \frac{C_P}{C_P - C_a}$$

Substituting $C_P = 2C_s - C_a$, $\quad \dfrac{D_a}{D_o} = \dfrac{2C_s - C_a}{2C_a - 2C_a} \qquad \ldots (2.6)$

Hill (1961) concluded that one of the primary purpose of leaching is the removal of prior accumulation of salt to restore the productivity of land. This requires that the large volume of water must be applied on the land surface, must be percolated through the soil and finally the percolated water which has picked up the accumulated salt must be disposed of as drainage effluent. Secondly, a salt balance should be maintained in the root zone of irrigated lands. This requires the passage of enough water through the soil to carry away the salts that are brought to the lands while irrigating. Thirdly the another function of leaching is to control the salinity of the soil solution from which the plants derive water.

Bower (1969) has given a simple procedure for calculating the amount of water necessary for leaching salt out of the root zone or irrigated fields to maintain salt balance. The simplest expression for salt balance is

$$D_i C_i = D_d C_d \qquad \ldots (2.7)$$

where,

D_i = depth of irrigation water applied,

D_d = depth of water draining from the root zone

C_i = salt concentration of irrigation water, and

C_d = concentration of the salt water draining from the boundary of the root zone.

Also

$$D_i = D_e + D_d \qquad \ldots (2.8)$$

where,

D_e = amount of water needed for evapotranspiration, and

D_d = amount of water needed for leaching the soil profile.

The procedure was based on the leaching efficiency, E_l which was defined as the fraction of the water draining from the lower boundary of the root zone that has the same salt concentration as the soil water in the root zone. The remaining fraction $(1 - E_1)$ is then considered to consist of irrigation water that has passed unchanged through the larger cracks and pores of the soil. Also, the procedure for calculating the amount of water, D_d, that should be applied in addition to that necessary for evapotranspiration of the crop, D_e, to avoid salt accumulation in the root zone were given and represented by term E_u, maximum irrigation efficiency.

$$E_u = \frac{D_e}{D_i} \times 100 \qquad \ldots (2.9)$$

$$= \frac{D_e}{D_e + D_d} \times 100$$

The parameter, E_u, was represented by the efficiency of water utilization since it reflects the portion of the irrigation water that can be utilized by the crop for evapotranspiration. An equation is derived which expresses, E_u, in terms of the leaching efficiency, the salt concentration of irrigation water and the maximum permissible salt concentration of the soil water in the root zone.

$$E_u = \frac{100.E_1.(C_s - C_i)}{C_i + E_1(C_s - C_i)} \qquad \ldots (2.10)$$

The volume of E_1 must be selected on the basis of the prevailing soils in the irrigated area. The value of E_1 ranges from about 0.2 for fine textured soils to about 0.6 for coarse textured soils. The effect of various parameters, E_1, C_s and C_i on E_u have also been estimated.

Schilfgaarde et al. (1974) expressed the leaching requirement as the ratio between the volume of water required for drainage, V_{dw} and irrigation water V_{iw} and the time period considered must be large enough so that steady state conditions can be assumed. Also, LR, can beexpressed in terms of electrical conductivity, EC.

$$LR = \frac{V_{dw}}{V_{iw}} = \frac{EC_{iw}}{EC_{dw}} \qquad \ldots (2.11)$$

This relationship has been used to determine a lower limit for the amount of irrigation water needed. The permissible level of EC_{dw} is estimated from crop tolerance data in order to obtain a value of LR. The purpose of this study was to reevaluate the aforementioned concepts in view of recent research findings. It was observed that irrigation can be managed in such a manner that crop yields are maintained, while the total salt discharge in the drainage water is substantially less than often found in current practice. He further concluded that reevaluation of established crop salt tolerance data, recent advances in understanding of soil chemistry and application of soil physics principles leads to a proposed management system for irrigation that can result in significant reductions in the amount of salt discharged for irrigation projects.

Hoffman (1985) reviewed the steady state models for predicting leaching requirement and compared with experimentally measured values. Five models considered for predicting leaching requirement were based on mass balance of water and salt.

The leaching fraction (L) defined as the steady state ratio of water leaving the profile as drainage to that applied can be expressed as

$$L = \frac{d_d}{d_a} = \frac{C_a}{C_d} \quad \ldots (2.12)$$

in which C_a = mean salt concentration of the applied water, and

C_d = salt concentration of water leaving the profile as drainage.

The leaching requirement was expressed as

$$L_r = \frac{d_d{}^*}{d_a} = \frac{C_a}{C_d{}^*} \quad \ldots (2.13)$$

in which subscript* distinguishes required value from actual values. Because electrical conductivity (σ) is easily measured and is linearly related to thesalt concentration of a relatively dilute soil solution, the L_r was expressed as

$$L_r = \sigma a / \sigma d^* \quad \ldots (2.14)$$

Hoffman (1985) conducted four independent studies to measure the leaching requirement of a number of crops with irrigation water of different salt concentrations. All of the models require salt tolerance data. Salt tolerance and leaching requirement experiments were conducted on sets of lysimeters. The linear correlations between the measured and predicted values of L_r for each model have been estimated. He concluded that the exponential model, based upon an exponential pattern of crop water uptake, correlated best with the measured values but underestimated at high L_r. The highest correlation coefficient between predicted and measured values of L_r was 0.67 indicating that none of the models is completely satisfactory.

Ayers and Westcot (1985) estimated the leaching requirement considering the irrigation water salinity (EC_w) and the crop tolerance to soil salinity (EC_e). The water salinity data can be obtained from Laboratory analysis while the EC_e value can be tabulated from appropriate crop tolerance data. The leaching requirement for a particular crop can be estimated by the following relationship:

$$LR = \frac{EC_w}{5(EC_e) - EC_w} \qquad \text{... (2.15)}$$

where,

LR = the minimum leaching requirement needed to control salt within the tolerance of the crop,

EC_w = salinity of the applied irrigation water ds/m, and

EC_e = average crop tolerance to soil salinity.

The total annual depth of water needed to be applied to meet both the crop demand and leaching requirement can be estimated by the relationship

$$AW = \frac{ET}{1 - LR} \qquad \ldots (2.16)$$

where,

AW = depth of applied water (mm/year),

ET = total annual crop demand (mm/year), and

LR = leaching requirement expressed as a fraction.

Smith and Hancock (1986) also reviewed the various methods available for estimation of leaching requirement and presented their inadequacies. The basic concept of leaching was reanalysed and a simple physicaly based equation was developed which only involves the concentration of the applied water C_i and a desired soil water salinity C_s*. The proposed equation was

$$\frac{C_s^*}{C_i} = \frac{1_n(LR)}{LR - 1} \qquad \ldots (2.17)$$

The above equation involves only the basic physics of the leaching process with the single assumption that the weighted average soil salinity C_s can be equated to the empirically derived salt concentration C_s*. The appropriate C_s* value can be determined for the desired crop yield reduction from the existing salt tolerance guidelines of Mass and Hoffman (1977).

Theoretical models to illustrate the process of solute movement through porous media have been developed and presented by Van Der Molen (1973). He considered the following cases for estimation of solute movement :

(1) Single reservoir,

(2) Single reservoir with by-pass,

(3) Series of reservoirs and

(4) Continuous column.

It is assumed that there is no chemical interaction between solute, solution and soil.

2.1 The Single Reservoir

Consider an open reservoir V filled with sea water of concentration C_o. The salt water is gradually replaced by fresh water (C_i) and during this process the level of reservoir is kept constant. The following two extreme leaching conditions may be distinguished:

One in which no mixing of fresh water with sea water occurs and the other in which complete mixing takes place. If no mixing occurs, the sea water is merely displaced by fresh water at a rate Q (Piston Flow). At the time $T = \frac{V}{Q}$, when all the sea water has been replaced by fresh water, the actual effluent concentration (C_u) will abruptly change from $C_u = C_o$ to $C_u = C_i$. But under natural conditions piston flow will seldom occur.

If complete mixing takes place in the reservoir and if the volume of water in the reservoir is constant, the salt balance equation

$$C_i Q dt = C_u Q dt + V.dc \qquad \dots (2.18)$$

where,

C = the average salt concentration of reservoir at any time t,

C_i = the salt concentration of the influent and

C_u = the salt concentration of effluent when mixing is complete,

C_u = C and the Eq. (2.18) becomes after rearrangemtnt

$$\frac{dc}{C-C_i} = - \frac{Q}{V} dt$$

Integrating and applying the condition $C = C_o$ at time t = Q, and C at time t yield the relatiuonship

$$C_u = C = C_i + (C_o - C_i) e^{-\frac{t}{T}} \qquad \dots (2.19)$$

Where $T = \frac{V}{Q}$ and C_o is the original salt concentration of the reservoir solution.

Studies show the equation (2.19) applies equally well to the root zone of a soil being subjected to leaching when the root zone is considered a single reservoir with complete mixing.

2.2 The Reservoir With Bypass

In soils, irrigation or rainwater is unlikely to mix completely with the woil solution. Part of it may move through the large pores (Cracks, rootholes) and arrive at the lower boundary of the rootzone without any mixing. This is expressed by

$$C_u = fC + (1-f)C_i \qquad \dots (2.20)$$

which states that a fraction (f) of the incoming water will flow out of the root zone with concentration C equal to that of the solution in soil and a fraction (1-f) will have the concentration same as that of the influent. Combining equation (2.18) and (2.20) and solving the resulting differential equation with the initial condition $C = C_o$ when $t = 0$,

$$C = C_i + (C_o - C_i)\, e^{-\frac{ft}{T}} \qquad \ldots (2.21)$$

in which f is referred as the leaching efficiency. For $C_i = 0$ equation (2.21) becomes

$$C = C_o \; e^{-\frac{ft}{T}} \qquad \ldots (2.22)$$

2.3 The Series of Reservoirs

If the process of leaching is examined more closely it will be clear that complete mixing over the entire depth of rootzone (often 1 m or more) is not very probable. To account for the limited range over which the mixing is effective it may be supposed that the soil consists of different reservoirs. Each reservoir receives the outflow from the overlying one; in each reservoir mixing is complete. For irrigation water with salt concentration C_i and for a leaching efficiency f, the following expressions are found for the salt concentrations in successive reservoirs of equal volume.

1st reservoir : $C_I = C_i + (C_o - C_i)\, e^{-\frac{ft}{T}}$

2nd reservoir : $C_{II} = C_i + (C_o - C_i)\,(1 + \frac{ft}{T})\, e^{-\frac{ft}{T}}$

3rd reservoir : $C_{III} = C_i + (C_o - C_i)\,(1 + \frac{ft}{T} + \frac{f^2 t^2}{2T^2})\, e^{-\frac{ft}{t}}$

4th reservoir : $C_{IV} = C_i + (C_o - C_i)\,(1 + \frac{ft}{T} + \frac{f^2 t^2}{2T^2} + \frac{f^3 t^3}{6T^3})\, e^{-\frac{ft}{T}}$

Nth reservoir : $C_N = C_i + (C_o - C_i)\, e^{-\frac{ft}{T}} \sum_{n=0}^{n=N-1} (1 + \frac{f^n t^n}{\underline{\lfloor n}\; T^n}) \qquad \ldots (2.23)$

2.4 Continuous Column

The soil profile is in fact not made up of several separated reservoirs, but forms a continuous column. Mixing takes place at every depth, but is effective over a limited range only.

Glueckauf (1949) developed a theory about behaviour of such columns. For desalinization of a soil, he found the following expression :

$$C = \frac{1}{2} C_o [\text{erfc}\ (\frac{V-ax}{2V})\ \sqrt{(\frac{V}{ak})}\ - e^{\frac{x}{k}}\ \text{erfc}(\frac{V+ax}{2V})\ \sqrt{\frac{V}{ak}})] \quad \ldots (2.24)$$

where,

C_o = Original salt concentration in soil moisture

V = depth of water percolated since the beginning of leaching

a = Volume fraction of soil filled with water

x = depth

2K = effective mixing length

$$\text{erfc}(z) = 1-\text{erf}(z) \frac{2}{\sqrt{\pi}} \int_x^z e^{-u^2} du \quad \ldots (2.25)$$

Putting $p = \frac{V}{ax}$ and $N = \frac{x}{2k}$, the equation (2.25) forms into

$$C = \frac{1}{2} C_o\ [\text{erfc}\ (\frac{p-1}{2p} \sqrt{N})\ - e^{2N}\ \text{erfc}\ (\frac{p+1}{\sqrt{2p}} \sqrt{N})\ ] \quad \ldots (2.26)$$

It is also found that in practice the difference between the two methods i.e. series of reservoir and continuous column in negligible.

In this study, Green and Ampt equation has been used for estimation of volume of water infiltrated into different layers.

Salt balance approach has been used for modelling the salt concentration and its variation with time and depth have been estimated.

3.0 PROBLEM DEFINITION

Let the top soil of thickness 'D' be divided into number of n layers of thickness D/n. Each layer can be assumed to act as a reservoir. Let Θ_i and C_o represent the initial soil moisture and initial solute concentration in each reservoir. When irrigation water, containing a salt less than that of the soil solution is passed through the soil, the concentration of salts in each reservoir changes gradually depending on the volume of water infiltrated from the beginning of the infiltration. It is aimed to estimate the variation of salt concentration with respect to depth and time due to application of irrigation water of depth 'H' at top of the 1st reservoir and to determine the leaching requirement of given soil,(Figure 1).

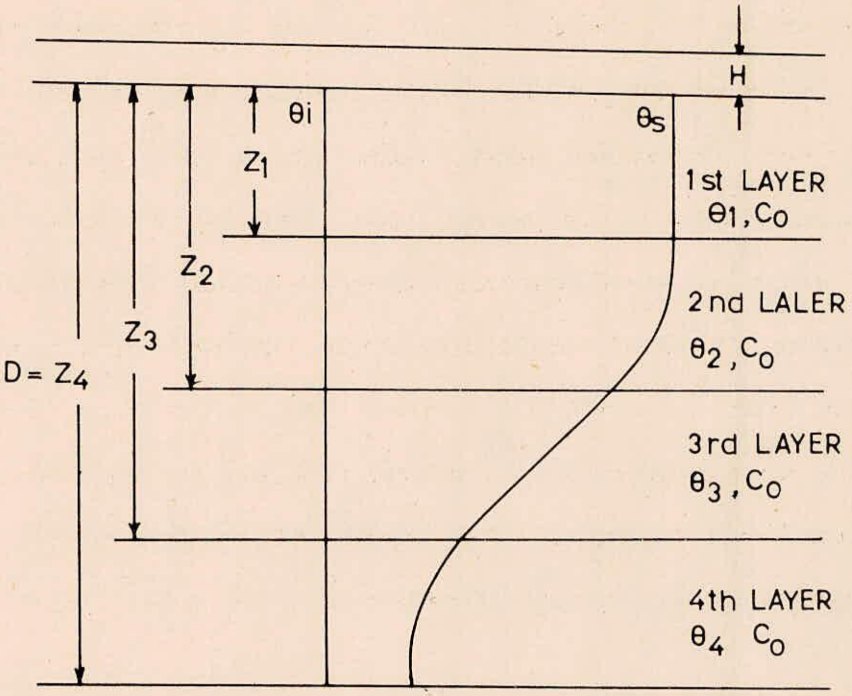

Fig. 1 : Variation of soil moisture with respect to depth for a typical soil

4.0 METHODOLOGY

4.1 Green and Ampt Infiltration Equation

The Green and Ampt infiltration equation has been used for estimation of infiltration rate. The equation is based on the assumption of a sharp wetting front, a constant hydraulic conductivity in the wetted zone and a constant negative water pressure at the wetting front.

Assuming

θ_i = initial soil moisture content,

θ_s = soil moisture at saturation,

H_f = capillary pressure head at the wetting front, m

H = depth of water applied at the top surface in the beginning, m

Z_f = distance from the surface to wetting front, m and

$\bar{K}$ = hydraulic conductivity in the wetted zone, m/hour

The rate of infiltration I at time t can be expressed as

$$I = (\theta_s - \theta_i) \frac{dz_f}{dt} \qquad \ldots (4.1)$$

Applying Darcy law to the wetted zone, the Green and Ampt equation can be written as

$$\frac{\bar{K}.(H_f + Z_f + H - \int_o^t I(\tau) d\tau)}{Z_f} = (\theta_s - \theta_i) \frac{dZ_f}{dt} \qquad \ldots (4.2)$$

upto any time t, $\int_{0}^{t} I(\tau)\, d\tau = w$, Hence,

$$\frac{\bar{K}.(H_f + Z_f + H - w)}{Z_f} = (\theta_s - \theta_i)\frac{dZ_f}{dt} \qquad ..(4.3)$$

Multiplying and dividing left hand term by $(\theta_s - \theta_i)$

$$\bar{K}\ \frac{(H_f+H)\ (\theta_s-\theta_i) + Z_f(\theta_s-\theta_i) - w(\theta_s-\theta_i)}{Z_f(\theta_s-\theta_i)} = \frac{dw}{dt}$$

$$\bar{K}\ \frac{(H_f+H)\ (\theta_s-\theta_i) + w(1-\theta_s+\theta_i)}{w} = \frac{dw}{dt}$$

where $w = Z_f\ (\theta_s-\theta_i)$

Rearranging,

$$\bar{K}.dt = \frac{w.dw}{(H_f+H)\ (\theta_s-\theta_i) + w(1-\theta_s-\theta_i)} \qquad ...\ (4.4)$$

Multiplying both sides by term $(1-\theta_s-\theta_i)$

$$\bar{K}\ (1-\theta_s-\theta_i)\ dt = \frac{w(1-\theta_s+\theta_i)dw}{(H_f+H)\ (\theta_s-\theta_i) + w(1-\theta_s+\theta_i)} \qquad ...(4.5)$$

Adding and substracting term $(H_f+H)\ (\theta_s-\theta_i)$ at the numerator of the term on the right

$$\bar{K}\ (1-\theta_s+\theta_i)dt = \frac{\left[\ w(1-\theta_s+\theta_i) + (H_f+H)\ (\theta_s-\theta_i) - (H_f+H)(\theta_s-\theta_i)\right]\ dw}{(H_f+H)\ (\theta_s-\theta_i) + w(1-\theta_s+\theta_i)}$$

or

$$\bar{K}\ (1-\theta_s+\theta_i)dt = dw - \frac{(H_f+H)\ (\theta_s-\theta_i)dw}{(H_f+H)\ (\theta_s-\theta_i) + w(1-\theta_s+\theta_i)}$$

or

$$\bar{K}(1-\theta_s+\theta_i)dt = dw - \frac{(H_f+H)(\theta_s-\theta_i)(1-\theta_s+\theta_i)dw}{(1-\theta_s+\theta_i)[(H_f+H)(\theta_s-\theta_i)+w(1-\theta_s+\theta_i)]} \qquad ..(4.6)$$

Integrating

$$\bar{K}(1-\theta_s+\theta_i)t = w - \frac{(H_f+H)(\theta_s-\theta_i)}{(1-\theta_s+\theta_i)} \log[(H_f+H)(\theta_s-\theta_i)+w(1-\theta_s+\theta_i)]+C \qquad ...(4.7)$$

when t=o, w=o,

Therefore,

$$C = \frac{(H_f+H)(\theta_s-\theta_i)}{(1-\theta_s+\theta_i)} \log(H_f+H)(\theta_s-\theta_i) \qquad ...(4.8)$$

Substituting value of C in equation (4.7)

$$\bar{K}(1-\theta_s+\theta_i)t = w - \frac{(H_f+H)(\theta_s-\theta_i)}{(1-\theta_s+\theta_i)} \log \frac{(H_f+H)(\theta_s-\theta_i)+w(1-\theta_s+\theta_i)}{(H_f+H)(\theta_s-\theta_i)} \qquad ..(4.9)$$

From equation (4.9), infiltration rate w can be estimated for any time t for known value of $\theta_i, H, \bar{K}, H_f$ and θ_s.

In situation when again another depth of water H is applied to top surface for further leaching, then the infiltration rate w_1 at time t can be expressed by:

$$\bar{K}\,\frac{(H_f+H)(\theta_s-\theta_i)+Z_f(\theta_s-\theta_i)-w_1(\theta_s-\theta_i)}{w_o+w_1} = \frac{dw_1}{dt} \qquad ...(4.10)$$

$$\bar{K}\,\frac{(H_f+H)(\theta_s-\theta_i)+w_0+w_1-w_1(\theta_s-\theta_i)}{w_o+w_1} = \frac{dw_1}{dt} \qquad ...(4.11)$$

$$\bar{K}dt = \frac{(w_o+w_1)dw_1}{(H_f+H)(\theta_s-\theta_i)+w_o+w_1(1-\theta_s+\theta_i)} \qquad ...(4.12)$$

Integrating and applying the condition that at $t=t_o$, $w_1=o$

$$\bar{K}(1-\theta_s+\theta_i)(t-t_o) = w_o \log \frac{(H_f+H)(\theta_s-\theta_i)+w_o+w_1(1-\theta_s+\theta_i)}{(H_f+H)(\theta_s-\theta_i)+w_o}$$

$$+w_1 - \frac{w_o+H_f(\theta_s-\theta_i)}{(1-\theta_s-\theta_i)} \log \frac{(H_f+H)(\theta_s-\theta_i)+w_o+w_1(1-\theta_s+\theta_i)}{(H_f+H)(\theta_s-\theta_i)+w_o} \quad \ldots(4.13)$$

4.2 Solute Movement in Different Layers: Salt Balance Approach

The irrigation water of concentration C_i applied to the first reservoir, infiltrates to the second, from second to third reservoir and likewise. Due to infiltration, the salt concentration in each reservoir decreases with time. The salt balance approach has been used for estimation of salt concentration in each reservoir when it is partially filled with infiltrated water and when it is fully filled.

4.2.1 Salt balance of top reservoir when saturation front crossed the reservoir.

For some time after onset of infiltration, the top reservoir receives water only. Since the saturation front has not crossed the depth Z_1, therefore no solute has left the reservoir. Under such situation, the salt concentration at any time t till the reservoir is filled is given by

$$C_{(t)} = \frac{\text{Quantity of salt added + Quantity of salt present}}{\text{Total volume of solute at time } t}$$

$$= \frac{C_i \int_o^t I(\tau)d\tau + C_o . Z_1 . \theta_i}{\int_o^t I(\tau)d\tau + Z_1 . \theta_i}$$

$$= \frac{C_i . w + C_o Z_1 \theta_i}{w + Z_1 \theta_i} \qquad \ldots(4.14)$$

where,

$C_{(t)}$ = concentration of solute after t,

t = time reckoned from the onset of infiltration,

C_i = salt concentration of irrigation water,

C_o = initial concentration of the solute,

Z = depth of reservoir from top surface,

w = volume of water infiltrated at time t,

$= \int_o^t I(\tau)d\tau$

4.2.2 Salt balance of top reservoir when saturation front has crossed the reservoir

When saturation front has crossed the reservoir, the salt balance is given by

salt in - salt out = change in mass of salt over a period Δt

or $$C_i . I(t)dt = C.I(t)dt + dC.Z_1 . \theta_s \qquad \ldots(4.15)$$

$$C_i . I(t) = C.I(t) + \frac{dC}{dt} . Z_1 \theta_s$$

or $$\frac{dC}{dt} + \frac{I(t)\ C}{Z_1 \theta_s} = \frac{C_i I(t)}{Z_1 \theta_s} \qquad \ldots(4.16)$$

Change in salt concentration after $t+\Delta t$ time will be

$$\frac{C_1(t+\Delta t)-C_1(t)}{\Delta t} + \frac{\bar{I}}{Z_1.\theta_s} C_1(t+\Delta t) = \frac{C_i\bar{I}}{Z_1\theta_s} \qquad \ldots(4.17)$$

$$C_1(t+\Delta t) + \frac{IC_1(t+\Delta t)\,\Delta t}{Z_1.\theta_s} = \frac{C_1(t)+C_i.\bar{I}.\,\Delta t}{Z_1.\theta_s}$$

$$\text{or}\quad C_1(t+\Delta t) = \frac{1}{1+\frac{\bar{I}.\,\Delta t}{Z_1.\theta_s}}\left[C_1(t)+\frac{C_i.\bar{I}\,\Delta t}{Z_1.\theta_s}\right] \qquad \ldots(4.18)$$

The time required to fill the top reservoir can be determined by equation (4.9) by substituting for $w = Z_1(\theta_s-\theta_i)$. Similarly the time required to fill the n^{th} reservoir can be determined by replacing w by $Z_n(\theta_s-\theta_i)$ and variation of salt concentration in different reservoirs have to be solved in succession starting from the top reservoir.

4.2.3 Salt balance of second reservoir when it is not filled with water

The equation for salt balance of second reservoir when it is not filled with water is given by:

$$C_2(t+\Delta t) = \frac{C_1(t+\Delta t).\bar{I}\,\Delta t+C_2(t).\,[(Z_2-Z_1).\theta_i+w(t)]}{(Z_2-Z_1).\theta_i+w(t)+\bar{I}.\,\Delta t} \qquad \ldots(4.19)$$

4.2.4 Salt balance of second reservoir when it is filled

When second reservoir is filled with water, the equation for salt balance is:

$$C_2(t+\Delta t) = \frac{1}{1+\frac{\bar{I}.\,\Delta t}{(Z_2-Z_1).\theta_s}}\left[\frac{C_2(t)+C_1(t+\Delta t)\bar{I}.\,\Delta t}{(Z_2-Z_1).\theta_s}\right] \qquad \ldots(4.20)$$

5.0 RESULTS AND DISCUSSIONS

The soil data required for estimation of infiltration rate have been obtained from the experimental results of Sonu (1973). The variation of capillary pressure (h_c) with the volumetric soil moisture content (θ) and relation of capillary pressure with relative permeability $k_{rw}(\theta)$ for Touchet Silt loam soil are shown in Figure 2 and 3 respectively. The soil system is divided into 4 layers of thickness 50 cm each as shown in Figure 1. The following steps were used for estimation of salt concentration in each layer with respect to depth and time.

1. The initial soil moisture content and concentration of solute in each layer were assumed to be constant. The initial moisture content, θ_i is assumed to be 0.290 for this study.

2. The capillary pressure head (H_f), as suggested by Bouwer was found using the following relationship

$$H_f = \int_o^{h_{ci}} k_{rw}(\theta)\, dh_c \qquad \ldots(5.1)$$

where h_{ci} is the capillary pressure head corresponding to initial soil moisture θ_i. For $\theta_i = 0.290$, h_{ci} is 114 cm. The H_f value was found to be 0.763 m.

3. The values of $\bar{K}$ and θ_s for Touchet silt loam were taken as 0.0288 m/hour and 0.485 respectively (Sonu, 1973).

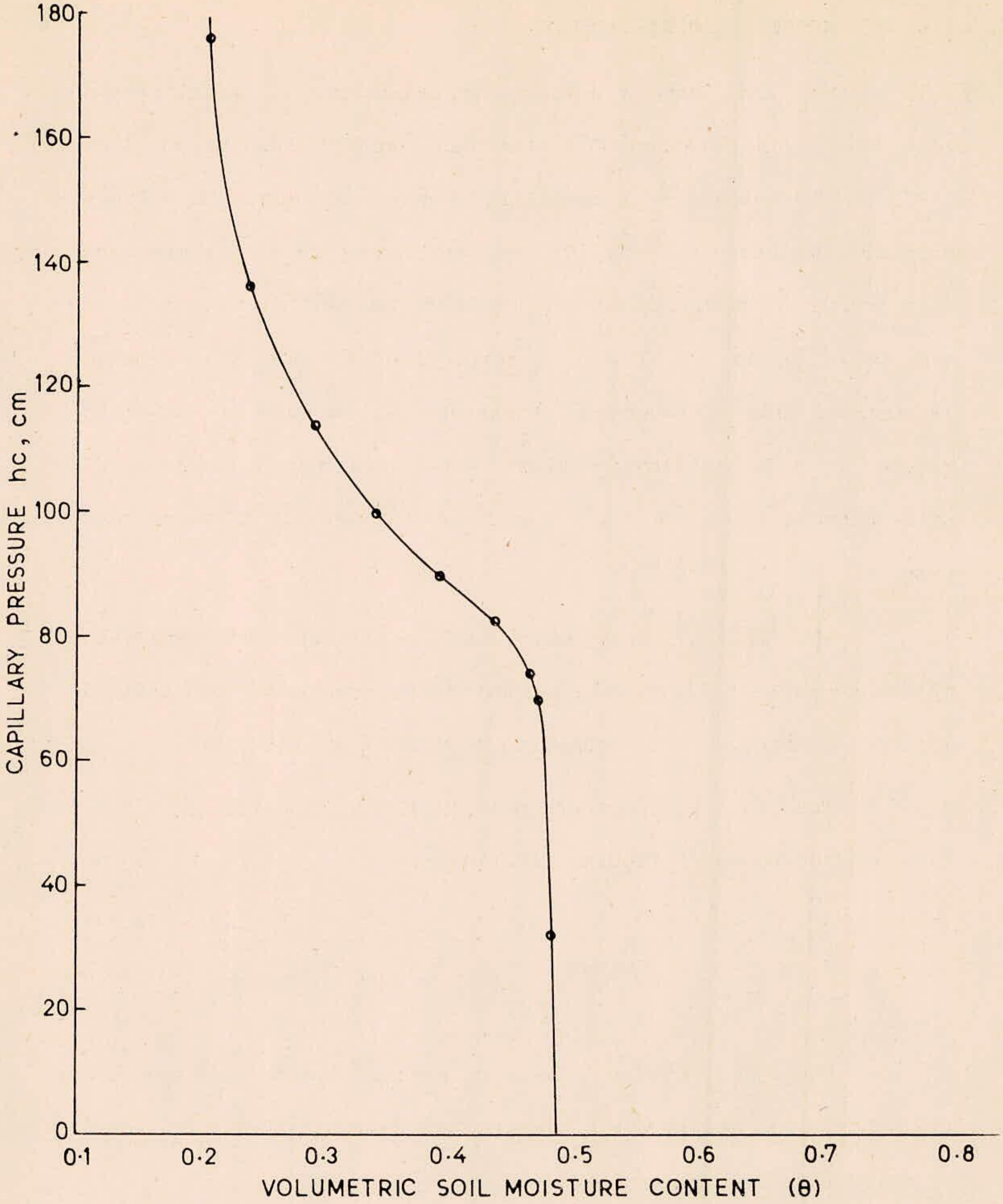

Fig. 2 : Variation of capillary pressure (hc) with volumetric soil moisture content (θ) for touchet silt loam

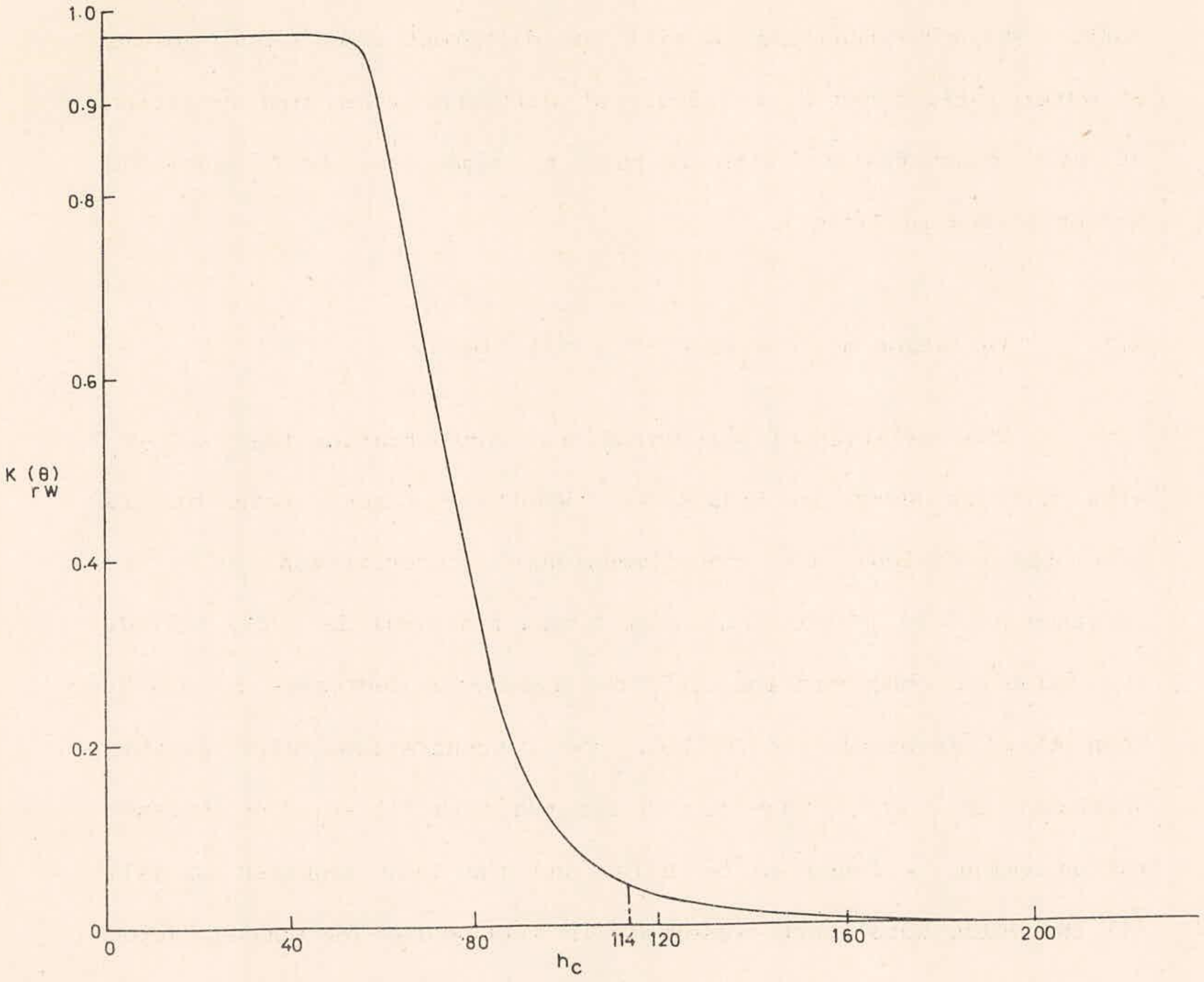

Fig. 3 : Variation of $K_{rw}(\Theta)$ with h_c for touchet silt loam

4. Irrigation water of depth 'H' (50 cm) having salt concentration (C_i) less than that of solute (C_o) is passed through the soil. The time required to fill the different reservoirs, volume of water infiltrated to reservoir at different times and variation of salt concentration with respect to time have been estimated and presented in Table 1.

5.1 Variation of $(C-C_i)/(C_o-C_i)$ with Time

The variation of non-dimensional concentration $(C-C_i)/(C_o-C_i)$ with time is shown in Figure 4. When the first reservoir is completely filled, the non-dimensional concentration value is obtained as 0.60 (Table 1). When second reservoir is fully filled, the value of concentration in first reservoir decreases to 0.405. When third reservoir is filled, the concentration value further decreases to 0.273. When fourth reservoir is filled, the concentration value is found to be 0.185 and the time required to fill all the voids upto fourth reservoir is 8.19 hours. The concentration in the first reservoir further decreases to 0.154, and at this stage all the water applied to top surface have been infiltrated.

Figure 5 shows the variation of non-dimensional concentration $(C-C_i)/(C_o-C_i)$ with respect to depth at time = 2, 4, 6, 8, 12, 14, 16, 18 and 20 hours. It is observed that at the end of 12 hours, the non-dimensional concentration in the first reservoir reduces from 1.0 to 0.155, in the second reservoir

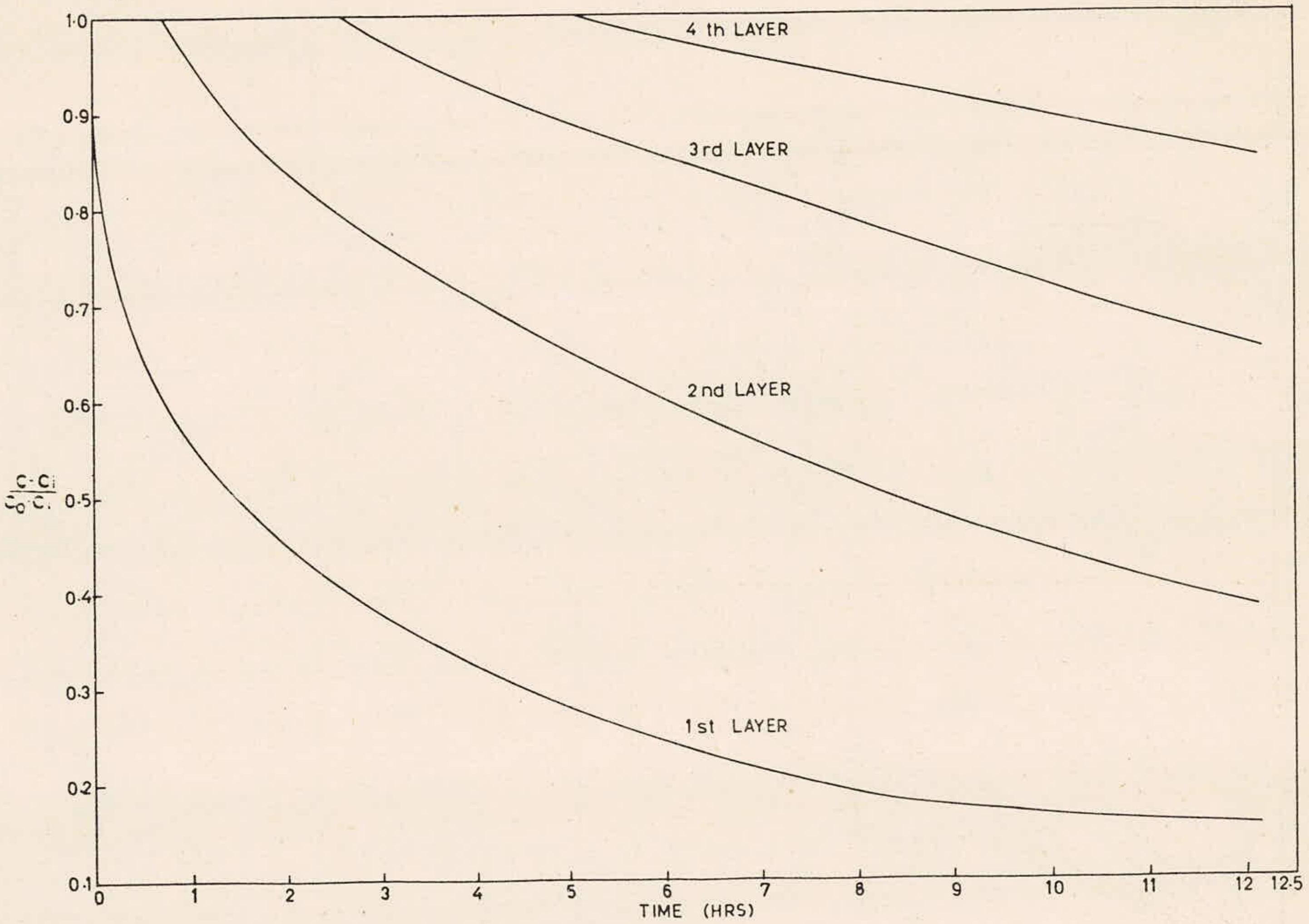

Fig. 4 : Variation of non-dimensional salt concentration with time for different reservoirs (layers)

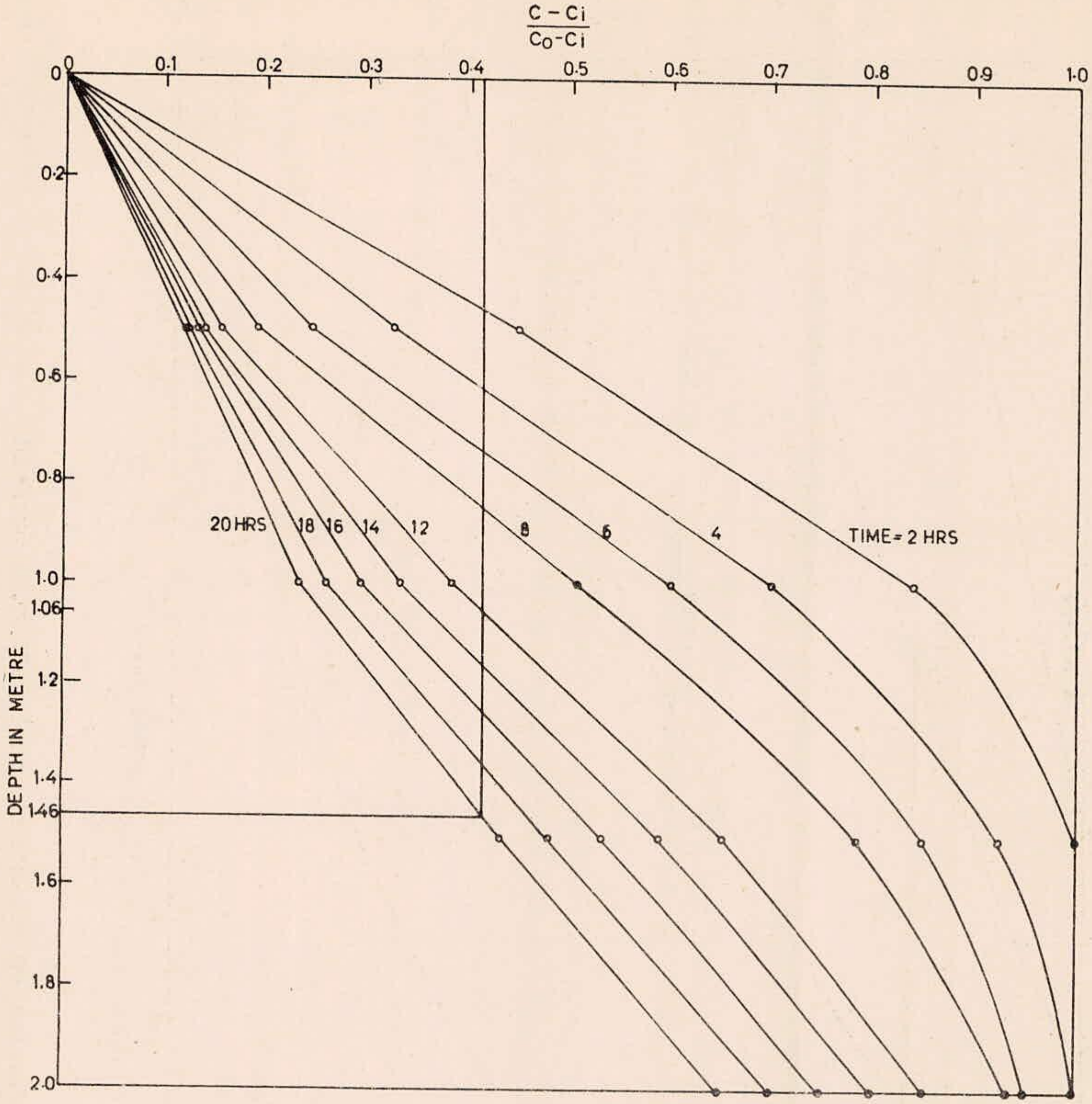

Fig. 5 : Variation of non-dimensional salt concentration with depth for different time periods

it reduces from 1.0 to 0.655 and in the fourth reservoir, non-dimensional concentraction reduces from 1.0 to 0.850.

It is observed that at the end of 12.14 hours, the depth of water on the surface is zero.

Table 1 : Variation of non demensional salt concentration $(C-C_i/C_o-C_i)$ in different reservoirs and volume of water infiltrated with time

1st RESERVOIR	2nd RESERVOIR	3rd RESERVOIR	4th RESERVOIR	INFILTRATION (m/hour)	TIME (hour)
0.93750	1.00000	1.00000	1.00000	0.00970	0.00900
0.88235	1.00000	1.00000	1.00000	0.01940	0.03529
0.83333	1.00000	1.00000	1.00000	0.02910	0.07783
0.78947	1.00000	1.00000	1.00000	0.03880	0.13570
0.75000	1.00000	1.00000	1.00000	0.04850	0.20803
0.71429	1.00000	1.00000	1.00000	0.05820	0.29405
0.68182	1.00000	1.00000	1.00000	0.06790	0.39303
0.65217	1.00000	1.00000	1.00000	0.07760	0.50431
0.62500	1.00000	1.00000	1.00000	0.08730	0.62725
0.60000	1.00000	1.00000	1.00000	0.09700	0.76131
0.57692	0.97356	1.00000	1.00000	0.10670	0.90593
0.55473	0.94892	1.00000	1.00000	0.11640	1.06063
0.53340	0.92584	1.00000	1.00000	0.12610	1.22496
0.51288	0.90410	1.00000	1.00000	0.13580	1.39847
0.49316	0.88355	1.00000	1.00000	0.14550	1.58077
0.47419	0.86406	1.00000	1.00000	0.15520	1.77149
0.45595	0.84551	1.00000	1.00000	0.16490	1.97027
0.43841	0.82781	1.00000	1.00000	0.17460	2.17678
0.42155	0.81088	1.00000	1.00000	0.18430	2.39071
0.40534	0.79466	1.00000	1.00000	0.19400	2.61177

1st RESERVOIR	2nd RESERVOIR	3rd RESERVOIR	4th RESERVOIR	INFILTRATION (m/hour)	TIME (hour)
0.38975	0.77909	0.98619	1.00000	0.20370	2.83969
0.37476	0.76354	0.97310	1.00000	0.21340	3.07420
0.36034	0.74803	0.96059	1.00000	0.22310	3.31506
0.34649	0.73259	0.94859	1.00000	0.23280	3.56204
0.33316	0.71722	0.93702	1.00000	0.24250	3.81492
0.32035	0.70196	0.92583	1.00000	0.25220	4.07349
0.30802	0.68681	0.91496	1.00000	0.26190	4.33755
0.29618	0.67178	0.90439	1.00000	0.27160	4.60693
0.28479	0.65690	0.89408	1.00000	0.28130	4.88143
0.27383	0.64217	0.88400	1.00000	0.29100	5.16090
0.26330	0.62759	0.87414	0.99213	0.30070	5.44517
0.25317	0.61319	0.86410	0.98460	0.31040	5.73408
0.24344	0.59897	0.85391	0.97734	0.32010	6.02750
0.23407	0.58494	0.84356	0.97030	0.32980	6.32528
0.22507	0.57110	0.83308	0.96344	0.33950	6.62730
0.21641	0.55745	0.82248	0.95673	0.34920	6.93342
0.20809	0.54402	0.81177	0.95014	0.35890	7.24352
0.20009	0.53079	0.80096	0.94365	0.36860	7.55749
0.19239	0.51777	0.79007	0.93725	0.37830	7.87522
0.18499	0.50497	0.77911	0.93093	0.38800	8.19660
0.18124	0.49069	0.76637	0.92366	0.39920	8.57209
0.17765	0.47686	0.75359	0.91616	0.41040	8.95216
0.17422	0.46350	0.74079	0.90841	0.42160	9.33667
0.17095	0.45059	0.72798	0.90045	0.43280	9.72549
0.16782	0.43810	0.71518	0.89227	0.44400	10.11848
0.16482	0.42604	0.70241	0.88389	0.45520	10.51552
0.16196	0.41438	0.68970	0.87531	0.46640	10.91649
0.15923	0.40312	0.67705	0.86656	0.47760	11.32128
0.15661	0.39223	0.66447	0.85764	0.48880	11.72978
0.15441	0.38172	0.65199	0.84856	0.50000	12.14188

1st RESERVOIR	2nd RESERVOIR	3rd RESERVOIR	4th RESERVOIR	INFILTRATION (m/hour)	TIME (hour)
0.15172	0.37157	0.63961	0.83934	0.51000	12.52534
0.14944	0.36176	0.62735	0.82998	0.52000	12.91016
0.14726	0.35229	0.61520	0.82050	0.53000	13.29630
0.14517	0.34315	0.60319	0.81090	0.54000	13.68373
0.14318	0.33432	0.59132	0.80121	0.55000	14.07241
0.14127	0.32580	0.57960	0.79143	0.56000	14.46231
0.13945	0.31757	0.56803	0.78156	0.57000	14.85340
0.13777	0.30963	0.55663	0.77163	0.58000	15.24564
0.13604	0.30197	0.54538	0.76165	0.59000	15.63900
0.13445	0.29457	0.53431	0.75161	0.60000	16.03346
0.13293	0.23744	0.52341	0.74153	0.61000	16.42899
0.13148	0.28055	0.51269	0.73143	0.62000	16.82556
0.13009	0.27391	0.50215	0.72131	0.63000	17.22315
0.12876	0.26750	0.49179	0.71118	0.64000	17.62173
0.12749	0.26132	0.48162	0.70104	0.65000	18.02127
0.12628	0.25536	0.47163	0.69092	0.66000	18.42176
0.12512	0.24961	0.46183	0.68080	0.67000	18.82318
0.12401	0.24406	0.45221	0.67071	0.68000	19.22549
0.12295	0.23872	0.44279	0.66065	0.69000	19.62868
0.12193	0.23356	0.43355	0.65062	0.70000	20.03273

5.2 Estimation of Leaching Requirement

The leaching requirement is the fraction of irrigation water above plant consumption which is required to leach the salts through the root zone. Different crops have different salt tolerance levels as given in Table 2. It indicates that if salt content is more than the prescribed limits, yield of crop will be reduced significantly. For example for wheat crop when salt content of solute is 6.0 mm ho/cm, yield will not be affected, but when salt content is 13.0 mm ho/cm, yield will be reduced by 50 per cent. When salt content reaches to maximum 20.00 mm ho/cm, 100 per cent yield reduction will be there.

The utility of the present study is shown through the following example. Let the irrigation water applied for leaching have very low salt content (1.0 mm ho/cm). Leaching Requirement (LR) can be estimated by the relationship

$$LR = \frac{EC - EC_i}{EC_o - EC_i} \qquad \text{... (5.2)}$$

where,

EC_i = salinity of the applied irrigation water,

EC = average soil salinity tolerated by the crop (for 100% yield potential), and

EC_o = solute concentration before leaching.

From table 2, for wheat crop when EC_o = 13.0, 50% yield will be affected and when EC_o = 6.0, yield will not be affected by salt present in the soil. Let concentration of solute before leaching is 13.00 mm hc/cm and let the irrigation water has salinity

1.0 mm ho/cm. Let it be intended to reduce the solute concentration from 13.0 to 6.0 mm ho/cm.

Table 2 : Crop Salt tolerance levels for different crops

Field Crops	100% EC_e	EC_w	90% EC_e	EC_w	75% EC_e	EC_w	50% EC_e	EC_w	Max. EC_e	EC_w
Barley	8.0	5.3	10	6.7	13	8.7	18	12	28	19
Wheat	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13
Soya bean	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0	10	6.7
Corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Ground nut	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4
Rice	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6
Cotton	7.7	5.1	9.6	6.4	[illegible]	8.4	17	12	27	18
Sugar cane	1.7	1.1	3.4	2.3	5.9	4.0	10	6.8	19	12

Source : Water quality for agriculture, FAO Irrigation and Drainage Paper 29 Rev.1, 1985.

The non-dimensional concentration at the end of the desired leaching is

$$\frac{EC - EC_i}{EC_o - EC_i} = \frac{6 - 1}{13 - 1} = \frac{5}{12} = 0.416$$

From Figure 5, it is seen that after 12 hours of leaching with 50 cm of water, only soil upto a depth of 106 cm has been leached upto desired level. As the root of wheat crop goes upto 140 - 150 cm depth, further addition of 20 cm of water will be required for leaching so that salts can move further downward beyond root zone depth. Figure 5 shows that by applying 20 cm of water, soil upto a depth of 146 cm has been leached out.

5.3 Breakthrough Curve

When irrigation water free from salt flows into the soil, the fraction of solute in the outflowing solution will be C/C_o. The relationship between C/C_o vs volume of the out flowing solution are called Breakthrough Curve. Figure 6 shows the relationship between C/C_o versus volume of outflowing water from different reservoir. In this study, it is found that when soil is near saturation and when one pore volume of water passes through the top soil of 50 cm thickness, the solute concentration predicted by the present model is 0.54. For an ideal Breakthrough curve, 50 per cent displacement of salts takes place at one pore volume. Thus the salt prediction by the present model is satisfactory. It has been said 1.2 to 2.0 times the pore volume replacement of the soil solution should remove about 80 per cent of the original

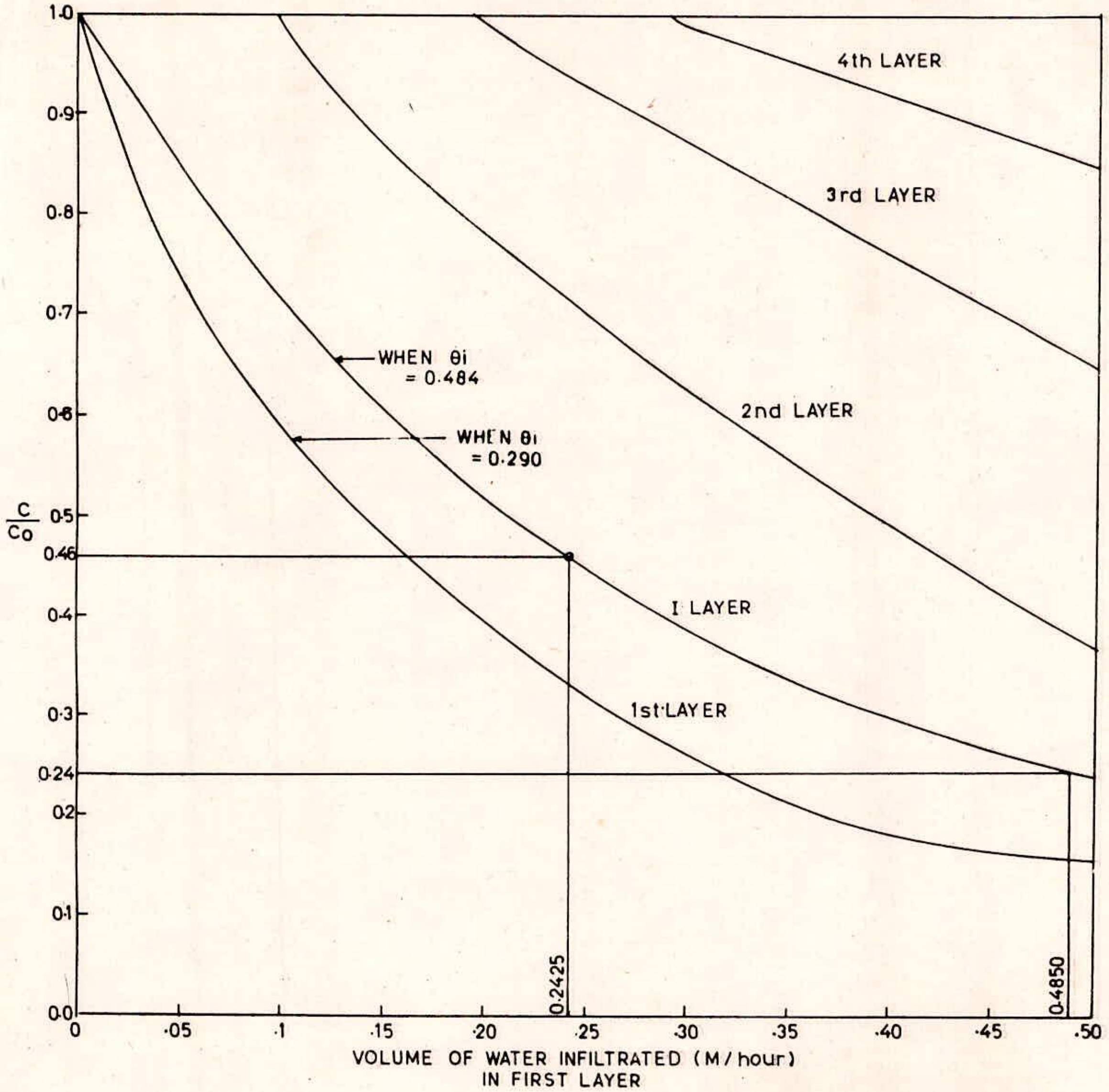

Fig. 6 : Breakthrough curve as a function of relative salt concentration and volume of infiltrated water in different reservoirs

salt content (Ravina, 1982). From this study, it is found that when water twice the pore volume is passed through the 50 cm of the top soil, 76 per cent of salt is removed, as shown in Figure 6.

6.0 CONCLUSION

The infiltration volume in different reservoirs have been determined by using Green and Ampt equation for a touchet silt loam soil for which the relationship between capillary pressure (h_c) and volumetric soil moisture content (θ) and relationship between relative permeability to water k_{rw} (θ) and capillary pressure (h_c) are available.

The variation of salt concentration in different reservoirs with time and depth have been estimated and presented. Breakthrough curves have been presented for different reservoirs. It is found that when soil is near saturation and when one pore volume of water passes through the top soil of 50 cm thickness, 54 percent of the salt is leached out. When water twice the pore volume is passed through the 50 cm of the top soil, 76 percent of salt is removed. An estimation of leaching requirement when wheat crop is grown, has been done and presented.

REFERENCES

1. Ayers, R.S. and D.W. Westcot (1985), 'Water Quality for Agriculture', FAO Irrigation and Drainage Paper, 29 Rev. 1, Rome, pp. 174.

2. Bouwer, H. (1969), 'Salt Balance, Irrigation Efficiency and Drainage Design', Journal of the Irrigation and Drainage Division, Proc. A.S.A.E., Vol. 95, No. IR-1, March, pp. 153-170.

3. Bower, C.A. and M. Fireman (1957), 'Saline Alkali Soils', U.S. Department of Agricultural, pp. 282-290.

4. Hill, R.A. (1961), 'Leaching Requirement in Irrigation', Journal of the Irrigation and Drainage Division, Proc. A.S.A.E., Vol. 87, No. IR-1, March, pp. 1-5.

5. Hoffman, G.J. (1985), 'Drainage Required to Manage Salinity', Journal of Irrigation and Drainage Division, Proc. A.S.A.E., Vol. III, No. 3, Sept., pp. 199-205.

6. Kovda, V.A. (1961), 'Principles of the Theory and Practice of Reclamation and Utilization of Saline Soils in the Arid Zones', Proceeding of Tehran Symposium on Salinity problems of Arid Zones, pp. 201.

7. Molen, V.D. (1973), 'Salt Balance and Leaching Requirement', Chapter 9: Drainage principles and Applications, Pub. 16, Vol.II, I.L.R.I., P.O.Box 45, Wageningen, The Netherlands.

8. Ravina, I. (1982), 'Soil Salinity and Water Quality', Handbook of Irrigation Technology, Vol.I, Edited by H.J. Finkel, C.R.C. Press, Inc. Florida.

9. Rhoades, J.D. (1974), 'Drainage for Salinity Control': Chapter 16, Drainage for Agriculture, Edited by Jan Van Schilfgaarde.

10. Schilfgaarde, J.V. Bernsteem, L. Rhoades, J.D. and S.L. Rawlins (1974), 'Irrigation Management for Salt Control', Journal of the Irrigation and Drainage Division, Proc. A.S.A.E., Vol. 100, No.IR-3, Sept., pp. 321-338.

11. Smith, R.J. and N.H. Hancock (1986), 'Leaching Requirement of Irrigated Soils', Journal Agric. Water Management. Vol.II, pp. 13-22.

12. Sonu, D. (1973), 'Water and Air Movement in Bounded Layered Soils', Ph.D. Thesis, Colorado State University, Fort Collins, U.S.A.