

MANAGEMENT OF WATERLOGGED SALINE SOILS AND STRATEGIES TO MINIMIZE PROBLEMS OF DRAINAGE EFFLUENT DISPOSAL

S. K. Gupta

ABSTRACT

Expansion of irrigation to arid and semi-arid regions through inter basin transfer of water together with research and development in agriculture were instrumental to tide over the food scarcity crisis in the country. The expansion based on inter basin transfer of water, however, led to adverse environmental impacts. Within 10-15 years of operation of the projects, conditions of waterlogging and soil salinization appeared in many irrigation projects. The present paper highlights the causes of waterlogging and soil salinity in irrigation commands with reference to the projects in the Gujarat and Karnataka States of India. Amongst the various factors, inadequate drainage ranks as number one cause for the development of waterlogging in the commands. In the monsoon climatic conditions as prevails in India, surface drainage seems to be essential although it may not be able to control the water table. The paper also deals with the attempts being made in various irrigation commands to establish the feasibility of subsurface drainage for the reclamation and management of waterlogged salt affected soils. Some of the major findings are discussed to show that drainage cost in monsoon climatic conditions could be substantially reduced over the conventional designs applicable to humid climatic regions. In recent years, it has been seen that drainage effluent disposal could be a serious issue in planning drainage programs. Present paper highlights the water quality issues in India under various kinds of drainage systems. Drainage design issues (depth, spacing and bi-level drainage) and operational schedules that help to minimize generation of drainage effluent have been discussed. Direct and conjunctive use strategies have been highlighted to show that reuse of poor quality drainage effluent near to the generation sites is feasible. Mathematical models have been used to show that such a strategy would be sustainable on a long term basis. It is argued that an approach based on these two strategies in combination would make the drainage system cost effective and eco-friendly.

INTRODUCTION

Irrigation is the most effective means of increasing and stabilizing agricultural production in areas where rainfall is erratic and inadequate to meet the crop consumptive requirements. India, therefore, decided to make huge investments in

Head, Indo-Dutch Network Project; Central Soil Salinity Research Institute, Karnal-132 001 (India)

Water Resources Development (WRD) to expand its irrigation network. It also invested heavily in agricultural research and technology development. Such a strategy paid rich dividends. We entered the most spectacular green revolution ever witnessed and became self sufficient in food production. Lately, the irrigation sector has come under attack because the productivity has not increased as much as it was expected.

Appearance of adverse environmental impacts have created doubts on the sustainability of irrigated agriculture. It has also emboldened the environmentalists to urge some rethinking on further investments in the major and medium sectors of irrigation development. According to a report of the working group set-up by the Ministry of Water Resources, it is assessed that as much as 5.86 million ha of irrigated land has been affected by the twin problems. Thus, huge investments made in developing irrigation potential for these lands are locked. Besides, annual losses on account of interest on this investment, loss of crop production sums up to several thousands crores (1 crore=10 million and 1 US \$ = Rs. 43) of rupees.

DRAINAGE: THE KEY FACTOR

Rise in water table is an inevitable consequence of surface irrigation through inter-basin transfer of water. Several factors together determine the rate at which water table would rise in a given setting. Some of these factors are common to many irrigation commands while few others are site specific and would be applicable only to specific commands. Amongst the common factors, inadequate drainage and poor maintenance of the drainage systems can be cited. As per the information supplied by the states to the working group, inadequate drainage has been cited as one of the reasons for the development of waterlogging. On the other hand, drainage improvement has also been suggested as a remedial measure for the amelioration of the problems of waterlogging and soil salinity (Report Working Group, 1991). The states which have given these reasons are: Andhra Pradesh, Haryana, Karnataka, Madhaya Pradesh., Bihar, Maharashtra, Punjab, Tamil Nadu and Uttar Pradesh. Attempts have been made in the past to determine and rank various factors/processes that are responsible for waterlogging and soil salinity in irrigation commands (Table 1). Amongst various factors, inadequate drainage takes the first rank in irrigation commands of the Karnataka and the Gujarat states (Reddy, 1991; Gupta and Khandelwal, 1996).

DRAINAGE ALTERNATIVES

Most common techniques to drain excess water are: A) Surface drainage and B) Subsurface drainage. Subsurface drainage could be achieved through i) horizontal subsurface drainage, ii) Tube well or vertical drainage. Many local alternate solutions to drain the lands have been identified but the basic principles of these

alternate techniques have been derived from one of the three alternatives.

Table 1 Response to Factors Leading to Waterlogging in Irrigation Commands

Reason	Weighted rank in Ukai-Kakrapar (%) ¹	% respondents in Commands ² in Karnataka
Inadequate drainage	74.1	100
Seepage and leakage	66.7	-
Excess water	65.6	-
Poor maintenance of drainage system	61.7	92
Change in cropping pattern in favour of waterloving crops	60.4	82
Poor on-Farm W.M.	56.0	46

- Not responded ¹ Source: Gupta and Khandelwal (1996)

² Source: Reddy (1991)

Surface Drainage

The surface drainage problem is most commonly associated with humid regions. However, in monsoon climatic condition as are prevalent in India, problem of surface drainage could be experienced even in the arid and the semi-arid regions. The problem may be quite serious in regions where average annual rainfall exceeds 500 mm. Analysis of daily rainfall data reveals that there are ample opportunities for water stagnation to occur in crop lands (Table 2). The unfavorable soil characteristics and flat topography may accentuate the problem. As the water table in irrigation commands rises, the absorption of water is reduced, so that the depth of stagnation and the duration for which stagnation occur also increases. For example; in the semi-arid region of Haryana, it is not uncommon to see pools of water for prolonged periods in areas with shallow water table. Rain water stagnation by more than one day could be experienced from storms of 5 year return period (Rain storms expected to occur once in five years i.e at a probability of 20 %). With storms of 10 year return period, the stagnation might continue for 3 days or more (Rao et al., 1994). Surface drainage requirements also depend upon the crop characteristics.

Degree of drainage required, therefore, could to some extent be manipulated through selection of crops. (Gupta et al. 1992) collated the available information on this aspect and determined the relative tolerance of some crops (Table 3). The data reveal that sunflower, cotton and wheat on normal lands are relatively more tolerant than other crops. Benefits of surface drainage have been reported by many workers particularly in heavy soils. The data from the Ukai-Kakrapar command reveal that by preventing surface stagnation for prolonged periods, yield improvement to varying degrees could be obtained (Table 4).

Table 2 Storm Rainfall of Various Duration at Different Probabilities

Station climate (Rainfall mm)	Duration (days)	Storm rainfall (mm) at % probability				
		10	25	50	75	90
Hisar, arid (375)	1	64	39	25	18	11
	2	102	75	60	42	39
	3	119	93	75	60	52
	4	135	110	81	78	62
Ludhiana semi-arid (681)	1	178	145	95	58	42
	2	220	179	116	69	50
	3	232	189	125	77	56
	4	237	195	132	85	66
Cuttack sub-humid (1514)	1	198	167	128	85	70
	2	275	229	173	109	87
	3	293	246	188	123	101
	4	312	264	205	138	115
Dapoli humid (3372)	1	363	309	227	166	140
	2	530	463	362	286	254
	3	623	555	452	376	342
	4	719	641	523	435	398

Table 3 Relative Tolerance of Crops to Surface Stagnation of Water

Threshold (t) (hrs)	Crops
0<t<12 (1 day)	Wheat (A), Groundnut Maize (*), Potato Green peas, Mustard
12<t<36 (1 to 2 days)	Pigeon pea, Cow pea, Barley(A)
36<t<60 (2 to 3 days)	Wheat(N), Beets, Forage Sunflower, Cotton

Threshold value indicate that if water stagnation does not exceed this value, there would be no decrease in the yield. Beyond this the crops would be adversely affected.

A=semi reclaimed alkali soils

N=normal soils

* at the most sensitive stage

Table 4 Yield Increase in Crops Achieved following Improvement in Surface Drainage

Crop	Yield improvement (% over poorly drained)
Sugarcane	19.1-27.7
Paddy	19.7-24.7
Gram	32.1
Indian bean	49.8

A group of engineers/planners believes that surface drainage is a panacea for all the ills of the irrigation commands in India. No doubt, problems to some extent could be traced to inadequate surface drainage; yet it has been shown beyond doubt that water table rise has occurred unabated even in areas where surface drainage has been provided. Surface drainage could reduce the rate of rise of the water table but can not prevent its rise altogether. Experiences have also revealed that surface drainage alone is not helpful in the reclamation of waterlogged saline lands. Reclamation of salt affected soils through leaching alone was not successful on a sustainable basis. A crop of wheat could be grown with rain water management during the monsoon season followed by leaching before the sowing of wheat. The following *kharif* crop could not be grown successfully due to salt accumulation in

the root zone due to secondary soil salinization during the summer season (Gupta, 1983). A surface drainage system installed at Mooraj in the Mahi-Kadana command failed to reclaim the waterlogged saline land. The system was, therefore, converted to a subsurface drainage system after 2 years of operation (Singh and Kumbhare, 1987). In RAJAD project in the Chambal command of Rajasthan, leaching in the controlled plots is reported to be less than 5 percent. Drainage improved the leaching pattern substantially and with surface drainage 20-22 percent of salts could be leached. But it failed to reclaim the land over a 1.5 year period (Tyagi et al. 1996).

From the foregoing, it seems that provision of surface drainage has to be made in most areas especially in humid, sub-humid and semi-arid areas. The surface drainage has to be an integral part of any water management or drainage plan. The cost of the system could be partially recovered as it helps to reduce the cost of subsurface drainage.

Subsurface Drainage

Subsurface drainage could be accomplished either with vertical or horizontal drainage. Our past experience with vertical drainage has been quite good so much so that many people think that this technology could be extended to waterlogged salt affected areas. The extension of this technology to such areas is subject to availability of good aquifers and quality of water. As a result of these limitations the progress of vertical drainage has been abysmally slow.

Horizontal Drainage: Sporadic experiments on horizontal drainage have been conducted in this country since the beginning of this century but concerted efforts have only been made during the last two decades. Well investigated and scientifically laid out systems have generated data on the usefulness of this technology to control water table in the pre-decided range as well as in helping to leach down the salts. The horizontal subsurface drainage is most suited to control water table in humid regions, in arid and semi-arid regions where water table in the month of June is within 2 m of the ground surface and is of poor quality, disposal outlets are limited and to reclaim highly salt affected soils where other kinds of drainage may not suit or may take longer time to leach down the salts. It appears at this stage that there are no doubts about its technical feasibility (Table 5).

The important questions agitating the researchers and planners however has been its initial cost and problems related to drainage effluent disposal. Thus, research efforts are directed to obtain general as well as site specific solutions to the problems so as to minimize the cost of the drainage systems. Mole drains, chimney drains, brick, bamboo and gravel drains (The last three names derived on the basis of material used for drains) have been designed as a result of these efforts. These alternatives could help to reduce the cost. Improved design criteria

Table 5 Benefits of Subsurface Drainage for Reclamation and Crop Production at Sampla

Particulars and years after installation	Reclamation and crop yield in drain spacings (m)		
	25	50	75
Soil EC _e (0-15)			
0 year	52.2	59.4	49.5
10 years after	4.7	4.7	4.9
Crop yield (t/ha)			
0 year	0.0	0.0	0.0
10 year average	4.9	4.4	4.0

Table 6 Cost of Different Drainage Systems

Drainage Technique	Cost (Rs./ha)
Surface drainage	7,000-10,000
Sub-surface drainage	20,000-30,000
Vertical drainage ¹	5,000- 7,500 +Rs 100,000/annum
Bio-drainage ²	11,000

¹ The lower value of cost/ha with the assumption that tube well serves an area of 5 ha. The value shown separately with plus sign is the operational and maintenance cost of a government tube well.

² It includes maintenance for 2 years and surface drainage cost. (Cost as per UPLDC (1991) document excluding the cost of gypsum)

are also being developed to reduce the cost. The cost of an integrated drainage system would be much less than a single drainage system. An idea of the cost of individual drainage systems could be had from the data on cost provided in Table 6. We have sufficient data and expertise to achieve this kind of integration. There is also a need of an unified apex organization that could integrate the activities such as monitoring of the problems, plan measures for prevention, take up surface

or subsurface drainage works and undertake reclamation of saline/alkali lands. A major limitation in this kind of drainage seems to be the disposal of drainage effluent as it might cause adverse environmental impacts. Studies are underway to develop technologies for minimizing return flow, (re)use of drainage effluents and disposal through various means including evaporation tanks and bio-drainage (Gupta, 1998).

STRATEGIES TO MINIMIZE DRAINAGE EFFLUENT

On-farm Water Management

Introduction of irrigation has generally created an imbalance between the recharge and discharge to the aquifer. As a result water has been taken into storage that led to the rise in the water table in the irrigation commands. Leakage and seepage from the system components and poor on-farm water management are often cited as contributing factors to this development. It is estimated that project efficiencies are as low as 30 percent. The state of affairs could also be visualized from the fact that at many places field to field irrigation is still practiced although more than 20 years have elapsed when the irrigation was introduced. Thus, the most cost effective approach to reduce drainage discharge could be to incorporate a fairly good degree of on-farm water management practices that reduce seepage and deep percolation losses. Technically feasible and cost effective measures could be lining of water courses, scientific irrigation scheduling, improved control and measurement of irrigation water, land leveling, proper design of conventional irrigation system or switch over from traditional to improved irrigation methods. Besides these, participatory irrigation management and pricing of water to recover at least the cost of operation and maintenance could help improve on-farm water management. The potential of these practices in improving irrigation efficiencies has been demonstrated widely in India, yet the implementation is subject to a wide range of economic, institutional, environmental and social constraints.

Drainage System Design and Operation

For sustained irrigated agriculture, drainage improvement is the key element. In the Indian context, however, improvement in drainage is required only for short critical period of time during a year (mostly the monsoon season). Thus, there could be several drainage system designs, which can be utilized to satisfy agricultural requirement. The drainage systems can also be managed through operational schedules, which could have a bearing on the quality of drainage effluent or the salt load.

Drainage Coefficient or Drainage Design Criterion: In the design of the subsurface drainage system, drainage coefficient determines the amount of discharge that would be expected during the operation of the system. Thus, an accurate estimate of

the drainage coefficient would not only help to reduce the drainage effluent but would also reduce the cost of the drainage system. It has been seen that a drainage coefficient calculated on the basis of water during the monsoon season would help to maintain the water table as well as ensure sufficient leaching. As an example, a drainage coefficient of 1.5 mm/day was worked out on the basis of this approach. For the same site, one would arrive at a drainage coefficient of 5.5 mm/day if leaching of salts from the upper 60 cm soil profile is taken as the criterion to assess the drainage coefficient. It may be noted that former value is less than 1/3 of the later.

Even under non-steady state conditions, a more conservative drainage design criterion could be adopted. The commonly used criterion in India states that water table be lowered to 30 cm below the ground surface in 2 days time once the water table reaches at the soil surface. Studies at one of the experimental site (Sampla, Haryana, India) for alluvial soils have revealed that in a system where lateral drain spacing lowered the water table in 2.5 days time, average yield of 90 % could be obtained over a 10 year period time (Gupta et al. 1998). There was little difference in salt leaching except during the first few years (Table 7). Experiences at other places have also shown that drains could be spaced farther apart compared to the conventional design criterion.

Table 7 Relative Salt Leaching (Top 60 cm Profile) in Plots With Different Drain Spacing (System Installed in 6/84)

Drain spacing (m)	Fraction of salt leached in month/year							
	10/84	3/85	4/86	11/86	6/87	11/87	4/90	6/95
25	0.66	0.85	0.89	0.87	0.88	0.85	0.93	0.91
50	0.45	0.69	0.78	0.88	0.78	0.76	0.87	0.92
75	0.36	0.36	0.60	0.74	0.66	0.65	0.84	0.90

Operational Schedules: Shallow water table may not always be a curse. Most crops are capable of drawing water from the shallow water table to meet their consumptive use requirement. The direct water use by the crops from the shallow water table could be aided by withholding irrigation or following what is usually called a deficit irrigation schedule. It could also be achieved by withholding water towards the end of the crop season (say by skipping the last irrigation). Such a strategy not only helps to reduce the irrigation water requirement of the crops but also reduces the drainage effluent. Experience in India have shown that once the water table approaches 1 m depth, pump operation could be so scheduled that water table remains at or around this depth. Any drainage at this depth could occur under natural conditions. The data reveal that with this strategy, yield with a water expense

of 245 mm is nearly the same as with an expense of 355 mm (Table 8). Thus, one could save about 2 irrigations provided water is maintained at about 1.0 m depth.

Bi-level Drainage: The strategy to withhold water table at about 1 m depth has been found beneficial in aiding the uptake of water by the crops. In addition to what has been stated in the foregoing paragraph, another way to achieve the same objective could be through the installation of bi-level drains. A bi-level drainage system is a system of horizontal drains in which two adjacent drain lines are laid at two different elevations or levels on an alternating basis. A line laid at relatively shallow depth (1 to 1.2m) is followed by a line at relatively deeper depth (1.5 to 1.8 m). It may be noted that the discharge from a bi-level drainage system once the water table reaches the shallow drain depth is much less than the conventional drainage system for the same drain spacing (Table 9). It is nearly equal to the discharge from drains spaced at double the spacing.

Table 8 Effect of Groundwater Salinity and Water Expense on Wheat Yield at Sampla

Water expense (mm)	Yield* (t/ha) with ground water salinity (dS/m)			
	3.0	5.5	20.0	Mean
135	4.55	3.20	2.45	3.55
190	4.95	4.70	3.85	4.50
245	5.45	4.45	5.05	5.00
300	5.50	4.80	4.85	5.05
355	5.30	4.85	4.90	5.00

* Average of 2 years; Source: Rao et al. (1992).

Table 9 Comparison of Discharge Rate from Deep Drain in a Bi-level and a Level Drainage System

	Spacing (m)	Discharge per unit length ($h_0=1.8$ m & $h_1=0.6$ m)	Discharge per unit length ($h_0=1.5$ m & $h_1=0.3$ m)
Bi-level	50.0	0.14	0.06
Level	50.0	0.23	0.11
	100.0	0.12	0.05

Source: Verma et al. (1998)

h_0 is the depth of the relatively deep drain while h_1 is the difference between the elevations of the two drains.

Integrated Drainage System

The importance of surface drains in fields where subsurface drainage has been implemented is often misunderstood. It is more so when the purpose of drainage is to reclaim the salt affected lands. Under these conditions, it is believed that most of the rainfall should be stored in fields with dykes of appropriate height and allowed to drain through subsurface drains to facilitate leaching of salts. It may be true in the first one or two seasons but later on the depth and duration of storage has to be commensurate with the tolerance of the crop to water stagnation. The surface drains should be designed on this basis as it would help to reduce the recharge to the groundwater as well as reduce drainage discharge to the extent water is removed by the surface drains.

It may be mentioned that implementation of an integrated drainage system combining surface/subsurface drainage would not only influence the time distribution of the water flow from the fields but also the salt loading. Usually surface run-off waters are of relatively better quality than subsurface drainage effluents (Table 10). The data reveal that the former could be directly used for most crop combinations. Moreover, surface run-off could usually be drained by gravity. Thus, the problems of drainage water disposal would be much less than with the drainage effluents from subsurface drains.

Table 10 Average Chemical Composition of Water from Various Sources in Haryana

Water	EC (dS/m)	SAR	Solute concentration (me/L)			
			Ca+Mg	Na	HCO ₃	Cl
Canal water (Western Jamuna canal, Sampla)	0.70	0.80	2.00	0.8	2.00	0.80
Drain No. 8 (Gohana)	0.55	2.24	2.60	2.56	2.55	1.80
Subsurface drainage water (Sampla)						
1986-87	26.50	16.80	173.00	156.00	1.80	315.00
1989-90	15.00	14.50	126.00	115.00	1.60	221.00

Source: compiled by Gupta and Gupta (1997)

Reuse Strategies

Reuse of drainage effluents at a place nearest to its generation is probably the best way to avoid problems related to its transportation and disposal to natural drains. It should be possible to reuse saline drainage effluents either directly or in conjunction with fresh water depending upon the quality of the drainage effluent. Choice of crops and choice of an irrigation method could help to widen the reuse alternatives.

Selection of Crops: Intragenic and intergenic differences in salt tolerance of crops could be exploited to use the saline drainage effluents. Usually grasses and forest trees are more tolerant to salts than many arable crops. Most tolerant being some of the halophytes. Thus, to widen the range of salt tolerance, these species could be considered and grown on some parcels of lands. These parcels of lands could be solely irrigated by saline water. Sequential application of drainage water to cereal crops, grasses, forest plantations and halophytes could be used to concentrate and reduce the saline drainage effluents for disposal. Although, such a complex system may not be needed at present, its potential may be kept in view for future research studies.

Irrigation Methods: The effect of saline environment on crop growth is basically due to the combined effect of matric and the osmotic stresses. To minimize the adverse effects due to osmotic stress, one could manipulate the matric stress

(minimize) to get good crop yields under saline environment. A irrigation method by which one could apply shallow but frequent irrigation would be helpful in minimizing matric stress. Evidences have been generated to show that with sprinklers and drip irrigation, relatively more saline waters could be applied than with surface irrigation. A pitcher irrigation technique developed at CSSRI, Karnal has been successfully used to grow even sensitive crops with saline waters (Table 11).

Table 11 Irrigation water salinity for equivalent yield as that with fresh water

Crop	Irrigation water salinity (dS/m)
Tomato	5.7
Brinjal	9.8
Cauliflower	15.0
Ridge-gourd	3.2
Cabbage	9.7
Water melon	9.0
Musk melon	9.0
Grapes	4.0

Source: Dubey et al. (1991)

Conjunctive Use: Without doubt, surface irrigation would continue to dominate Indian agriculture for the next few decades. Thus strategies which would allow use of saline waters with surface irrigation would have a greater potential of their application. Conjunctive use of surface (fresh quality) and poor quality waters through blending or cyclic application could be employed to minimize adverse effects of poor quality ground waters on land and water resource. It would allow to achieve yield potentials which are nearly equal to the one attained with fresh water alone.

Both the blending and cyclic use strategies have been adopted for reuse of drainage waters (Sharma et al. 1991). Practically speaking, blending is useful in cases when fresh and drainage water qualities are such that mix water would have salinity less than the threshold salinity up to which there is no yield reduction of a given crop. In other cases cyclic use strategy would be more beneficial.

Notwithstanding the salinity build - up in the soil profile in conjunctive use, the monsoon climatic conditions that are prevalent in India, favor the adoption of cyclic use strategy. More than 80% of the salts accumulated in the root zone during the winter season are leached down the profile during the monsoon season. Thus, the root zone becomes fit for cultivation and recycling of the drainage effluent. Model

studies have also revealed that some accumulation of salts may occur on annual basis in years when the monsoon season rainfall is below the average. However, above average rainfall years helps to maintain the salt balance in the root zone over the long run. Thus, one could overlook the salt accumulation over a season or even during an abnormal year (Below average rainfall year).

CONCLUDING REMARKS

Reclamation and management of waterlogged salt affected soils seems to be the key element in generating confidence on the sustainability of irrigated agriculture in the country. The inevitability of drainage is now being realized at different levels. It seems that the cost of drainage and the huge investments that are needed are the biggest impediments in implementing drainage plans. As much as 20-25 million tonnes of food grains could be produced as a result of reclamation of these lands in irrigation commands. An integrated drainage system with surface and horizontal pipe drainage seems to be one of the most appropriate strategy to reclaim the lands already affected by waterlogging and soil salinity. Although technical and economic feasibility of the system has been established, disposal of drainage effluent seems to be still a critical issue. For this purpose, several strategies have been described. It is, however, visualized that no single strategy would be able to solve the problems. Since most drainage water may not have lost their potential for reuse, we are optimistic that strategies, which reduce the drainage discharge together with its reuse could help plan the effluent disposal in a far better manner than without these strategies.

REFERENCES

- Dubey, S.K., Gupta, S.K. and Mondal, R.C. 1991. Pitcher irrigation techniques for arid and semi-arid zones. *Dry land Resources and Technology*-6. 137-177.
- Gupta, S.K. and Gupta, I.C. 1997. *Management of Saline Soils and Waters* (2nd revised Edition). Scientific Publishers, Jodhpur. 299 pp.
- Gupta, S.K. 1983. Evaluation of leaching and resalinization behaviour of saline soils in relation to crop growth. Annual Report, Central Soil Salinity Research Institute, Karnal. 114- 115.
- Gupta, S. K. and Khandelwal, M.K.1996. A critical analysis of waterlogging in the Ukai-Kakrapar irrigation Project. Proc. 3rd Int. Agricultural Engineering conference of the Asian Association of Agricultural Engineering.9-12 Dec. Pune. Vol. 1.561-570.
- Gupta, S.K.; Singh, R.K. and Pandey, R.S. 1992 : Surface drainage requirement of

crops: A piecewise linear model for evaluating submergence tolerance. *Irrig. and Drainage Systems* 6 : 249 - 261.

Reddy, M.V. 1991. Environmentally sound irrigation system development, problems and prospects- a case study from India. Paper presented at Alexandria Symposium in ODU Bulletin 24,6.

Report of the Working Group on Problem Identification in Irrigated Areas with Suggested Remedial Measures, 1991. Ministry of Water Resources, Government of India, New Delhi.

Singh, O.P. and Kumbhare, P.S. 1987. Evaluation of drainage design parameters under different soil and climatic conditions. Annual Report, Central Soil Salinity Research Institute, Karnal. 60-61.

Tyagi, S.C.; Nagar, R.P.; Tejawat, C.M. and Singh, H.H. 1996. Efficacy of gypsum in amelioration of saline sodic soils of Chambal command, Rajasthan. Proc. National Workshop on Reclamation of Waterlogged Saline and Alkali Soils and Prevention Thereof. Min. of Water Resources, Govt. New Delhi.

Rao, K.V.G.K., Sharma, D.P. and Oosterbaan, R.J. 1992. Sub-irrigation by groundwater management with controlled drainage in semi-arid areas. Proc. Int. Conf. Supplementry Irrigation and Drought- Water Management. 7.1-7.9.

Sharma, D.P., Singh, K.N. and Rao, K.V.G.K. 1991. Reuse of Saline Drainage for Irrigation. Brochure No. 16. Central Soil Salinity Research Institute, Karnal. pp 16.

Verma, A.K., Gupta, S.K. Singh, K.K. and Chauhan, H.S. 1998. Bi-level drainage: an analytical solution of the Boussinesq equation. *Agricultural water Mgt.* (Accepted).