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Leaching for Salinity Control

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Abstract : *Leaching is an important tool for reclamation of saline lands and their management in post drainage phase. Research advances in India in respect of theoretical developments, methodology and design practices of leaching are reviewed. The report identifies problems looking for solutions and includes suggestions for future research.*

1.0 Introduction

Salinity refers to the occurrence of salts in soil or water in concentration that may interfere with plant growth. When evaporation exceeds rainfall in irrigated areas, salinity is a potential hazard. Although manifesting in different forms, the problem is largely caused by rise in watertable. Groundwater accessions due to losses from extensive irrigated irrigation distribution system and field application disturb the dynamic equilibrium in saturated (aquifer) as well as in unsaturated (crop root) zones in the irrigated system. All irrigation waters, be they from surface or ground water sources contain some mineral derived from natural dissolution of rocks and soil. When water is applied or enter the root zone through capillary action (under conditions of high water table), most of it is evaporated and salts are left behind. More the aridity, greater is the quantity of applied water or water due to capillary rise (under high water table), and, hence, the salts added. Increasing salt concentrations in soils ultimately reach levels that are harmful to plant growth and consequently crop production decreases.

Reports indicate that, of the total area of 985.7m ha occupied by problem soils the worldover, soil salinity/sodicity alone has taken 322.9m ha out of production (Brinkman 1980). Estimates prepared by specialised agencies of U.N. show that nearly 50 per cent of the irrigated areas in the world is either already salinized or is in potential danger of being salinized at some future date. In India, where irrigation has progressed at a rapid pace, the incidence of waterlogging and salinity is also on the increase. Estimate of affected area vary from 6-15 m ha. Salinity is, therefore, one of the most serious problems facing irrigated agriculture and coming to terms with problems raised by it, is essential for long term survival of arid area irrigation (Moore, 1972). The most economical and proven means of reclaiming saline soils and managing them in post drainage phase is by leaching. Indian research on salinity management through leaching is reviewed.

2.0 Definition and Scope

If the salinity in the soil is intially too high for efficient crop production, it has to be reduced by applying additional quantity of irrigation water or rainwater which has got less salinity than the soil solution. This application of an additional amount of water to prevent the harmful accumulation of soluble salts is called leaching, USSL (1954) defined leaching requirement (LR) as the ratio of the additional increment of water beyond that required for crop evapotranspiration that must pass through the root zone to prevent harmful salt accumulation in the soil, to the total applied water. By leaching, the salts are dissolved in the water passing through the soil and are removed beyond the root zone depth in natural or artificial drainage conditions.

The soil having problem of the excess salt can be grouped into two classes :

* Salt effected land where water table is too deep to influence the root zone salt content.

* Salt affected land where sub-surface water logging problem exists.

In the first case, salinity generally occurs due to the irrigation with poor quality water. Under such situations the excess salt can be leached below the root zone with the application of excess good quality water. The second case where the shallow water table is present, salt accumulates in the root zone due to the evaporation of saline subsoil water.

The possible management strategies for salinity control in this case include :

* Improved irrigation management to reduce the amount of ground water recharge so that water table does not rise to such an extent that it may affect the root zone salinity. It will however, be necessary to apply certain minimum leaching fraction.

* To grow salt tolerant crops so that sustained economic crop benefits can be taken in the existing salt affected soils in the presence of water table.

* To reclaim the soil in the presence of shallow ground water table. This can be accomplished in two ways; (i) by leaching salt when water table is lower than the root zone, or (ii) by leaching on side by drip or other methods or irrigation

* Taking actions to lower the water table and leach the salt to allow continuous cropping.

This paper focusses attention on post-drainage salinity management. In the process watertable is first lowered with the help of sub-subsurface drainage system, followed by initial leaching of salts. Subsequently, leaching is practised to maintain salinity balance in the root zone. Thus, leaching for salinity control is accomplished in two stages; the first phase being leaching for reclamation and the second leaching for salt balance. The theoretical concept of leaching is addressed first followed by considerations in designing the leaching programmes.

3.0 Leaching Theory

The prediction of salinity with space and time is required for planning the leaching programme for reclamation of saline soils and maintenance of salt balance in irrigated or reclaimed land. The theoretical concepts developed for this purpose fall in two main classes :

(1) Models based on layerwise equilibrium theory which may consider :

(a) sub-layers (b) layers. The latter class of models can be further sub divided into (i) single layer model and (ii) multi layer model

(2) Models based on hydrodynamic dispersion theory

3.1 Sub-layers

Simple analytical solution reported by Burns (1975, 76) can be classified into this category. Though in the analytical development, the soils appear to have been divided into sevefal layers, but Gupta and Pandey (1983) have proved that these could better be termed as sub-layers instead of layers.

3.1.1 Empirical equations and sub-layers concept.

Empirical equations have been fitted to the observed data at several places. These equations, however may be of local interest as the variables in the equations pertain to only that of local soil used in the study. Lefaller and Sharma (1977) and Raj and Nath (1984) reported some empirical equations for leaching of saline soils in Hisar region of Haryana. There is striking similarity between these equations and those based on the sub-layers models which are more general.

3.2 Layerwise equilibrium model—single and multi layers.

In the development of mathematical models soil profile is assumed as a single layer containing salts. The differential equation **describing the leaching of salt can be described by Eq. as**

$$\frac{dc}{dt} = \frac{Vi}{d\theta} (C - Ci) + \text{other source}$$

and sink terms ...... (1)

where,

C is the concentration of drainage water, Vi is the amount of water drained, d is the depth of reservoir and θ is the pore fraction. Source and sink terms can be adsorption, precipitation, salt taken by roots and an ion-exclusion.

The solution of this equation for the uniformly distributed salt and for the salts concentrated only on surface with adsorption as a sink term was obtained by Gupta and Pandey (1979)

Models based on the multi-layers concept assume the soil profile consisting of several layers instead of one. The models based on this concept give results similar to those based on hydrodynamic dispersion theory.

3.3 Models based on hydrodynamic dispersion theory

For a homogeneous, isotropic porous medium at constant moisture content, the one dimensional dispersion convection equation for miscible solute is given by :

$$D \frac{\partial c}{\partial x} - V \frac{\partial c}{\partial x} = \frac{\partial c}{\partial t} + \text{other source and}$$

sink terms ......(2)

where D = hydrodynamic dispersion coefficient V = pore water velocity, c = solute concentration, x = space coordinate, t = time.

The process of hydrodynamic dispersion in a porous media is a offspring of two parent phenomenon : (i) physico-chemical and (ii) mechanical. The former known as molecular diffusian is on account of chemical potential gradients and is active even in the fluid at rest inside the cavities or pores of the medium. The latter is due to non uniform velocity distribution in the soil pores. Analytical as well as numerical solutions of Eq. (2) have **been obtained by different workers (Gupta, 1976, Pandey et al 1982).**

To use Eq. (2) for the prediction of salt concentration one needs two parameters i.e. velocity and dispersion coefficient. Velocity can be determined as the infiltration rate determined in the field or the saturated hydraulic conductivity in the column study. Hydrodynamic dispersion coefficient can be determined by the method given by Kirkham and Power (1973). This method can be used for the column study and it requires the entire breakthrough curve. Basak and Murty (1979) reported quick method for determining the dispersion coefficients from data obtained at any arbitrary experimental point and this eleminated the need for obtaining the entire breakthrough curve for this purpose. A method was given by Batta (1977) by which the dispersion coefficient could be determined in the field. He showed that the values of D obtained in in-situ determination on the field were 1.3 to 1.6 times as large as those obtained with the soil column packed to field bulk densities and layering sequence.

Among the different models given above single layer model has got wider applicability under field conditions (Leffelaar and Sharma, 1977, Khosla et al. 1979, Pandey and Bandyopadhya, 1980). Hydrodynamic dispersion model can also be used under field conditions with Paclet number (VL/D) = 5, (where L is the length of root zone) (Gupta and Gupta, 1987).

4.0 Leaching Methodology

To understand leaching phenomenon under drainage conditions several studies have been made. These can be divided into 3 groups :

(a) Infiltrometer leaching studies to find out the leaching requirement considering that the vertical flow occured under the subsurface drainage. Empirical equations and hydrodynamic dispersion equation can be tested and used afterwards to find out leaching requirement with different quality waters (Ranade, 1984).

(b) Leaching under sand tank model of the same soil where subsurface drainage was installed to suggest the leaching method under field in order to maintain the uniformity of the leaching. Batta et al (1979) tried three methods for leaching by ponding.

(i) Ponding over whole surface between the two tile lines

(ii) Ponding over the central 50 per cent area between the tile lines first and extending it to hundred percent area subsequently

(iii) Ponding of the central 25% area first and then extending it to the central 75% area and finally to cover 100% area between two lines.

Leaching treatment (II) was found better than (I) and (III) in terms of the amount of water needed and time taken for leaching for a given level of heterogeneity.

(c) Field scale leaching study with horizontal subsurface drainage have also been conducted (Dhruvanarayana and Kamra, 1981). Though it may be difficult to control several variables in the field to establish the cause and effect relationship, data from field studies would have greater applicability as compared to those from infiltration and sand tank studies. It may, however be desirable to standardise the methodology to have uniform interpretation of results.

5.0 Consideration in Design of Leaching Programme

5.1 Site conditions

The important factors influencing leaching are the land surface uniformity, surface configuration and soil compaction.

In natural conditions fields have variations in land surface that affect uniformity of water distribution and hence, leaching. This can be overcome by precision levelling. The reasonable uniformity in water distribution are ensured if levelling index is within 3cm (Tyagi, 1985). Bunding of field is useful if advantage of rain water is to be taken for leaching. Normally bunds upto 20cm may serve the purpose of storing water in most of the arid regions.

Upper layers of barren saline lands get compacted due to movement of a man and animals. High bulk density reduces the infiltration rate and the rate and duration flow of water passing through the soil. This affects the leachability of the soil. Tillage practices can improve leachability to a great extent. Bandyopadhya and Pandey (1984) conducted experiment on land preparation and found that deep ploughing with soil inversion increased the leachability of the heavy textured coastal saline soils of West Bengal. In Haryana, also in sandy loam soil, deep ploughing increased infiltration rate by 3 to 4 times (Gupta and Gupta, 1987).

5 2 Time of leaching

In waterlogged saline soils water table fluctuates from surface in the monsoon season to about 2m depth from below the surface in summer season. These fluctuations affect the moisture content of the top soil. Pandey and Singh (1984) conducted leaching studies in column for finding the effect of initial moisture content on the leaching of salts. It was found that leaching was most efficient when the soil was dry. This is probably due to restricted leaching of salts in dead end pores at higher moisture content. Under field conditions the lower moisture contents are found in the summer. So the summer season may be the most desirable time for leaching. But leaching operation depends on the availability of water which is a major constraint.

5 3 How much to leach

The ultimate aim of leaching a saline soil is to grow crops. The crop tolerance to saline water irrigations seems to be one criterion by which one can decide the salinity status of the soil profile to be achieved. To obtain under research experiments, it is now well established that with increasing amount of water applied, crop yield in saline soils increases. There is an optimum level beyond which there is no further increase in yield. It is because at this stage soil salinity is already brought to a level at which optimum yield are expected. Effect of initial soil salinity and the quantity of the water applied for wheat crop reveal that with high initial salinities increasing amount of water is necessary to achieve similar yield.

Extensive advancement in irrigation technology is needed to achieve the correct leaching requirement application efficiencies. The cost of excessive leaching may be sometime significant in terms of loss of nutrient, water and energy.

5.4 Leaching efficiency

Leaching efficiency has been defined by several workers in different ways. Bouwer (1969) defined the leaching efficiency as the hypothetical fraction of the total water applied that passed through the root zone and contained displaced soil solution.

$$EI = (Cd - Ci)/(Cs - Ci) \quad ......(3)$$

where,

EI has been defined as the leaching efficiency, Cs, Ci and Cd are the concentrations of the soil, irrigation and drainage waters, respectively. The value of EI depends mainly on the size distribution of the water filled pores, which in turn is governed by the texture, structure and swelling properties of the soils. Generally the value of EI varies from 0.2 for heavy clay soils to 0.6 for light soils. The soil crack routes, worm holes and other large diameter pores affect the leaching efficiency. The leaching efficiency would also be dependent on the average flow velocity, dispersion coefficient and non-uniformity of the initial salt distribution in the soil system.

6.0 Method of Leaching

The two common methods of leaching are (1) continuous ponding of water at the soil surface known as continuous leaching and (2) water application in splits at several small intervals. In the case of continuous leaching only unsaturated flow occurs in the beginning, but afterwards flow turns saturated. In case of intermittent leaching, flow at most of the time is unsaturated.

Both the methods of leaching have their own advantages and disadvantages. The amount of water required for leaching soluble salts, particularly for fine textured soils can be reduced by intermittent ponding of water or sprinkling.

It is the differences in hydrodynamic dispersion and molecular diffusion that cause differential leaching efficiency (Gradner and Brooks, 1957). Drier the soil, as is the case with intermittant ponding or sprinkling, the larger is the percentage of water flowing through fine pores and more efficient the leaching water displacing the saline solution. The sprinkler method has the added advantage over ponding because precision land levelling is not required. Intermittant ponding, however, takes more time for leaching and in the process considerable amount of water is lost by evaporation.

6.1 Leaching for reclamation

Leaching for reclamation can be performed in two ways : (1) continuous ponding with good quality water, and (2) intermittant or unsaturated leaching. In both the cases drainage system is assumed to be in operation,

Rao and Lead Harison have studied leaching phenomenon undar horizontal sub-surface drainage with continuous flooding. They solved the Laplace equation by the finite difference method and drew the stream lines and the potential lines for the 75m drain spacing. It was suggested that flooding of the entire plot for about 300 hrs and quarter of the plot until complete desalinization, would save water by about 50 percent as compared to the flooding of whole plot continuously. Procedures described in leaching theory can be used to predict salinity in the stream line. Another way to get the uniform leaching is through the unsaturated leaching. The highest efficiency is obtained by a parallel stream line (vertical flow) and an attempt should be made to keep the flow vertical. One of the most efficient ways of leaching is to create unsaturated soil condition with the water table depth deep enough to be below the root zone so as to accept the displaced water. In practice, carrying out the operations when water table is deep solves this problem to a large extent. In the monsoonal climatic, May-June is the best period for leachIng. Another important way is to operate the drainage system first to lower the water table and start leaching only after sometime, when water table has been brought to deeper levels. In this method the required amount can be given in several applications without raising the watertable within the root zone. To calculate the number of pore volumes required to get the desired salinity when different quality of leaching water is used, the correlation graph (Fig. 1) can be used. The pore volume will depend upon soil characteristics.

6.2 Leaching for the salt balance

After the initial leaching the crops can be grown but salts accumulate in the root zone due to the evaporation from the saline watertable and from the salinity of the applied irrigation water. This increased salt can be leached below the root zone by applyiug excess water and this is called leaching requirement for the salt balance. The equation for the salt balance can be written as :

$$Ci\ di + Cg\ dg = Cd\ dd \qquad ......(4)$$

where,

Ci, Cg and Cd are the concentration of irrigation water, ground water and leached drained water, respectively, di is the depth of irrigation water applied. dg is the depth of saline water evaporated and dd is the depth of water leached below the root zone. So to keep the salt balance, it is necessary to apply extra water dd alongwith the irrigation water. Ci and Cg can be measured directly from the electrical conductivity meter. Cd can be predicted by the models described in the leaching theory.

6.2.1. Evaporation from the shallow ground water table (dd)

An important mechanism leading to salinization of the soils is the upward movement of saline ground water and evaporation at the soil

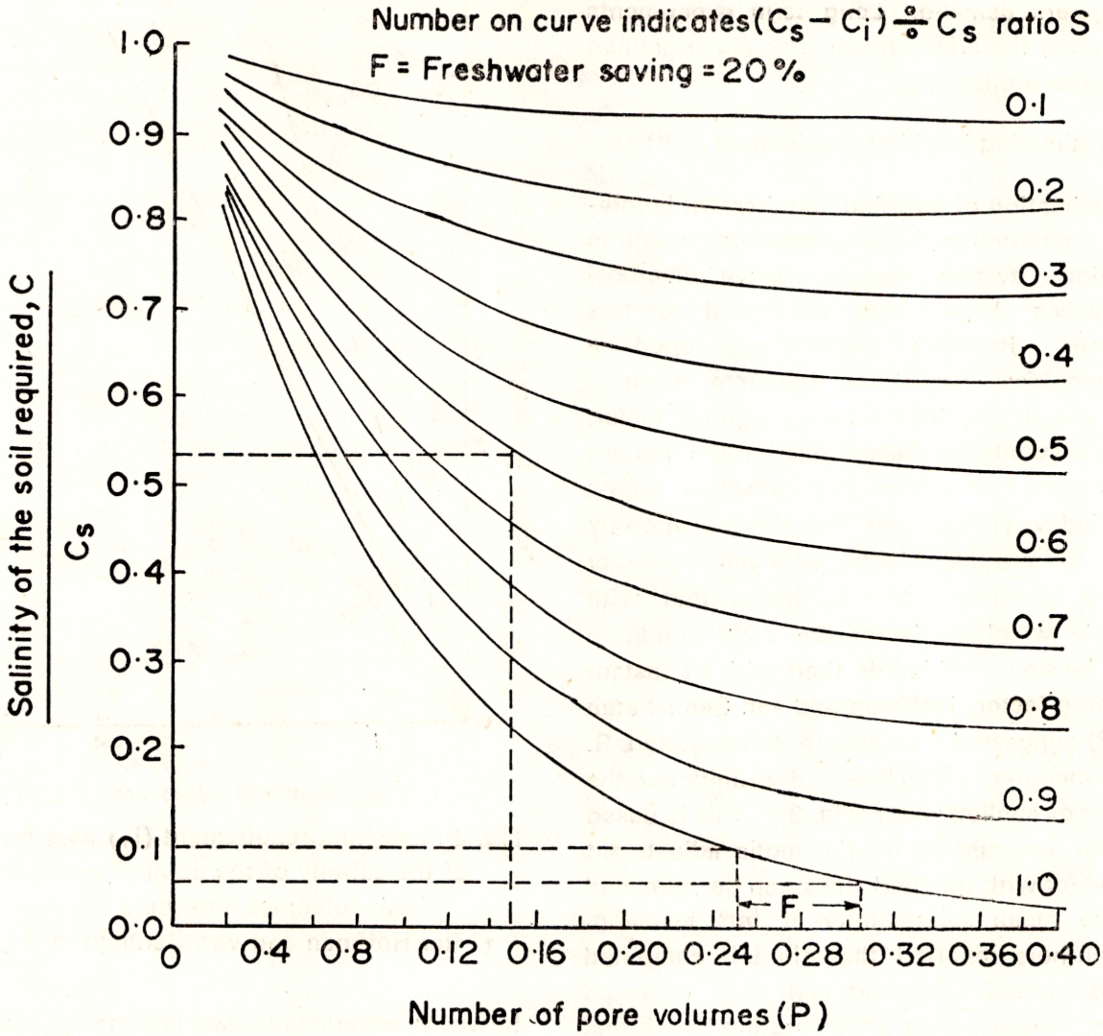

Fig. 1 : Correlation diagram for leaching the soil to the desired salinity (After Gupta and Pandey, 1983)

surface. The ground watertable fluctuate from surface to the drain depth and evporation also changes alongwith the water table.

The relation between the upward flow rate and depth of water table was established in the soil column studies by Gardner and Fireman (1958). His solutions of the steady state flow equation were based upon the relations between hydraulic conductivity (K) and soil matric potential (Suction S) of the form :

$$K = a/ (S^n+b) \qquad ......(5)$$

where, a, n and b are constants. For many soils, value of n = 2 or 3 gives the best fit with experimental data Pandey et al (1987) predicted the evaporation rate from the shallow ground water table with the method given by the Gardner (1958) and compared with the observed data obtained from the salinization values.

The depth to which watertable should be lowered is an important consideration. Upward flow at shallow water table depths may be more than 2.5mm per day for clay and even higher for sandy soils depending upon the atmospheric demand. Long term experiments to quantify the effect of leaching under drained conditions are lacking.

6.3 Estimating leaching requirement (LR)

Estimation of leaching requirement beforehand is required to make necessary provision in irrigation system design. Some empirical approaches have been advocated for this purpose. Rhoades (1974) developed a semi-empirical model to calculate leaching requirement. In this model a weighing factor, which accounts for the salt distributien pattern in the profile, was taken as a constant. Gupta and Yadav (1988) modified this equation by taking the weighing factor as a variable rather than a constant. It was found that with variable weighiug factor the field condition could be simulated better than with a constant weighing factor. Hoffman and van Genuchetan (1983) suggested a procedure to compute L.R. as a function of crop threshold salinity and the salinity of applied water (Fig. 2). This is based on the assumption that osmotic adjustment consistent with no yield loss can be estimated by the mean soil salinity at 50% leaching. The authors reported that the L.R. computed by this method compared well with observed values. Approaches incorporating the effect of evaporation in leaching requirements are yet to be perfected.

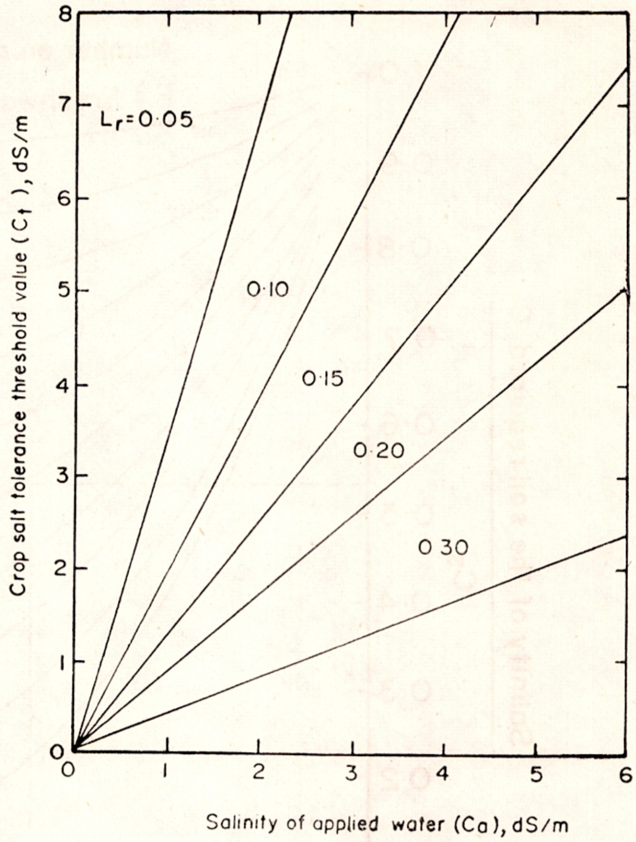

Fig. 2 : Leaching requirement (L_r) as a function of the salinity of the applied water and salt-tolerance threshold value (After Hoffman and Van Genuchten, 1983)

7.0 Summary and Recommendations

Soil salinity is a major threat to irrigated agriculture in areas where evaporation exceeds rainfall. Reclamation of saline lands and their management is often possible through the process of leaching. Considerable progress has been made in conceptualization of leaching phenomenon and development of field practices to achieve efficient leaching. The gap between leaching requiremunts and the degree of leaching achieved is being reduced with increase in understanding of the processes and problems in leaching saline lands. There are, however, several problems looking for solution. Some of the areas that need attention are :

* Appropriate methodology for conducting field and laboratory studies. The methodology needs to be standardized for comparing results obtained at various locations.
* Leaching behaviour of soil with cracking properties
* Correct assessment ef leaching requirement for maintaining salt balance
* Precise estimate of salt tolerances of crops to varying salinity levels during the period of crop growth.
* Assessment of the benefits of leaching with presumed irrigation application systems.

References

Bandyopadhya, A.K. and Pandey, R.S.. 1984. Effect of deep ploughing on leaching of salts from heavy textured coastal saline soils, J. Ind. Soc. of Soil Sci. 32 : 361-363

Basak, P. and V.V.N. Murty. 1979. Determination of hydrodynamic dispersion coefficient using invenfc, J. Hydrol, 41-43.

Batta, R.K. 1977. Correlation of the hydrodynamic coefficient in one dimensional solute transport under laboratory and field conditions. M.Sc. Thesis, Punjab Agric. University, Ludhiana, India

Batta, R.K., R.N, Pandey and S.K. Gupta, 1979. Studies to improve uniformity of leaching under the drainage system, Annual Report CSSRI, Karnal, pp. 96.

Bouwer, H. 1969. Salt balance irrigation efficiency and drainage design, Proc. ASCE, J. Irrig. Drain, Div.. 95 : 153-170.

Brinkman, R. 1980. Saline and sodic soils, In : Land reclamation and water management, I.I.L.R.I., Wageningen. The Netherlands, Pub. No. 27, 62-72.

Burns, I.G. 1975. An equation to predict the leaching of surface applied nitrate, J. Agric Sci.. Cambridge, 85 : 443-54.

Burns, I.G. 1976. Equation to predict the leaching of nitrate uniformity incorporated to a known depth or uniformly distributed throughout soil profile. J. Agric. Sci., Cambridge, 88 : 365-13.

Dhruvanarayana, V.V, and S.K. Kamna, 1981. Studies on the design and performance of the drainage system for saline soils of Bidu), Gujarat, Anuual Report, CSSRI, Karnal, pp. 106.

Gatdner, W.R. and Brooks, R.H. 1957. A descriptive theory of leaching soil science, 83 : 295-204,

Gardner, W.R. 1958. Some steady state solution of the unsaturated moistore flow equation with application to evaporation from a water table. Soil Sci. 85 (4) : 228-232.

Gardner, W.R. and Fireman, M. 1959. Laboratory studies of evaporation from soil column in the presence of water table, Soil Sci. 85 (5) ; 244-249.

Gupta, S.K. 1976. Mathematical simulation of one dimensional solute transport in saturated saline soils, M.Sc. Theais, Punjab Agricultural University, Ludhiana, India.

Gupta, S.K. and R.N. Pandey, 1979. A simplified prediction equation for reacting solute transport in saline soils. J. Agric. Sci. Cambridge, 92 : 587-589.

Gupta, S.K. and Pandey, R.S., 1983. A mathematical model for evaluating leaching of saline soils when saline and fresh water are used in conjunction, Indian, J. Agric. Sci. 53 (8) : 701-706.

Gupta S.K. and Pandey, R.N. 1983. Layer wise eqoilibrium theory for predicting salt movement and its limitations. Curr. Agric. 7 : 30-35.

Gupta, S.K. and I.C. Gupta, 1987. Land development and leaching in management of saline soils and water, Oxford & IBH Publications Co., New Delhi, 339.

Gupta, S.K. and Yadav, R.N. 1988. Note on leaching requirement for salt balance in irrigated lands, Curr, Agric.. Vol. 12 : 101-104.

Hoffman, G.J. and M.T. Van Genucheten, 1983 Soil properties and efficient water use, management for salinity control. In limitation to efficient water use in crop production (Eds. Taylor et. al). Am. Soc. of Agronomy Madison.

Kirkhalm, D. and Powers, W.L. 1972. Advanced soil physics, Wiley Inc. New York.

Khosla, B.K., Gupta, R.K. and Abrol, I.P. 1979. Salt leaching and effect of gypsum application in saline sodic soils. Agriculture Water management 2 : 193-302.

Leffelaan, P.R. and Sharma, R.P. 1977. Leach ing of high saline soil Hydrol ; 32 : 203-18

Moore, C.V. 1972. On the necessity and sufficient conditions for long term irrigated agriculture. Water Resources Bulletin, 8 (4).

Pandey, R.N. 1979. Dispersion of applied salts in porous media, J. Agric. Sci. Cambridge 92 : 663-668.

Pandey, R.S. 1978. Simulation of interaction solute transport in soil system, M. Tech. Thesis, PAU, Ludhiana, India.

Pandey, R.N., Gupta, S.K. and Batta, R.K. 1980. Evaluation of drainage methods and leaching criterion for saline soils, Annual Report, CSSRI, Karnal, pp. 87.

Pandey, R.S. and Bandyopadhya, A.K, 1980. Prediction of salt movement in heavy textured cracked soils. J. Agric. Engg. 17 : 93-106.

Pandey, R.S., Singh, S.R. and Sinha, B.K. 1982. An extrapolated Crank-Nocobon method for solving the convection dispersion equation with non linear adsorption, J. of Hydrol. 56 (4) : 277-285.

Pandey, R.S. and Singh, O.P. 1984. Effect of drainage depth on moisture salt distribution and leaching of salts in sub-surface drainage system, Annual Report, CSSRI, Karnal, pp. 124,

Pandey, R.S. and Singh, G,P. 1986. Evaporation from saline waterlogged soils and their salinization (in press), Proc. of national Symposium on 'Drainage of Waterlogged and Salt Soils, J. of Agril. Engg., 23(i) : 42-52

Pandey, R.S., Gupta, S.K. and Singh, O.P. 1987 Cooperative performance of exact and simplified equation for predicting evaporation rates, J. of Ind. Soc. of Soil Sci. 33 (3) : 502-504.

Rhoades, J.D. 1974. Drainage for salinity control. In. J. van Schilfgaarde (Editor), Drainage for Agriculture Monograph 17, Am. Soc. of Agronomy, Madison, Wi, pp 433-461.

Raj, M. and Nath, J. 1984. Evaluation of water requirement for reclaiming saline soils, Ind. Soc. Soil. Sci. 32 : 245-52.

Ranade, D.H. 1984. Leaching phenomenon in sandy loam soils, M. Tech, Thesis, I.I.T., Kharagpur,

Rao, K V.G.K. and Leeds Harrison, P.B. 1989. Water management strategies for improving leaching with subsurface drainage, In Proc. National Symposium on Management of Irrigation System (Eds. Tyagi et al), CSSRI. Karnal, Feg. 24-27, 1988 (in press)

Tyagi, N.K. 1984. Effect of land surface uniformity on some economic parameters of irrigation in sodic soils under reclamation, Irrigation Science 5 (3) : 151-160.

U.S. salinity laboratory Staff 1954. Diagnosis and improvement of saline and alkali soils, Agric, Handbook No. 60, USDA, Washington, D.C.