MODELLING OF SALINIZATION AND NITROGEN LOSSES UNDER SUBSURFACE DRAINAGE SYSTEM

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2000

MODELLING OF SALINIZATION AND NITROGEN LOSSES UNDER SUBSURFACE DRAINAGE SYSTEM

By

MAN SINGH

A Thesis

submitted to the Faculty of Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfilment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

AGRICULTURAL ENGINEERING

2000

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This is to certify that the thesis entitled **"Modelling of Salinization and Nitrogen Losses Under Subsurface Drainage System"**, submitted to the Faculty of the Post Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy in Agricultural Engineering,** is a record of *bona fide* research work carried out by **Mr. Man Singh,** under my guidance and supervision and that no part of this thesis has been submitted for any other degree or diploma. All the assistance and help availed during the course of investigation as well as source of information have been duly acknowledged by him.

Place : New Delhi

Date : August 14, 2000

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ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Dr. A.K. Bhattacharya, Principal Scientist and Project Coordinator (Agril. Drainage) & Chairman of the Advisory Committee, Water Technology Centre (WTC), Indian Agricultural Research Institute (IARI), New Delhi for his continued encouragement, able guidance, constructive criticisms and keen interest in this work throughout the course of study.

Sincere thanks are extended to Dr. A.K. Singh, Project Director, W.T.C. and Member, Advisory Committee for providing all possible facilities and also for his valuable suggestions and guidance offered from time to time.

The author gratefully acknowledges the useful discussions held with Dr. A. Singh, Professor, W.T.C. and Dr. P.K. Malhotra, Head, Division of Computing Science, IASRI, New Delhi, both members of the Advisory Committee.

Special appreciation goes to Dr. T.V.R. Nair, Project Director (retired), Nuclear Research Laboratory (NRL) and Member, Advisory Committee who has provided the lab facility and contributed in many ways through frequent interactions.

Sincere thanks are due to Dr. J.S. Panwar, Head of the Division and Dr. O.P. Singhal, Professor of Agricultural Engineering for their constructive criticism and suggestions offered at the time of formulation of the objectives of the study and also during the seminar.

The author is indebted to Mr. K.R.K. Prasad, In-charge, Mr. Ramesh Chandra and Mr. Shyam Sunder both scientists of Agricultural Research Station of A.N.G. Ranga Agricultural University, Machiliptanam, A.P. for their kind cooperation during field investigation of the study. Thanks are also due to all the technical and supporting staff of the cooperating centre of the All India Co-ordinated Research Project on Agricultural Drainage, for their hardwork and tireless support in data collection.

The author is indeed grateful to Mr. R.J. Oosterbaan of ILRI, Wageningen, the Netherlands, for providing him the latest version for SALTMOD free of cost and promptly interacting through electronic mails. Also, the author appreciates the help rendered by Prof. J. Letey and Mr. X.P. Pang, Department of Environmental Science, University of California, Riverside, USA, in application of ENVIRO-GRO model for modelling studies.

Due appreciation goes to Drs. B.R. Yadav, Subedar Singh, R.K. Rattan, Y.K. Sud, Shivadhar Singh and K.K. Sharma, all senior members of faculty of P.G. School, IARI, for their contribution in many ways through frequent contacts and discussion. Also, the author is thankful to his colleagues, Dr. D.K. Singh and Dr. A. Sarangi for their endeavour in making the computing facility of W.T.C. up to date and available round the clock. The author is grateful to Drs. S.P.S. Tomar, Birendra Singh, R.P. Lohumi, Jagdish Prasad for their technical assistance in performing physical and chemical analysis of soil and water samples. Also, special word of thanks are due to Dr. Bhupinder Singh and Mr. Mohan Lal of NRL for their help in analysing the plant samples.

The assistance received from Mr. Tirtha Dasgupta, Division of Agricultural Extension, IARI in preparing and organizing most of the illustrations, is highly appreciated and acknowledged.

The author is grateful to Director, IARI for granting him study leave and to the Dean and Joint Director (Education), P.G. School, for granting the partial financial support for the period of study.

I also thank Mr. P.K. Garg who typed the manuscript neatly.

The author cherishes the blessings and best wishes of his mother, brother and in-laws though staying miles away.

Lastly, I would like to name my wife Anju who's endurance and co-operation has always energized me to meet my goal.

The author dedicates his thesis to the memory of his beloved father late Shri Jai Singh.

Man Singh

Date : August 14, 2000 **(Man Singh)**

Place : New Delhi

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LIST OF SYMBOLS AND ABBREVIATIONS

cm	:	Centimeter
cm ha^{-1}	:	Centimetre per hour
c.mol (p^{+}) kg^{-1}	:	Centimole proton per kilogram, unit of CEC
^{0}C	:	Degree celcius
ds/m, dS m^{-1}	:	Deci Siemens per metre
g/l, g l^{-1}	:	Gram per litre
ha	:	hectare
ha.mm	:	Hectare.millimetre
kg ha^{-1} yr^{-1}	:	Kilogram per hectare per year
kg N ha^{-1}	:	Kilogram nitrogen per hectare
kg	:	Kilogram
km	:	Kilometre
m	:	Meter
m d^{-1}	:	Metre per day
m d^{-1} m^{-1}	:	Metre per day per metre
m d^{-1} · m^{-2}	:	Metre per day per square metre
me l^{-1}, me/l	:	Milliequivalent per litre
Mg ha^{-1}	:	Mega gram per hectare
mg l^{-1}	:	Milligram per litre
Mg m^{-3}	:	Mega-gram per cubic metre
mm	:	Millimeter
mm d^{-1}	:	Millimetre per day
N	:	Nitrogen
NH_4^+	:	Ammonium ion
NH_4-N	:	Ammonium nitrogen
NO_2^-	:	Nitrite ion
NO_2-N	:	Nitrite nitrogen
NO_3^-	:	Nitrate ion

NO_3-N	:	Nitrate nitrogen
sq. km	:	Square kilometre
t ha^{-1}	:	metric tonnes per hectare
@	:	At the rate of
%	:	Per cent
AICRPAD	:	All India Coordinated Research Project on Agricultural Drainage
CEC	:	Cation exchange capacity
conc.	:	Concentration
CWC	:	Central Water Commission
DAT	:	Days after transplanting
EC	:	Electrical conductivity
EC_e	:	Electrical conductivity of saturation extract
ESP	:	Exchangeable sodium percentage
Fig.	:	Figure
Max	:	Maximum
Min	:	Minimum
PET	:	Potential evapotranspiration
S.D.	:	Standard deviation
SSD	:	Subsurface drainage
Temp	:	Temperature

CHAPTER-I

INTRODUCTION

Irrigation water, even if of good quality, contains some amount of dissolved salts. Continuous application of irrigation water over the years means a continuous addition of salts to the cropped land. The water is consumed by the crop or evaporates directly from the soil. The salts, however, are left behind in the soil profile. This process is called salinization. If the salts accumulate in the soil profile beyond a threshold limit, which is different for different crops, optimum uptake of water and nutrients by the crop plants is impeded, decreasing the crop yield considerably. If soil salinization is to be avoided, the dissolved salts have to be leached out of the root zone by the water percolating to the sub soil. This percolating water may further cause the water table to rise and needs to be drained out. If not drained, the percolated water may cause the water table to come sufficiently close to the soil surface and contribute to upward flux of relatively poorer quality of water. Apart from this, salinization of soil is also influenced by climate, soil type, irrigation water quality, water management practices and the depth to, and salinity of the water below the water table. The current estimate of saline soil in the irrigated areas is about 3.3 million hectare in the country (CWC, 1998).

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Saline to saline sodic clay soils are found in the low lands of coastal region of India. Salinization of such heavy textured soils is primarily caused by tidal backwater flow, long term evaporation from shallow water table, capillary flux from brackish ground water etc. When adequately drained, these heavy textured soils offer good prospects for agricultural production (Devadattam and Ramesh Chandra, 1995; Rycroft and Amer, 1995; Bhattacharaya, 1996). A subsurface drainage system controls the water table, restricts the salinization caused by capillary flux from saline ground water and facilitates the leaching of the salts from the root zone soil profile. However, as a subsurface drainage system continuously removes salt and water from the soil profile, it is apprehended that some amount of nutrients applied to the cropped land may also be lost through subsurface drainage effluent.

Nitrogenous fertiliser is easily soluble in water and its species like NH_4^+ and NO_3^- are mobile and thus N is one of the nutrients which may be partially depleted through leaching losses. Studies on the quantification of nitrogen losses under the influence of sub-surface drainage systems are very limited in India. A probable reason for not conducting studies on this aspect in the past, could have been a very low national average N-fertiliser application rates like 60-120 kg ha^{-1} $year^{-1}$ with an exception of the state of Punjab where N- fertiliser consumption ranged from 150 to 250 kg ha^{-1} $year^{-1}$ (Aulakh and Singh, 1997). The other reason could be that a very limited area is under subsurface drainage in the country at present, vis-a-vis the salinized irrigated area.

In the last 15 years, subsurface drainage systems have been installed in around 25,000 ha. of cultivable lands which are waterlogged or salt affected distributed in 8 states of India. Such affected areas under the sub-surface drainage are likely to increase manifolds in years to come, should India want to sustain the health of the key production base, i.e., the land resources, on a long term basis.

The recovery of nitrogen by plant and soil were found to be 47 to 61% and 24 to 36%, respectively, in wetland rice without sub-surface drainage (Koyama *et al.,* 1977; Reddy and Patrick, 1978). The recovery may go down further where sub-surface drainage systems have been installed to reclaim the salt affected lands and for salinity control. Keeping the future needs in mind, scientific studies pertaining to the quantification of such nutrient losses under the influence of subsurface drainage system and the rate of salinization in the absence of subsurface drainage systems are of considerable importance. Besides, knowledge of the chemical composition of drainage effluents from the various kinds of land reclamation projects is necessary to understand the long term environmental impact of such projects. The goal of this study is to add to the existing knowledge to help formulating operational policies of the subsurface drainage system and the nitrogen fertiliser application schedule (timing, rate and forms of placement) with the objective of reducing the nutrient losses and salinity control via sub-surface drainage system.

The specific objectives of the study undertaken are:

i) Measurement of salinity levels and nitrogen losses under subsurface drainage system.

ii) Selection of an appropriate model using field observed data on salinity and nitrogen losses.

iii) Simulation of salinization of soil profile during non-drainage period and validation of the results.

CHAPTER-II

REVIEW OF LITERATURE

2.1 General

The state of the development of drainage in arid and semi-arid regions of the country is lagging far behind as compared to the development of irrigation. This leaves the irrigated agriculture at high risk of losing productive lands to waterlogging and salinization. New and large irrigation projects may not be envisaged any more as was done in the sixties and seventies because of the financial and also site constraints. Therefore, scientific management of land and water is the key to food security both by increasing the productivity and avoiding any further degradation of the resource bases of land and water. Drainage is an important technological component of this management activity.

In the field, irrigation water and rainfall received at the surface is partly held on the surface (temporarily), partly infiltrates down and partly flows out as runoff. The part of the water that infiltrates into the soil, is stored in the soil pores and used by the crop. If the rain or irrigation continues for longer period or in excess of the storage capacity of the soil, a pool may be formed on soil surface and/or part of the infiltrated water is lost as deep percolation beyond the root zone. When percolating water reaches that part of the soil which is saturated with water, it causes the water table to rise. If the water table reaches the root zone, then the soil is called waterlogged. Even if, irrigation water is of good quality, it contains some salts. Thus, bringing irrigation water without appropriate management leads to waterlogging and salinization.

To combat the twin problems of waterlogging and salinity, drainage is needed. Waterlogging and salinity was first noticed in the upper region of Rechana duab a few years after the opening of lower Chenab canal in 1892 whereas the problem of drainage and salinity were observed in the Meenak area of Karnal in 1855. Both of these places were in the greater Punjab of the erstwhile undivided India. An attempt was made by the Punjab Government for the control of salinity in 1908. Inglis and Gokhale (1928) conducted drainage studies at Baramati experimental farm and reported that the drains effectively lowered the water table and reduced the salinity.

As subsurface drainage system continuously removes dissolved salts from soil profile, it is apprehended that some amount of various species of water soluble nitrogen namely, ammonium, nitrite and nitrate may also be lost through sub surface drainage water. Thus, the author has chosen to review and comment on some of the studies related to water table and salinity control by subsurface drainage in chemically degraded lands. The findings of such studies were based on modelling as well as experimental approaches to assess desalinization in the presence of subsurface drainage; salinization in the absence of adequate drainage; water quality monitoring of drainage effluents; soil salinity distribution in space and time; nitrogen losses via leaching and subsurface drainage effluents.

2.2 Water movement and leaching of salt

Salt affected heavy textured soils were found to be susceptible to deflocculation, dispersion of clay and clogging of the soil macropores (Rands *et al.*, 1986). If economic drainage systems are to be designed for salt affected clay soils, it is essential to understand the nature of leaching process. Clay soils characteristically have two distinct groups of pore sizes, namely, micropores and macropores. The largest groups occupy the mass of the clay and consists of the smaller micropores. The other group consists of the larger macropores, formed by shrinkage cracks or by the channels created by the activity of soil fauna, roots etc. Virtually all drainage in cracking clay soils takes place through these macropores, (Bouma, 1985 ; Singh and Kanwar, 1991). During leaching, salt contained in the water within the micropores may be considered to be immobile compared with that contained in the water passing through the macropores, (Wagenet, 1983; Tanton *et al.*, 1988).

Tanton *et al.* (1988) suggested that the leaching process in clay soils was a two phase process, with salt being transported by diffusion form the immobile phase within the micropores to the mobile phase in the macropores. It was argued that the rate of leaching was not limited by the diffusion process but by insufficient flow through the macropores. Their results indicated that leaching could be very effective if the soil was flood irrigated and the soil either naturally or artificially well drained. Under the influence of rainfall, however, infiltration into the macropores is known to occur down a very limited number of pathways (Bouma and Dekker, 1978) and these may be too few in numbers to provide effective leaching.

Tanton *et al.* (1995) designed an experiment to investigate the efficiency of leaching in a freely drained clay sub soil under both, at low steady application rate and high intermittent application rate of water. At the low steady rate, 118 mm of drainage had leached 27% of the salt over a period of 90 days and 33% of the salt was leached by 244 mm of drainage with intermittent application rate of water in the same period. The results clearly suggest that the installation of an intensive subsurface drainage system is expected to remove soluble salts from a saline sodic clay soils rapidly.

Beven and Germann (1982) observed that water movement in clay soils is dominated by water flowing rapidly down the cracks and the fissures, as well as in the root and worm channels. Reid and Parkinson (1984) found that the subsurface drains started flowing in the autumn season well before the soil profile attained the 'field capacity' and attributed this early onset of the flow through drains to the flow of water down the cracks widened by summer drought.

Leeds–Harrison *et al.* (1986) have described a layered drainage model for swelling clay soils based on seepage potential theory (Youngs, 1980) and experimental relationships between hydraulic conductivity and drainable porosity. In deriving this model it was assumed that excess rainfall instantaneously recharged a water table in the cracks, and that no uptake of water into soil peds occurred. Although the involvement of water in cracks and fissures to drains in heavy clay soils is to some extent qualitatively understood, but the range and variety of factors which affect drain response and the complexity of their interaction, suggest the need of a predictive, quantitative hydrological model of a drained clay soils.

Jarvis and Leeds–Harrison (1987a) developed a two domain model of water flow, storage and drainage in clay soils. The basic assumption of the model was that only the cracks and fissures in the soil provide a continuous system or network of pathways for water movement to the drains (pipe, tile or mole). In the model, the soil structure (crack spacing, width, porosity etc.) controls the flow rate in the cracks and also the rate of water uptake from the cracks into the peds that constitute the soil matrix.

Jarvis and Leeds–Harrison (1987b) applied and tested the model and demonstrated an excellent agreement with the observed hydrologic response in an undisturbed natural lysimeter for a wide range of initial soil water contents. Having tested the model against measured data, Jarvis and Leads–Harrison (1987b) opined that their model would be able to simulate soil water distribution and drainage for longer time periods using both current and historic meteorological data.

The phenomenon of preferential solute movement has recently been conceptualized with dual porosity models in which the porous medium is considered to consist of two separate but connected continua (Jarvis *et al.*, 1991; Gerke and van Genuchten, 1993). The independent determination of the resulting numerous model parameters of such mechanistic- based dual porosity model has still not been performed because of the enormous difficulties arising from the practical separation of the two domains and the subsequent *in situ* measurements on each flow fraction. Furthermore, it is not certain whether the model concept, mainly the convective dispersion equation, remains valid when transferred from the laboratory to the field scale (Jury and Fluhler, 1992).

Tile-drained field sites integrate the effects of spatial heterogeneity, including the preferential flow characteristics of soils, and are consequently recognized as an excellent experimental means for monitoring water and solute movements at field scale (Richard and Steenhuis, 1988). Kladivko *et al.* (1991) have reported that following a single application to the surface of tile drained silt loam soil, traces of four pesticides of different reactivity appeared in drain water after only 20 mm of net discharge. Southwick *et al.* (1992) have found 97 to 98 % of the total atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) that was lost into tile drains occurred within the first 21 days after chemical application.

Rana *et al.* (2000) reported that salts leached through sub surface drainage was eight times higher than the salts removed by surface drainage and yield of wheat was 57% higher in case of subsurface drained land.

2.3 Modelling approach

2.3.1 Simulation models for water table management

Simulation models have been developed to describe the performance of drainage systems. Such models are capable of making predictions on effects of system design on crop yields, hydrology and soil conditions and water quality. These models have been described by Haan *et al.* (1982), Feddes (1987) and Skaggs (1991). Numerous models have also been proposed to predict movement and fate of nutrients and pesticides. Utilities and performances of the important simulation models developed on the topic under consideration are reviewed in this section.

SIDRA (SImulation of DRAainage) model is based on a semi-analytical and semi-numerical solution to Boussinesq equation. The model uses climatic data (rainfall, evapotranspiration) and soil properties and generates sequences of mid- point water table elevations and drain flow rates at an hourly time step (Guyon, 1980; Lesaffre and Zimmer, 1987 and Lesaffre and Zimmer, 1988). Pandey (1989) modified Boussinesq equation for non-steady state ground water flow by incorporating the drainable porosity and evaporation functions. The modified equation was numerically solved for predicting the water table depth in space and time. Such a treatment resulted in a better agreement between the observed and predicted water tables in a lysimetric study. He further suggested that by incorporating the evaporation and drainable porosity as function of water table depth in the mathematical formulation of the subsurface drainage flow problem, the drainage system design could be made more economical. Field evaluation of model by Zimmer *et al.* (1995) suggested that the model over estimated the drain flow rates when recharge rate was less than 1.5 l s^{-1} ha^{-1} and slightly under estimated when the recharge rate was greater than 1.5 l s^{-1} ha^{-1}. Water table predictions were found to be very close to the observed ones. Also, Zimmer *et al.* (1995) concluded that SIDRA could be a useful tool to evaluate the performances and the relevance of a given subsurface drainage design. The model may find a wider applicability where the main objective of the subsurface drainage system is water table control by withdrawal of excess water in the soil profile. However, this may not be suitable for the wetland rice soils which are salt affected wherein water table control is not the priority.

Skaggs (1978,1991) developed DRAINMOD, a computer simulation model to describe the performance of drainage and associated water table control system in shallow water table soils. The model is based on water balances in the soil profile and at the soil surface. It uses functional relations to describe hydrologic components such as infiltration, subsurface drainage, subirrigation, surface runoff, evaptranspiration , deep percolation and lateral seepage. Hydrologic predictions of the model have been tested and found to be reliable under a wide range of soil, crop and climatological conditions (e.g. Skaggs, 1982; Fouss *et al.*, 1987; McMahon *et al.*, 1987).

Stress-day-index methods were employed to predict effects of excessive and deficient soil water conditions and planting delays on yields (Evans and Skaggs, 1993). Later on mass balance concepts were added to compute average daily soil water fluxes as a function of profile depth (Skaggs *et al.*, 1991). Borin *et al.* (2000) attempted to analyse the performance of DRAINMOD with an objective to determine whether a minimal set of field data would suffice the application of DRAINMOD for predictions. They observed that even very limited input data (texture and porosity of the top 30 cm of soil) gave good predictions.

Feddes *et al.* (1988) developed SWACROP by combining a drainage simulation model, SWATRE (Belmans *et al.*, 1983) with a crop production model CROP. SWACROP solves Richard's equation for unsaturated flow numerically using a finite difference method.

Prasher *et al.* (1996) compared and contrasted, the two water table management models, DRAINMOD and SWACROP, with the field data generated through the three drainage treatments, consisting of 3,6 and 12 m drain spacing. They found that both the models simulated water table depths and drain outflow rates quite close to each other. The study further revealed that the performance of DRAINMOD was slightly better than SWACROP, though DRAINMOD is based on water balance approach and is based on a greater number of assumptions. Computer run times for DRAINMOD are much shorter than for SWACROP. SWACROP is more versatile than DRAINMOD, as its provides a wider range of choices for the upper and lower boundary conditions and it is not limited to humid areas. Some other major limitations and criticisms were raised by van Hoorn (1998). He argued that steady state equation is indeed a simple model and there is a good reason to use such equation in practice. One does not need data of soil physical properties like capillary conductivity and drainable porosity and data of crop and root development, which are difficult and expensive to determine. The main problem in introducing the sophisticated models like DRAINMOD and

SWACROP in practice consists of collecting these data in a reliable way, because the models are very sensitive to these parameters.

van Hoorn (1998) opined that it was more important to use correct values for the hydraulic conductivity and to take seepage into account in the steady state approach than to neglect these in the more complicated models. Prasher (1998) in his defence, suggested that they did not disregard the importance of simplified models such as the Hooghoudt's equation. They emphasized that the real system such as hydrologic processes in soils behave in complex manner and they should be analyzed and treated as such by using appropriate tools and input data. Advances in technology such as powerful computers and field/laboratory equipments have paved the way for the determination and incorporation of more input parameters in newly developed complex, numerical models. Developments of such models are the signs of changing times and technological advancements which researchers need to keep pace with.

2.3.2 Transport models for agricultural chemicals

CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) was developed to simulate the effects of agricultural management systems on non point source of water pollution (Knisel 1980). The model consists of three components which describe field hydrology, erosion, sedimentation and chemistry. The chemistry component contains the plant nutrient sub model as well as the pesticide sub model. Parsons and Skaggs (1988) and Parsons *et al.* (1989) modified the DRAINMOD to create a "passfile" of hydrologic parameters for input to the CREAMS erosion component. This model was called DRAINMOD-CREAMS. Heatwole *et al.* (1987) evaluated the CREAMS nutrient model and concluded that CREAMS did not adequately represent nutrient movement in sandy soils having low buffering capacity. Wright *et al.* (1992) revised the DRAINMOD–CREAMS model by adding a dimensionless empirical water function to the denitrification equation. Saleh *et al.* (1994) validated the DRAINMOD–CREAMS model with nitrogen loss from subsurface and non-subsurface drained plots. They found that the CRERAMS model overestimated the total nitrogen losses from the subsurface drained field by 61% and from non-subsurface drained field by 91%. The modified DRAINMOD–CREAMS model overestimated the total nitrogen loss from the subsurface drained field by 36% and from the non-subsurface drained field by 40%. Thus, the modified model significantly improves the prediction of the nitrogen loss from subsurface drained and non subsurface drained fields by reducing the simulation error by 25 and 51%, respectively.

The DRAINMOD–CREAMS model cannot adequately represent chemical movement within the soil profile, and into the subsurface drains because the CREAMS model was designed primarily for estimating surface movement of agricultural chemicals. Further more, DRAINMOD requires hourly rainfall which limits its application. The Green-Ampt infiltration parameters required by DRAINMOD are also not available for many locations and soils. Other models dealing with plant growth, water flow, and agricultural chemical movement are the CERES (Crop–Environemnt-Resourcesd-Synthesis) (Jones and Kiniry, 1986), GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) Leonard *et al.*, 1987), LEACH (Leaching Estimation and Chemistry) model (Hutson and Wagenet, 1992) and the RZWQ (Root Zone Water Quality) model (Great Plains Systems Research, 1992).

Progress in modelling of nutrient transport is more evident at the small catchment or field scale than at the scale of large basins (Krysanova *et al.*, 1996). SWIM (Soil and Water Integrated Model; Krysanova *et al.*, 1996, Krysanova *et al.*, 1998) is a continuous - time, spatially distributed river basin model. It simulates hydrology, vegetation, erosion and nutrient dynamics at river basin scale. It is based on two other models: SWAT (Arnold *et al.*, 1993) and MATSALU (Krysanova *et al.*, 1989). A three-level scheme areal disaggregation, basin-sub basins-hydrotopes, plus a vertical subdivision in to a maximum of 10 soil layers are used. A hydrotope is defined as a set of disconnected unit in the sub basin, which have the same land use and soil type.

Krysanova *et al.* (1999) applied the model SWIM and termed it a robust model for the simulation of nutrient dynamics. It was found to be appropriate for coupled hydrological/water quality modelling in mesoscale basins with different topography and soils. The data requirements of the model are modest, as the model can be initialized using three to four basic things viz. digital map, climatological data, soil parameters and regional data on crop management. On the other hand, the model is quite complicated and it can not be run as a black box, the understanding of the code and interrelations between different processes is a prerequisite for successful applications.

Models for estimating nitrate fluxes at the catchment scale are available in the literature (e.g. Knisel, 1985; Young *et al.*, 1989; Chansheng *et al.*, 1993). Generally these models comprise a complex mechanistic approach, requiring a considerable amount of input data and parameters making them unsuitable for wider application in water management activities. Furthermore, the difficulties encountered in quantifying the effects of parameter uncertainty on the model output and a complex modelling approach is hampered. Therefore, the concept of Minimum Information Requirement (MIR) models was suggested by Anthony *et al.* (1996) for catchment scale modelling. The MIR model is characterized by a simple configuration and depends upon fewer input parameters than that of physically based models. The MIR model concept allows an easy analysis of the interacting effects of parameter uncertainties, whilst preserving a level of complexity that causes the output to be sensitive to key environmental parameters that are variable in space and time.

van Herpe *et al.* (1999) developed a conceptual catchment-scale model for simulating nitrate transport. The model consists of a hydrological part and a nitrate transport module. The latter comprises two functions: a production function controlling nitrate release from unsaturated zone and a transfer function controlling the discharge of nitrate into surface water. The production function simulates surface runoff and nitrate leaching towards the saturated zone.

CERES AND GLEAMS use available water capacity to calculate crop water uptake. These models do not use the Richard's equation to describe water flow or the effect of salinity on crop water uptake. LEACH and RZWQ models use the Richard's equation and a register–type plant water uptake term proposed by Nimah and Hanks (1973). The register- type plant water uptake term describes the micro-scale physics of water flow from the soil to, and through, the plant roots. However, this type of water uptake function was shown to be insensitive to salinity and generally inadequate to properly evaluate plant water uptake (Cardon and Letey, 1992).

ADAPT (Agricultural Drainage And Pesticide Transport), a subsurface water quality model was developed by modifying GLEAMS and incorporating drainage algorithms form DRAINMOD. Model predictions were within the range of field variations (Chung *et al.*, 1992). The ADAPT model does not account for the contribution of evapotranspiration flux from water table, when water table is below the root zone. A rise in water table is simulated by filling the soil pore spaces with percolated water from field capacity to saturation. A fall in water table caused by sub-surface drainage and deep seepage is simulated by draining the root zone to field capacity. There is a discontinuity in the soil water potential versus moisture content relationship and this affects the simulation of moisture regimes in the root zone, and the predictions of percolate leaving the root zone. Under shallow water conditions, the ADAPT can not perform well.

Simpler approaches include coupling DRAINMOD with water quality models such as CREAMS (Knisel, 1980) or GLEAMS (Leonard *et al.*, 1987). While the models that use such approach are relatively in wider use (Chung *et al.*, 1992; Singh *et al.*,1992; Wright *et al.*, 1992; Saleh *et al.*, 1994), they do not treat the subsurface process in much detail. An alternative approach was used to develop DRAINMOD–N.

DRAINMOD-N is a quasi two- dimensional model that simulates the movement and fate of nitrogen in artificially drained soils with shallow water table (Breve, 1994; Breve *et al.*, 1997). The flow component of the model is based on the water balance calculations in DRAINMOD to determine average daily soil water fluxes and water contents (Skaggs, 1978; Skaggs *et al.*, 1991). The solute transport component is based on an explicit solution to the advective-dispersive–reactive (ADR) equation (Breve, 1994). Functional relationships are used to quantify the processes of rainfall deposition, fertilizer dissolution, net mineralization, denitrificaiton, plant uptake, runoff and drainage losses. DRAINMOD–N runs separately, but it is lined to the standard DRAINMOD model; it uses daily outputs from DRAINMOD as inputs for nitrogen simulations. Field application and testing of DRAINMOD-N was doen by Skaggs *et al.* (1995a) and Breve *et al.* (1997). Skaggs *et al.* (1995a) found that the predicted losses of NO_3-N were significantly affected by drainage design and management e.g. increasing drain spacing from 20 to 40 m in poorly drained soils, decreased NO_3-N losses by 47%; the losses may be reduced further by placing a weir in the drainage outlet so as to raise the water level at the outlet and reduce subsurface drainage rate. Also, it was found that controlled drainage during both the growing season and winter months reduced NO_3-N losses from an annual average of 21.8 kg ha^{-1} to 10.5 kg ha^{-1} (52%) for a 30 m drain spacing, without affecting crop yields (Skaggs *et al.* 1995a).

Skaggs *et al.* (1995b) conducted simulation run with DRAINMOD to study the impact of drain spacing on the NO_3-N losses. They found that increasing the drain spacing from 20 to 40 m would reduce yields by only 3 % but reduce NO_3-N losses from 31.9 to 16.6 kg ha^{-1} $year^{-1}$ (48% reduction).

Lalonde *et al.* (1996) studied the effects of controlled drainage on nitrate concentration in subsurface drain discharge and reported that controlled drainage had a significant effect on drain discharge quantity and quality. The controlled water table of 0.25 and 0.50 m above the drain level reduced drain flow by 58.7% and 65.3%, respectively, compared with the free drainage treatment and the corresponding reduction of nitrate concentration in drain flow was 75.9% and 68.9% respectively, with the 0.25 and 0.50 m controlled water table.

Breve *et al.* (1997) suggested that DRAINMOD-N consistently underestimated NO_3–N concentration in the soil solution. However, differences between simulated and observed NO_3-N losses in subsurface drainage for the observation period were within 1.5 kg ha^{-1}. Simulated total NO_3-N losses (Surface runoff plus sub-surface drainage) were within 3.0 kg ha^{-1} of the observed values. On an average, plant uptake was under predicted by 20%. The authors concluded that DRAINMOD-N could be used to simulate the effect of water table management practices on nitrogen losses in naturally poorly drained soils with artificial drainage. However, the model needs to be tested for longer duration and under different climatic conditions and soil types, before it can be recommended for general application.

Pang and Letey (1998) developed ENVIRO-GRO model to simulate (i) water, salt, and N movement through soil with growing plant; (ii) plant response to matric potential, salinity and N stresses; (iii) salt and N leaching to tile drains; and (iv) cumulatively relative transpiration and relative N uptake, and consequent relative crop yield. The relative crop yield mentioned above is defined as : RY = f (R Nup) where RY is relative dry matter and R Nup is the ratio of crop total N uptake to the potential total N uptake, f is the functional relationship between RY and R Nup. From the field experimental data, Sexton (1993) found a quadratic relationship between RY and R Nup. This model does not account for denitrification. The utility of the model was illustrated by simulating the effects of irrigation amount, soil and water salinity, and N application on yield and N leaching. The results demonstrated the effects of complex interactions and feedback mechanisms in the plant-soil-water-salinity-nitrogen system. Evaluation was done by comparing simulated results of an experiment that had N application rates of 0, 90, 180 and 360 kg N ha^{-1} and water application rate of 21, 63 and 105 cm. Agreement between simulated and observed relative corn (*Zea mays* L.) yield and total N uptake was generally good.

The ENVIRO-GRO model did a better job as compared to other models used for crop yield and total N uptake predictions. Also, it has flexibility to deal with salinity problems in a given environment. Comparison of simulated N leaching by ENVIRO-GRO and the N leaching calculated by Tanji *et al.* (1979) were made. Tanji *et al.* (1979) predicted zero leaching under 21 cm irrigation, whereas a small amount of leaching was simulated by the ENVIRO-GRO model. Both the ENVIRO-GRO and Tanji *et al.* (1979) predict increasing N leaching with increasing N application for the 105 cm irrigation treatment in the same order of magnitude.

Ng *et al.* (2000) used LEACH model to study the effects of tillage, cropping and water management practices on nitrate leaching in clay loam soil. They reported that the LEACH model predicted nitrate leaching better in plots under controlled drainage system than in plots under free drainage system. The predicted scenario and field sampled data showed that controlled drainage system reduced nitrate leaching substantially.

2.4 Simulation model for salt balance

SALTMOD (Oosterbaan, 1989) is a computer program coded in Fortran. It is a computation method which enables prediction of soil and water salinity and water table depth in agricultural land under different geo-hydrological conditions and varying water management scenarios. Few applications of SALTMOD viz. Oosterbaan and Abu Senna (1989) in pilot area of Nile delta in Egypt; Rao *et al.* (1992) in Tungbhadra Irrigation Project, Karnataka, India;

and Vanegas Chacon (1993) in the Leziria Grande Polder, Portugal, are found in the literature. They reported that the predicted values of water table were in close agreement to the observed values. They also simulated the fluctuations of water table and soil salinity in next 20 seasons (2 seasons in a year) from 1990 to 2000, with the assumption that during the simulation period the yearly deviation of some of the important parameters e.g. rainfall, irrigation, evapotranspiration, crop rotation and cropping pattern etc from the observed data as input to model for years 1986-89 would be negligible.

SALTMOD (Oosterbaan, 1998) is an extended version of SALTMOD (Oosterbaan, 1989). A user shell in Turbopascal was developed and added to facilitate the management of input and output data in users' friendly manner. It takes a number of iterative calculations to find the correct equilibrium of the water and salt balance, which would be a tedious job if done manually. SALTMOD (Oosterbaan, 1998) has been selected as an application model for the study under reporting. The model is quite versatile and efficient. It facilitates the computation of soil salinity in root zone, salinity of drainage effluent, drain/ well flow rates, water table and several water balance components for different water management options over long period of time with the aim to simulate their long term impacts.

2.4.1 Modelling solute transport in tile drained fields

Singh (1989) developed a semi-analytical method to solute transport modelling of soil aquifer system. He descretized the space coordinate using Galerkin's finite element method which gave a solution that was continuous in time. Euler's technique was used to solve the resulting system of time dependent ordinary differential equations. Later on the usefulness of this model was demonstrated by scientists of Central Soil Salinity Research Institute who were studying soil salinization of tile drained experimental fields at sampla, Karnal, Haryana.

Kamra *et al.* (1991a) presented a semi-discrete model for solute transport in tile drained soil aquifer system. Water flow in the unsaturated and saturated zone was vertically downward and magnitude was equal to net steady downward flux of water. Their analysis showed that the error in numerical solution was relatively sensitive to seepage velocity but fairly insensitive to variations in longitudinal and transverse dispersion coefficients.

Kamra *et al.* (1991b) calibrated the model using the field data from a highly saline tile drained site, sampla, Haryana. After calibration, the model was used to obtain long term predictions of the salt distribution in the soil, the ground water, and the drain effluent. The model has two major limitations: (1) The predicted salinity in the top 20 cm layer did not match with the observed ones and (2) long term prediction of the salinity of the ground water and drain effluent were not in good agreement with the observed values. The model further suggested that the deep and widely spaced drains were found to be relatively more effective in desalinizing the entire soil profile, than the shallower and closely spaced drains.

Rao and Leeds-Harrison (1991) simulated the desalinization by surface irrigation of a tile drained two layered saline soil . The Laplace equation was solved numerically to obtain the water flow pattern and a mass flow equation given by Molen van der (1973) was applied to individual stream tubes to give the spatial and temporal distribution of salt. The mass flow equation was used for computing the leached volume in each stream tube. Desalinization curves were found by calculating the volume within each stream tube which is desalinized to 20 % of the initial value. For finding salinity of drainage effluent each stream tube was divided in to five layers. The effluent from the top layer was taken as influent in to the next layer and the mass flow equation was applied to each layer. The arithmetic mean of the salinities of the effluent from the bottom most layer of the stream tube was taken as salinity of the drainage water.

Kandil *et al.* (1992) used the soil water fluxes predicted by DRAINMOD, in combination with numerical solutions to the advective- dispersive-reactive (ADR) equation to simulate the transport of salt and salinity distribution in space and time. This version of the model was referred as DRAINMOD- S and was extended to predict effects of salinity on crop yield.

Ramaswamy (1993) developed a numerical model to predict the salinity distribution in space and time under ponded water conditions of tile drained rice fields. The flow domain for 15 and 30 m drain spacings were divided in to a number of spatial segements by constructing the stream tubes. The Crank-Nicholson numerical scheme was used to solve the one dimensional convective dispersion equation with zero distribution coefficient and having no production or decay term applied to each stream tube to predict the soil salinity distribution in the root zone. This model was exclusively developed for a ponded water case and found to be inefficient and inadequate to predict the root zone salinity when an unsaturated conditions prevail on the field. Such model has low level applicability and lacks generality.

On the lines of Ramaswamy (1993), Ramana Rao (1998) adopted a mathematical modelling approach to investigate the consequences of using different subsurface drain spacings (e. g. 10, 15, 25 and 35 m) in the coastal saline soils on the paddy yield and economics of the tile drainage system. Ramana Rao (1998) used two essential parameters viz. The pore water velocity and the dispersion coefficient as model input. The pore water velocity was estimated by dividing the Darcian velocity by the drainable porosity. However, the dispersion coefficient was fitted by trial and error procedure till the average absolute deviation between the predicted and observed soil salinities became minimum. Dispersivity and drainable porosity of a heterogeneous porous medium like soil, are highly variable in space and time and much more difficult to measure in the field. Unless one has field or laboratory measured data of dispersion coefficient and drainable porosity and the same are input to the model to compare the predicted and observed salinities, simply theoretical calibration of the model is not adequate to judge the performance of the Model. Moreover, the time step chosen for the scheme of numerical model is too short i.e. 0.005 day and the root zone soil salinity predictions have been made over fortnightly or monthly. In any cropped land that is being reclaimed with subsurface drainage system, the root zone salinity does not change much in such a short period. And that is the major weakness of the model. If any user wishes to increase the time step to daily, weekly, monthly or seasonal which has significance in the context of agricultural drainage the model becomes extremely inefficient and solution becomes unstable. If suitable modification is introduced and measured values of the parameters are used as input and close agreement between the observed and predicted root zone salinities are found then such mathematical modeling approach could become practically acceptable.

2.5 Experimental approach

2.5.1 Nitrogen transport from agricultural field

Movement of nitrogen species, such as NH_3 (aq), NH_4^+, NO_3^- and NO_2^- occurs in soil through diffusion, or mass flow or both. In the wetland soil, liquid phase diffusion, solid phase (adsorbed phase) diffusion, and mass flow may predominate and may play an important role in accelerating different nitrogen loss mechanisms such as volatilization, nitrification-denitrification and leaching.

2.5.2 Ammonium loss from flooded soil

Bilal (1977) studied transport of surface applied ammonium sulphate in a flooded Sacramento clay, he noticed an appreciable concentration of nitrogen as NH_4^+ remaining in flood water and upto a depth of 1.2 cm.

Substantial losses of surface applied N fertilizer from flooded rice fields through volatilization of ammonia have been reported (Mikkelson *et al.*, 1978; Vlek and Craswell, 1979). Placement of N fertilizer in soil at depths of 10 to 12 cm could reduce NH_3 volatilization losses to less than 1% of the applied N (Mikkelson *et al.*, 1978). Vlek *et al.* (1980) suggested that leaching loss of NH_4^+-N in wetland soils could be very serious if percolation rate exceeds 5 mm d^{-1}. The first direct measurement of ammonia loss with micrometeorological technique in tropical irrigated rice fields were made by Freney *et al.* (1981). Their study was conducted with ammonium sulphate applied to a puddled lowland rice field in Philippines.

The volatilisation loss of ammonia accounted for 5% of the ammonium sulphate which was broadcast before transplanting and 11% of the ammonium sulphate through surface run-off from the flooded rice fields at panicle initiation. Subsequent field measurements of ammonia loss have focused primarily on urea. Volatilisation loss of ammonia from urea broadcast before transplanting was 9% and total N loss by other mechanisms such as nitrification, denitrification, leaching and artificial drainage etc. were much higher (Cai *et al.*, 1986). Ammonia volatilization losses in flooded soils range from negligible to almost 60% of applied N (Savant and De Datta, 1982). Volatilization losses of nitrogen from rice field increased by about 100% when soil salinity increased from 4 to 8 dS m^{-1} (Swarup, 1994). Results further suggested that poor nitrification rates of NH_4-N at high salinity was chiefly responsible for higher volatilization of nitrogen from saline soil. Juhasz *et al.* (1997) showed that 5 % of the total inorganic nitrogen found in subsurface drainage water, was in the form of NH_4^+-N.

Results of the aforementioned field studies reveal that NH_4-N in flood water is readily transported to subsurface soil layers along with percolating water. Ammonium displaced to deeper layer may not move back to soil surface because there is always downward flux of percolating water under repeatedly irrigated rice culture. Under such environment loss via ammonia volatilization may not take place in wetland rice fields but there may be a significant loss of ammonium through leaching if the soil is porous and field is equipped with subsurface drainage system.

2.5.3 Nitrification - denitrification in wetland soil system

The wetland soil system is a complex matrix consisting of aerobic and anaerobic sites. The two aerobic sites are the oxidised surface soil layer and the rhizosphere. These two favour biological oxidation of ammonium to nitrate in wetland soil. It is an inevitable process but not desirable because it leads to loss of nitrogen. The reduced soil is highly conducive to biological denitrification, during which the NO_3^- is readily reduced to N_2O or N_2 or both and escapes to the atmosphere. Aulakh (1986) and Aulakh *et al.* (1992) have reported that concurrent nitrification and denitrification enhances nitrogen loss under flooded rice soil system.

2.5.4 Nitrate leaching and ground water pollution

In tropical climates rainfall often exceeds crop evapotranspiration, and in arid and semi-arid regions, unscientific application of irrigation water is common. As a result, nitrate derived from the fertilizer and from mineralization of soil organic matter is subjected to loss by leaching. Arora and Juo (1982) reported that 53% of the nitrogen applied to maize and rice was displaced below 1.2 m within one year. Generally, leaching losses of N occur in the form of NO_3^--N and not in the form of NH_4^+-N (Rossi *et al.*, 1991). Field experiment on non-rice crops (Juhasz *et al.*, 1997) showed that 92 to 95% of the total inorganic nitrogen found in the sub surface drainage water was in the form of nitrate.

Nitrate pollution of lakes, rivers and ground water has been well documented (Coote *et al.*, 1982; Polglese *et al.*, 1995), however there is very little information available on remedial measures for reducing nitrate losses from the agricultural fields. Due to rapid movement of water and salt, increasing concern is being expressed that excessive NO_3-N may leach down below the root zone of crops in porous soils causing a potential threat to ground water pollution. Ground water contamination with nitrate is of particular concern because drinking water often originates directly from ground water. High NO_3-N levels in drinking water are unsafe especially to infants and the animals. Fraser and Chilvers (1981) summarised that current World Health Organisation (WHO) and European standards for drinking water recommended that concentration of nitrate and nitrite in potable water should be less than 50 and 3 mg l^{-1}, respectively. However, the local standards of the level of nitrate in drinking water varies between 50 to 100 mg l^{-1} in most of the developing countries. The nitrate can be converted in to nitrite in the digestive tracts and lead to methemoglobinemia a condition in which nitrite binds to haemoglobin and causes suffocation (Haynes *et al.*, 1986; Sittig, 1991).

Mitchell *et al.* (1999) have monitored nitrate concentration in subsurface tile flow for six years from field with various tillage and cropping management practices. They reported that 16.8 mg l^{-1} mean nitrate-N was present in the subsurface drainage water with an average nitrogen application of 108 kg ha^{-1} year $^{-1}$. The manure application along with nitrogen application of 92 kg ha^{-1} year $^{-1}$ had a mean concentration of nitrate -N of 10.2 mg l^{-1} and these values exceed the drinking water standard of 10 mg l^{-1} nitrate-N.

Taniguchi and Tase (1999) reported that the NO_3^- concentration of the ground water discharged from the bottom of the Lake Biwa basin, Japan, was 7.2 mg l^{-1} , which was found to be three times larger than that of river water.

Paasonen-Kivekas *et al.* (1999) conducted experiment on nitrogen transport from clay field in southern Finland. They reported that nitrate nitrogen formed 32- 96% of the total N load. NO_3-N in the subsurface drainage water rapidly increased from 2 to 60 mg l^{-1} after the sequence of fertilization and rainfalls. NO_3-N in the soil water indicated prominent preferential flow from the top layer in to the tile drains. Total N in runoff waters remained less than 5 mg l^{-1} during the snow melt and less than 10 mg l^{-1} in the autumn.

From the above review, it is clear that a good deal of information have been generated on salinization, desalinization, nitrate leaching and nutrient losses through subsurface drainage, adopting modelling as well as experimental approaches. It is also found that most of the researchers concentrated on nitrate loss only. Though a few researchers have pointed out about ammonium loss, it was mainly through volatilization. Specific studies on ammonium loss through percolating water does not appear to have caught researchers' attention so far. India has a sizeable extent of coastal agricultural land, which are predominantly clayey. The coastal clay soils are affected with salinity and sodicity. Under such an adverse environment nitrogen transformation may not take place in a manner as in the case of normal to moderately saline soils. In turn there may not be only usual nitrate losses due to anion exclusion but there could be direct ammonium losses via mass flow if the adverse environment does not permit nitritification. Obviously, this will lead to inefficient utilization of the applied nitrogenous fertilizer. No measured data from the salt affected rice fields on nitrogen loss particularly, in the ammonium form via subsurface drainage system, are available in the country. Therefore, further research is needed in order to acquire a better understanding of nitrogen transport in coastal environment. Such an understanding can aid in the development of best management strategies both on land reclamation through drainage and application of nitrogenous fertilizer. In order to evaluate these management strategies, there is a need for adopting a modelling approach and its validation with the field data.

CHAPTER-III

THEORY AND UTILIZATION OF MODELS

3.1 General

In agriculture, the problems of irrigation and drainage need to be examined together particularly in the humid and coastal areas where there is a succession of dry and wet seasons with opposing irrigation and drainage needs. The problem becomes even more complex if the land suffers from waterlogging and salinity. Given the complexity of the problem, simulation models are useful tools to understand the processes (salinization, desalinization viz., water, salt and nitrogen transport) better in soil-water-plant system. These tools help evaluation of different developmental strategies, to suggest solutions and to predict medium to long term consequences of adopting such strategies.

The selection of models for practical purposes involves some preliminary considerations. Many of them are simple emperical models, requiring few input data, and unsuitable for environments differing greatly from those where the models were developed. Other models like physical based, analytical and numerical, are more complex. These models require more parameters than the simple models. Analytical models are limited to certain idealised situations such as homogeneous and isotropic conditions. Numerical models are capable of accommodating spatial and temporal variations of soil properties and plant growth but the application of numerical models to complex conditions is generally restricted by the limited availability of temporal and spatial data. They are often difficult to calibrate and do not always guarantee better predictions.

Several models, which simulate the transport of solutes in the soil-water-plant system, have been reviewed in Chapter II. Considering the literature reviewed and the sets of data collected at the experimental site, the two simulation models namely, SALTMOD (Oosterbaan, 1998) and ENVIRO-GRO (Pang and Letey, 1998) were selected for the current study on modelling of salinization and nitrogen loss under sub surface drainage system. In this chapter, the theory and principles applied in model development, brief description of the models along with their input requirements, initial and boundary conditions required by the models are presented.

3.2 Principles and description of SALTMOD

SALTMOD is based on seasonal water balances of agricultural lands. Seasonal time step is considered in the computation method. The number of seasons (Ns) are chosen between a minimum of one and a maximum of four. The duration of each season (Ts) is given in number of months ($0 \leq Ts \leq 12$). The model needs seasonal water alance components as input data. These are related to head water hydrology (e.g. rainfall, evaporation, irrigation reuse of drainage water and runoff) and to the ground water hydrology (e.g. upward seepage, natural drainage and pumping from wells). The other water balance components (e.g. percolation, capillary flux and drainage) are obtained as output. The input data on irrigation, evaporation and surface runoff are specified per season for three kinds of agricultural practices which are chosen by the user. These practices are (i) irrigated land with crops other than rice and sugarcane, (ii) irrigated land with heavily irrigated crops like sugarcane and rice, and (iii) unirrigated land and/or fallow land.

SALTMOD accepts four different reservoirs of which three are in the soil profile and one is above the soil surface. These are named as (i) surface reservoir, (ii) shallow soil reservoir or root zone reservoir, (iii) an intermediate soil reservoir or transition zone and (iv) deep ground water or aquifer reservoir. If a hrozional subsurface drainage system is present, the transition zone is divided into two parts : an upper transition zone above drain level and a lower transition zone below the drain. Water balance are calculated for each reservoir separately. The excess water leaving one reservoir is converted into incoming water for the next reservoir. The three porous reservoirs are assigned with three different thickness and storage coefficients, as input data.

The upper soil reservoir is defined by the soil depth from which water can evaporate or be taken up by plant root. The reservoir may be saturated or unsaturated depending on the water balance. All water movements in this zone are vertical, either upward or downward. The transition zone, too may be saturated or unsaturated. All flows in that zone are vertical except the flow to subsurface drains, if it exists. The deep ground water reservoir has both horizonal and vertical flows.

The salt balances are calculated for each reservoir separately. They are based on water balances and on the salt concentrations of the incoming and outgoing water. Some concentrations e.g. the initial salt concentrations of the water in the different soil reservoirs, in the irrigation water and in the incoming ground water from the deep aquifer are desired as input data to the model. Usually, salt concentrations of the soil are measured in extracts and represented by ECe. The salt concentration in the model is expressed as the EC of the soil moisture when saturated under field conditions. As a rule, one may use the conversion rate : EC = 2 ECe. Salt concentrations of outgoing water, either from one reservoir into the other or by drainage are computed on the basis of the salt balance, with different leaching or salt mixing efficiencies. The amount of salt removed during a season is based on the weighted average salt concentration during the season.

3.3 Scope and limitations of the SALTMOD

The output of SALTMOD consists of the following :

— the salt concentration of different soil reservoirs at the end of the season

— the seasonal average salt concentration of the drainage water

— the seasonal average depth of water table and

— the season volumes of drainage water etc.

The output of the model is given for each season of any year for any number of years as specified in the input data. If required, farmers' responses to waterlogging and salinity may be taken into account. If simulation results suggest that the water table has become shallower in the study area, the model has an option to increase the fraction of paddy land gradually. On the contrary the fraction of cultivated land and amount of irrigation water applied may be reduced should the output of simulation suggest an increase in the average soil salinity. Provisions of such adjustments influence the water and salt balances, which in turn slow down the process of waterlogging and salinization which may lead to an equilibrium ultimately.

The area to be modelled by SALTMOD must be governed by the uniformity of the distribution of the cropping, irrigation and drainage characteristics over the area. The effects of dissolution of solid soil minerals, macro and micro nutrients and the chemical precipitation of poorly soluble salts are not included in the model. The model offers the possibility of developing a multitude of relations between varied input data, resulting outputs and time. Different modelers can establish different cause-effect or correlation relationships. The model is highly interactive but lacks in standard graphics.

3.4 Calibration and application of the SALTMOD

At the study site, several water and salt balance factors were measured, some specific parameters of the model were estimated, however, some factors notably the leaching efficiency of the root zone and surface run off could not be measured. Before application of the SALTMOD, these factors were determined by trials with the model, using different values of leaching efficiency and surface runoff from the boundary of the study site. The chosen values of leaching efficiency and surface runoff were those which produced soil salinities and depths to water table that corresponded well with the actually measured values. These chosen trial values were considered the true values of leaching efficiency and surface runoff. Such a trial and error procedure is referred as the calibration of the model. The various input parameters with respect to different treatments of drain spacing are given in Table 3.1. The set of sample input and output files are given in Appendix I.

3.5 ENVIRO-GRO model

ENVIRO-GRO is a simulation model which describes water, salt and nitrogen movement through soil, plant and water and nitrogen uptake and translates the results in terms of crop yield and nitrogen leaching. Also, it evaluates the interactions amongst plant-water-salt and nitrogen under different irrigation and drainage conditions. The theoretical considerations that have been used in developing this integrated model are given in the following sections.

Table 3.1. Summary of input parameters needed by SALTMOD

1. Duration of season (months)	
Season 1 (January to May)	5
Season 2 (June to December)	7
2. Soil Properties	
Fraction of irrigation or rain water stored in root zone	0.65
Total porosity of root zone	0.60
Total porosity of transition zone	0.45
Total porosity of aquifer (assumed)	0.35
Drainable porosity of root zone	0.05
Drainable porosity of transition zone	0.08
Drainable porosity of aquifer	0.25
Leaching efficiency of root zone (calibrated)	0.60
Leaching efficiency of transition zone (assumed)	0.80
Leaching efficiency of aquifer (assumed)	1.00
3. Water Balance Components	
Irrigation in season 1 (m)	1.25
Irrigation season 2 (m)	0.00
Rainfall in season 1 (m)	0.04
Rainfall in season 2 (m)	1.007
Evapotranspiration in season 1 (m)	0.766
Evapotranspiration in season 2 (m)	0.888
Incoming groundwater flow through aquifer in both season (assumed) (m)	0.0
Outgoing groundwater flow through aquifer in both season (assumed) (m)	0.0
Surface runoff in season 1 - calibrated (m)	0.350
Surface runoff in season 2 - calibrated (m)	0.250
4. Drainage criteria and System Parameters	
Root zone thickness (m)	0.30
Depth of subsurface strains (m)	1.00
Drain spacings (m)	35 and 55
Thickness of transition zone between rootzone and aquifer (m)	1.60
Thickness of aquifer - assumed (m)	5.00
Ratio of drain discharge and height of the watertable above drain (m d^{-1} m^{-1})	0.0011-0.015
Rate of drain discharge and squared height of the watertable above drain (md^{-1} m^{-2})	0.00015-0.002

Drainage reduction factor in season 1	0.2
Drainage reduction factor in season 2	0.8
5. Initial and Boundary Conditions	
Depth of watertable in the beginning of season 1 (m)	0.30
Initial salt concentration of soil moisture in rootzone at field saturation (dS m^{-1})	35.0
Initial salt concentration of the soil moisture in transition zone (dS m^{-1})	40.0
Average salt concentration of incoming irrigation water (dS m^{-1})	1.5
Average salt concentration of incoming groundwater (dS m^{-1})	50.0

3.6 Theory of water flow and solute movement

3.6.1 Water flow

The general water flow equation in one dimension with root extraction is given by Nimah and Hanks (1973)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}[K(\theta)\frac{\partial H}{\partial z}] + A(z,t) \qquad \text{... (3.1)}$$

where, θ is volumetric water content; t is time; z is depth; K (θ) is hydraulic conductivity; H is soil hydraulic head and A (z, t) is the plant root extraction term.

Nimah and Hanks (1973) used a register type plant water uptake term to describe the microscopic physics of water flow from the soil to, and through, the plant roots. However, this type of water uptake function was shown to be insensitive to salinity and was generally inconsistent with plant behaviour in its root water uptake (Cardon and Letey, 1992).

van Genuchten (1987) used a macroscopic, empirical function to describe plant water uptake based on observed response to water potential. The root extraction term is defined as follows :

$$A(z, t) = Tp(t)\,\Gamma(z, t)\,\sigma(h, \pi) \qquad \ldots (3.2)$$

where, Tp(t) is potential transpiration rate

$\Gamma(z, t)$ is plant root distribution function which varies with respect to depth (z) and time (t),

$\sigma(h, \pi)$ is crop matric potential-salinity stress function.

The $\sigma(h, \pi)$ function is given below :

$$\sigma(h, \pi) = \frac{1}{1 + [\frac{\beta h(z,t) + \pi(z,t)}{\pi_{50}}]^3} \qquad \ldots (3.3)$$

where, β accounts for the differential response of the crop to matric and osmotic influences and is equal to the ratio of π_{50} to h_{50}, where h_{50} and π_{50} are soil matric potential (h) and osmotic potential (π) at which maximum transpiration is reduced by 50 %. The plant water uptake function given by Eq. 3.2 was sensitive to fluctuations in both the matric and osmotic potentials of the soil, and provides reasonable calculation of transpiration rates (Cardon and Letey, 1992).

3.6.2 Salt movement

The governing equation for solute transport is :

$$\frac{\partial(\theta Cs)}{\partial t} = \frac{\partial}{\partial z}[D_s(\theta, v)(\frac{\partial Cs}{\partial z}) - vCs] \qquad \ldots (3.4)$$

where, θ is volumetric water content,

Cs is salt concentration

v is pore water velocity defined as $v = q/\theta$, q is volumetric flux of solution

D_s (θ, ν) is a combined diffusion and hydrodynamic disperson coefficient of salt given by :

$$D_s(\theta, \nu) = D_o \xi + \lambda |\nu| \quad \text{... (3.5)}$$

where, D_o is a diffusion coefficient of salt in pure water, λ is dispersivity.

ξ is a tortuosity factor given by Millington-Quirk relation

where, $$\xi = \theta^{10/3} / \Phi^2 \quad \text{... (3.6)}$$

where θ is water content (volumetric) and Φ is total porosity of soil.

3.6.3 Nitrogen movement

Nitrogen movement through soil is governed by convective-dispersion equation with the source and sink terms as given by :

$$\frac{\partial(\theta C_N)}{\partial t} = \frac{\partial}{\partial z}[D_N(\theta, \nu)\frac{\partial C_N}{\partial z} - \nu C_N] + Source(z,t) - Sink(z,t) \quad \text{... (3.7)}$$

where, C_N is nitrogen concentration in soil water

D_N (θ, ν) is a combined diffusion and hydrodynamic dispersion coefficient of nitrogen and is calculated by Eq. 3.5 with D_o of nitrogen

Source (z, t) represents the amount of mineralized organic nitrogen from the surface added organic crop residues, and

Sink (z, t) is the total N-uptake by the crop.

Source (z, t) is defined as follows :

$$\text{Source} = ON\ (1 - \exp^{-\alpha t}) \quad \text{... (3.8)}$$

where, ON is amount of organic nitrogen of crop residues added at the soil surface, α is the first-order-decay rate constant. It is assumed that the plant residue was incorporated into the top 20 cm soil.

Sink (z, t) is defined as follows :

$$Sink = Nup\_pot(t)\ \Gamma(z,t)\ \gamma(C_N, C_N up\_pot) \qquad \dots (3.9)$$

where, Nup_pot (t) is modified potential crop total N-uptake rate at a given time for a specific crop,

Γ (z, t) is crop root distribution

γ (C_N, $C_N$up_pot) is a crop N stress factor.

The procedure of calculation of γ is described in detail by Pang and Letey (1998).

3.6.4 Soil hydraulic functions

Solving the water flow equation requires hydraulic factors. A non-hysteretic two part retention function of Hutson and Cass (1987) was used because of its utility across the entire moisture range including the saturated condition. The function of Hutson and Cass (1987) is as follows :

$$\psi_i = a\left(\frac{2b}{1+2b}\right)^{-b} \qquad \theta = \theta_i \qquad \dots (3.10)$$

$$\psi = a\left(\frac{\theta}{\theta_s}\right)^{-b} \qquad \theta \le \theta_i, \psi \le \psi_i \qquad \dots (3.11)$$

$$\psi = \frac{a(1-\theta/\theta_s)^{1/2}.(\theta_i/\theta_s)^{-b}}{(1-\theta_i/\theta_s)^{1/2}} \qquad \theta \ge \theta_i, \psi \ge \psi_i \qquad \dots (3.12)$$

$$\theta_i = \frac{2b\theta_s}{(1+2b)} \qquad \dots (3.13)$$

where,

θ_s(TSAT) : Saturation water content

θ_i (THIN) : Water content at the inflection point (at the PSIN point)

ψ_i (PSIN) : Matric potential at the inflection point where the two parts of the hydraulic properties function of Hutson and Cass join

a (ATA) : Air entry matric potential for the soil under consideration

b (BATA) : Exponent of the equation relating matric potential water content as developed by Campbell. These values are determined for the soil under consideration.

Hydraulic conductivity as a function of matric potential is given by :

$$K = K_s \quad \text{when} \quad \psi \geq \psi_s \qquad \ldots (3.14)$$

$$K = K_s \{ (\psi/a)^{-1/b} \}^{bhb}, \quad \psi < \psi_s \qquad \ldots (3.15)$$

where,

K_s (CONDS) : Saturated hydraulic conductivity, cm/hr

bhb (BHB) : Exponent of the equations relating hydraulic conductivity to water content as developed by Campbell (1974).

The expression given in parenthesis against the symbols used in equations 3.10 to 3.15 are the names of the parameters used in the model.

3.6.5 Initial conditions

While using the model to simulate plant uptake of water and nitrogen, and water flow and solute movement in the soil, the initial distribution of water, salt and nitrogen in the soil profile is provided as Input. The time needed for a soil to reach an equilibrium state greatly depends on its hydraulic properties and does vary from soil to soil. The best way to assign an initial water content profile is based on the soil matric potential (h) distribution. The procedure of doing this is (1) choosing a preferred 'h' value at the lower boundary, (2) calculating 'h' distribution from this point back upto the soil surface for a hydraulic equilibrium condition, (3) translate 'h' to water content based on the soil-water retention function. Initial nitrogen concentration was assumed to be uniformly distributed throughout the soil profile and its magnitude was determined by analysing the soil, its organic carbon content and available nitrogen before the crop season (i.e. before simulation starts).

3.6.6 Boundary conditions

Boundary conditions for simulations are classified as (i) upper boundary conditions and (ii) lower boundary condition. The rate and duration of rain or irrigation, potential evapotranspiration, concentration of salt in irrigation water, and applied fertilizer dose are defined as upper boundary condition in the input data file. It was assumed that during plant growing season, water would have been transpired only from the soil profile by crop water uptake. The evaporation was included in the potential evapotranspiration rate which was estimated using the crop coefficient for rice crop (Mohan and Arumugam, 1994).

Thus, the model does not account for the evaporation from soil surface during the crop growth period. Furthermore, it is assumed that there is no evapotranspiration during the rain or irrigation event. The time and amount of irrigation is specified while organising the input data file. The format of sample set of input and output files and the description of input and output data are given in appendix II. Also, it is assumed that nitrogen is completely dissolved in the irrigation water.

The physical lower boundary was considered at a depth of 1 m below the ground surface and was the same as the average depth of subsurface drain in the experimental area. Accordingly, the drain discharge rate was the sole lower boundary condition. This condition was practically constant during the cropping period when water was standing on the rice field. Nearing the harvest time the drain discharge rate (lower boundary condition) reduced as the irrigation supply over the land surface was stopped. The simulation modelling was done only during the crop growth period. The model, however, does not recognize the *lower boundary*. It considers the *bottom boundary* which is the depth of the root zone (35 cm for rice crop). In this specific situation, there is no fluctuation in the location of the water table and not much change in the water regime and therefore, the drainage amount at the lower boundary was considered the same as below the bottom boundary which is recognized by the model. the nitrogen leaching was computed by multiplying drainage amount by the nitrogen concentration in the bottom boundary layer. The input parameters needed for simulation studies by ENVIRO-GRO model are detailed in Table 3.2.

Table 3.2. **Summary of input data needed by ENVIRO-GRO**

1. Soil Hydraulic Properties	
Saturated hydraulic conductivity (cm ha^{-1})	0.5
Saturated volumetric water content ($cm^3.cm^{-3}$)	0.85-0.98
Parameters of soil water retention curves	from Table 4.5
Exponent for the equation relating hydraulic conductivity to water content developed by Campbell	18.148 - 20.602
Bulk density (g cm^{-3})	1.01 - 1.29
2. Drainage System Parameters	as per item 4 of Table 3.1
3. Rice Production Parameters	as per Table 4.3
Maximum root depth (cm)	30-35
Root characteristics	from Literature, Yashida (1981)
Potential evapotranspiration (cm hr^{-1})	derived from Table 4.1
Crop water use coefficients	Mohan and Arumugam (1994)
Irrigation depth (cm) duration (hr) and irrigation interval (hr)	Appendix-I (data file #2)
Nitrogen uptake rate by rice (kg/hr/ha)	Measured value*
Salt concentration of irrigation water (dS m^{-1})	observed value* *Organized in 2nd part of data file #2
Date and amount of applied nitrogen	Known from the fertilizer schedule of the experiment
4. Initial and Boundary Conditions	
Available nitrogen in soil before the crop season (kg ha^{-1})	Devadattam and Ramesh Chandra (1995)
Initial root zone salinity (dS m^{-1})	30-40
Lower boundary from soil surface (cm)	100
Depth of increment (cm)	5
Bottom of the root zone (cm)	30-35
5. Crop stress factor	
Osmotic head at which transpiration is reduced by 50%, cm	-8592
Matric potential at which transpiration is reduced by 50%, cm	-1100
Threshold value of matric potential below which plants feel stressed, cm	-360
Threshold value of osmotic potential below which plants feels stressed, cm	-1836

CHAPTER-IV

MATERIALS AND METHODS

4.1 Description of the study site

The study site is located at the Endakuduru village in Ghantasala mandal of Krishna district in Andhra Pradesh (Fig. 4.1). The village is located on the Machilipatnam-Chalapalli road at a distance of about 18 km southwards from the district headquarter, Machilipatnam (Fig. 4.1d). Krishna district lies in southern coastal Andhra Pradesh between 15^{0}43' and 17^{0}10' N latitude and 80^{0}0' and 81^{0}35' E longitude extending over an area of 8727 sq. km. with a coast line of 88 km (Fig. 4.1b, c). Majority of the people of the study area are marginal farmers with an average land holding of 0.61 ha. These marginal farmers are generally poor and earn their livelihood by working as labourers to big farmers.

The district occupies an important place in agriculture and rice is the main food crop occupying about 58 % of the gross cropped area of 7.59 lakh hectares. The other crops are black gram, green gram, groundnut and sugarcane grown in 1.29, 0.36, 0.29 and 0.17 lakh hectare, respectively. The gross irrigated area is about 63 % of the gross cropped area.

4.1.1 Climate

The site is characterised by a moderate coastal climate throughout the year. The mean annual maximum and minimum temperatures are 36.6^{0}C and 19.3^{0}C respectively. The mean annual rainfall is 975 mm of which about 60 % occurs during the south-west monsoon from June to September. A

Fig. 4.1 Successive maps (not to scale) of the study area

specific feature of the area is occurrence of cyclonic storms, any time usually during September to November, causing torrential rains. The rainfall during September to November, may be as high as 40 to 45 % of the annual rainfall. The period from December to May is relatively dry and hot with some scanty rains. The monthly data of a few selected climatological parameters for the experimental site are presented in Table 4.1.

4.1.2 Physiography and soil

Endakuduru village and the experimental fields are 1.5 to 2 m above the mean sea level (Fig. 4.1d). The land is flat and is diked in small units for rice cultivation. It is saline to saline sodic with high clay (58 %) content. The soil is deep with no rock formation. A sandy layer exists at depths varying between 1 to 2 m from the soil surface. The average relief is in the east direction. The Bay of Bengal is about 18 km towards south east from the study site. The mean slope of the Inampudi drain from the village to the sea is 0.006 %. The physical and chemical properties of the soils at the experimental site are presented in section 4.4.

4.1.3 Surface and ground water quality

Surface water resource is drawn from river Krishna through canals. The electrical conductivity of canal water ranges from 1.2 to 1.9 dS m^{-1} in the irrigation period i.e. from December/January to March/April. Quality of surface water deteriorates gradually as the dry season advances. In order to study the quality of ground water with respect to 15, 25, 35 and 55 m drain spacing area in detail, four pits (one in each) of one metre depth were dug at site in May 1999. Water samples were collected when the ground water attained the static water level in the pits. The samples of canal water, ground water

Table 4.1. Selected climatological parameters of experimental site

Year	Parameter	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1997[a]	Max. Temp. (^{0}C)	27.9	31.3	33.5	34.5	38.3	39.2	34.9	34.2	32.7	31.6	30.2	29.2
	Min. Temp. (^{0}C)	19.7	20.8	22.9	25.2	27.8	28.6	26.6	26.6	26.0	24.9	24.3	23.5
	Rainfall (mm)	9.4	0.0	9.6	7.7	1.2	56.9	247.9	135.0	491.6	125.1	194.1	87.1
1998[a]	Max. Temp. (^{0}C)	29.8	31.5	33.1	35.1	39.0	38.6	33.4	32.6	32.6	31.3	31.0	29.4
	Min. Temp. (^{0}C)	22.6	23.3	25.0	26.4	28.9	28.9	26.6	26.4	26.4	25.3	23.7	19.4
	Rainfall (mm)	19.6	0.0	0.4	19.8	0.2	78.2	162.5	181.5	216.5	311.1	57.5	0.0
Normal	Rainfall[b] (mm)	7.9	8.3	7.6	4.2	28.1	86.8	169.7	182.0	166.6	153.9	140.7	19.2
	PET[a] (mm)	109	122	166	176	193	167	134	136	123	118	108	102
Daily (mean) PET (mm)		3.5	4.2	5.3	5.8	6.2	5.5	4.3	4.4	4.1	3.8	3.6	3.3

India Meteorological Department (IMD, 1999)
Devadattam and Ramesh Chandra (1995)
PET: Potential Evapotranspiration.

and subsurface drainage water of new project area (vide section 4.2) were analysed and are reported in Table 4.2.

4.1.4 Cropping system and land use

Rice-rice crop rotation is followed at the site. The area is irrigated by canals of Krishna river. Rice transplanting is done any time between first week of January to first week of February for *rabi* season and between mid July to mid August for *kharif* season. The raising of *rabi* rice is fully dependent on canal water supply. As the site is located at the tail end of the canal, the rice nursery is raised late and subsequently transplantation is delayed. As a result of delayed transplanting, poor soil condition due to high salinity and inadequate drainage facility, the yields are lower as compared to those lands which are better located and free from high soil salinity problems.

The rice varieties viz. IR-64, MTU-1001, MTU-1010 of duration of 80-90 days after transplanting (DAT) and Chaitanya (MTU-2067), Krishnaveni (MTU-2077) and Swarn of duration of 120-130 DAT are generally cultivated in *rabi* and *kharif* respectively. The rice yields are in the range of 2.8-3.4 t ha^{-1} during *rabi* and 2.3-3.0 t ha^{-1} during *kharif* season. Most of the cultivable lands remain under fallow for about 60 to 75 days during late April to early July after *rabi* harvest and 30 to 45 days during November to December after *kharif* harvest. During the fallow period the land is subjected to salinization due to high evaporative flux from a shallow and saline ground water table, absence of rainfall and irrigation and also due to non-operation of subsurface drainage system. A pictorial view of the salinization process in the fallow period is presented in Fig. 4.2, 4.3. The situation shown in Fig. 4.12 corresponds to a highly salinized land where weeds grow for some period and soon these also wither as the dry season approaches.

Table 4.2. Analysis of water quality at new project site*

Description	pH	E.C. (dS m^{-1})	Na^+	Ca^{++}	K^+	Mg^{++} (me/l)	CO_3^{--}	HCO_3^-	Cl^-
Canal Water (Jan., 99)	7.01	1.2	—	—	—	—	—	—	—
Canal water (Feb., 99)	7.04	1.6	—	—	—	—	—	—	—
Canal water (March, 99)	7.10	1.9	—	—	—	—	—	—	—
Subsurface drainage water at the outlet	7.34	28.3	100	6	2.0	29	Nil	21.0	165
Ground water $P@_{15}$	7.14	39.5	300	8	2.6	86	Nil	17.5	335
Ground water P_{25}	7.20	40.3	200	13	3.0	69	Nil	31.5	325
Ground water P_{35}	7.45	50.9	500	9	4.0	95	Nil	24.5	480
Ground water P_{55}	7.60	55.2	600	6	3.0	89	Nil	24.5	510

* Vide section 4.2
— Not determined
@ Subscript to P denotes the drain spacing and P stands for pit in area vide section 4.2.

Fig. 4.2 First view of salinization in non-drainage period

Fig. 4.3 Second view of salinization in non-drainage period

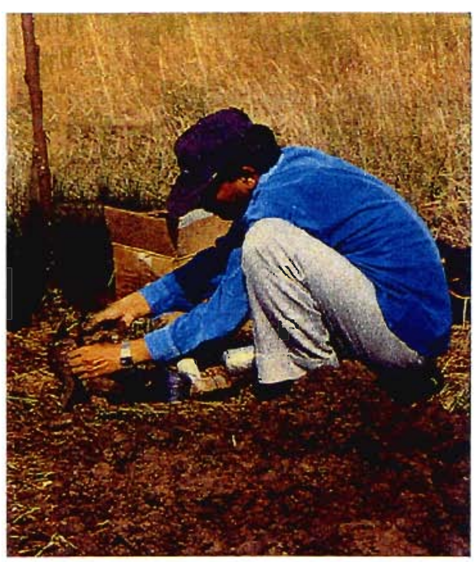

Fig. 4.4 Soil sampling for measuring salinity and moisture content

4.2 Subsurface drainage installations

Subsurface tile drains were installed in farmers' fields for a pilot study. The objectives were to reclaim the chemically degraded soil and to intercept the capillary flux towards the root zone from the brackish ground water below. A steady state drainage rate of 6 mm d^{-1} and a dewatering depth of 0.5 m below soil surface were adopted as drainage design criteria. These design criteria are based on a judicious combination of scientific analyses and practical experiences from field research (Devadattam and Ramesh Chandra, 1995). To achieve the dewatering criterion at the design discharge rate, drain spacing was found to be 12.5 m by Hooghoudt's steady state equation.

Initially 5 lines of tile drains of 60 m length each were laid at a narrow spacing of 10 and 15 m in the summer of 1986 in 0.4 ha area at an average depth of 1.0 m. Another 3.2 ha adjacent area was put under subsurface drainage in the summer of 1987. In this plot 5 laterals of 150 m length each, were laid at the spacings of 25 and 35 m and at the same depth. The performance evaluation in terms of physical and chemical properties of the soil and rice yield were continuously monitored for a decade (Devadattam and Ramesh Chandra, 1995; Bhattacharya, 1996; AICRPAD, 1986-1998). Field data suggested the possibility of adopting even wider spacing of tile drains and thus, two more spacings of 35 m and 55 m at 1.0 m depth were laid in the summer of 1997 in a 4.0 ha area. These lateral drains are 120 m in length. Thus, the site is equipped with several drain spacings. Four spacings namely, 15, 25, 35 and 55 m were selected for the experiment.

Parallel lateral drains are connected at right angles into the collectors in the drainage lay out. The discharge from laterals of 10 and 15 m spacings and 25 and 35 m spacings area (i.e. old reclaimed area) were collected through two independent collector pipes in a sump, and discharge from laterals of 35 and 55 m spacings area (new area under reclamation) were collected in another sump through one collector pipe and subsequently, the leachate was pumped out into an open drain which ultimately discharges into the sea. The various processes viz. layout, installation and components are depicted in Figs. 4.5, 4.6 and 4.7.

4.3 Design of field experiments

Field experiments on farmers' land were conducted in 1999 and 2000 for the measurment of salinity levels in soil and drainage effluent, and various forms of nitrogen (NH_4^+, NO_3^- and NO_2^-) losses through subsurface drainage effluent in the four drain spacing areas. The area with 15 and 25 m drain spacing commissioned earlier, and 35 m and 55 m, newly commissioned in 1997 were selected for the field measurements. The objective of the design of four spacing treatments was to see the effects of drain spacing on rate of salt and nitrogen removal in reclaimed and unreclaimed area with corresponding performance of the crop. One month old rice (variety : MTU-1010) seedlings were transplanted on 15 m, 35 m and 55 m spacing plots whereas, the 25 m spacing plot was left fallow for the studies on salinization. In the second season i.e. in 2000, 15 m spacing plot could not be taken for rice crop because the farmer had converted the reclaimed land into a fish pond. The agricultural practices used during the study period are shown in the Table 4.3. A view of fertilizer application and transplanting of rice is shown in Fig. 4.8 and Fig. 4.9, respectively. Canal irrigation water of 125-130 cm depth was applied during the crop season in 20 irrigations.

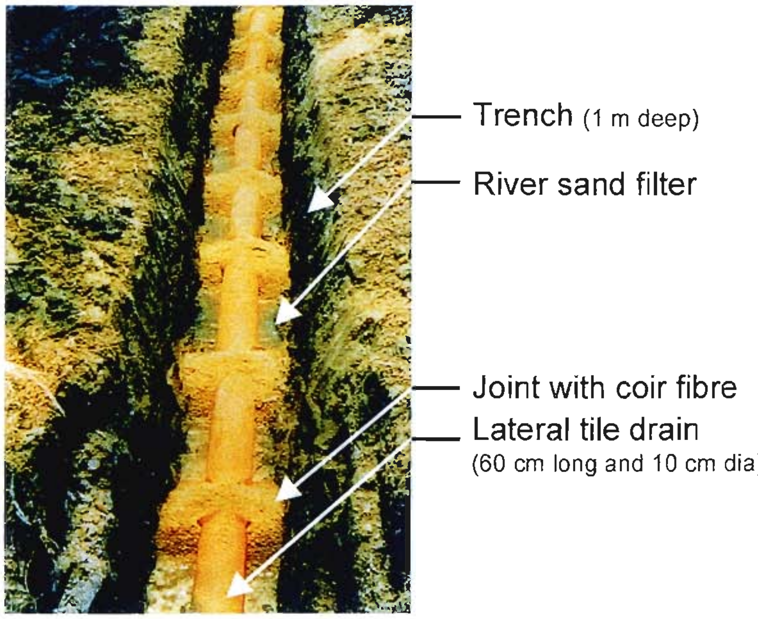

Fig. 4.5 Laying of subsurface drain

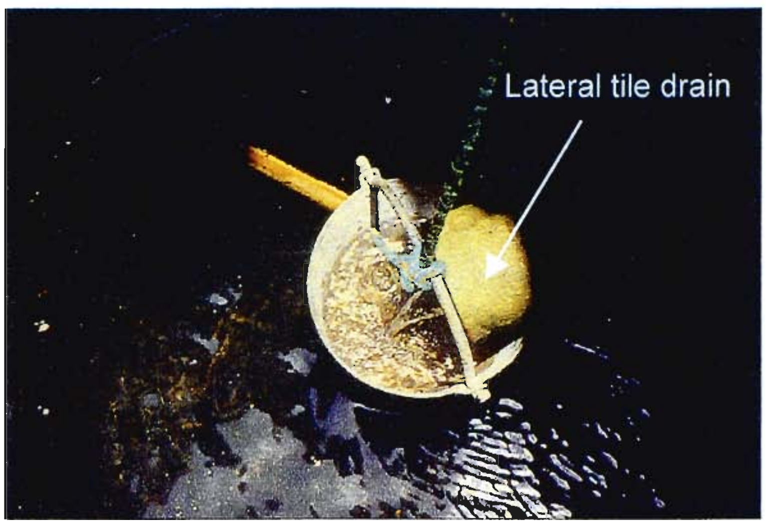

Fig. 4.6 Discharge measurement

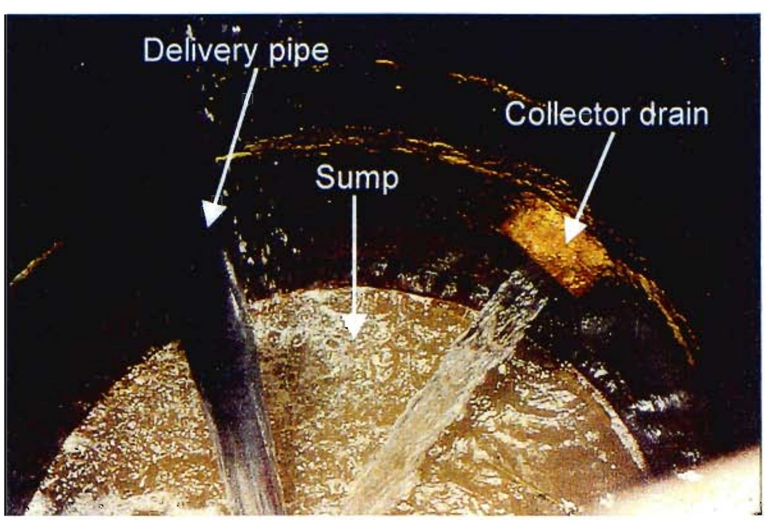

Fig. 4.7 Free flow of collector drain into sump

Fig. 4.8 Fertilizer application (basal dose) after puddling

Fig. 4.9 Rice transplanting after fertilizer application

Fig. 4.10 Spectrophotometer used for analysis of drainage effluent

Table 4.3. **Agricultural practice**

Year	Crop	Plant density (hill m^{-2})	Date of transplanting	N fertilization ($kg\ ha^{-1}$)	Harvesting date
1999	Rice	33	February 2	120	April 24
2000	Rice	33	January 26	120	April 20

Such an irrigation practice is adopted with a view to keep the rice field under standing water with a depth of 4-6 cm throughout the crop season. However, nearing harvest and also after application of basal dose of nitrogen, the surface ponding is kept to a minimum (almost nil). For this, the excess water is allowed to drain out as surface flow by cutting the dikes of the paddy fields. A typical pictorial view of the rice crops in reclaimed and unreclaimed land is given in Fig. 4.11 and Fig. 4.13, respectively.

4.4 Soil properties

The soils of the experimental fields have two distinct layers. The top one metre layer is dark, heavy and consists of clay soil. The soil is of swelling and shrinking type. The hydraulic conductivity of the layer is very low. The soil below one metre is deep and its texture varies from clay loam to sandy soil. The detailed investigations were carried out for the selected physico-chemical properties of different horizons of four treatments of drain spacings. The cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) of the soil were determined by the procedure adopted from Richards (1954). All other parameters were estimated by adopting standard procedures. The physical and chemical properties for the selected parameters are given in Table 4.4.

Fig. 4.11 Rice crop in reclaimed land with 15 m drain spacing

Fig. 4.12 Uncropped land for salinization studies with 25 m drain spacing

Fig. 4.13 Land under reclamation with 35 and 55 m drain spacing

Table 4.4. Physical and chemical properties of the soils

Sampling location and depth* (cm)	Bulk density (Mg m^{-3})	Texture			Salinity@ (dS m^{-1})	pH	CEC (cmol $(p^+)kg^{-1}$)	ESP
		Sand (%)	Silt (%)	Clay (%)				
			15 m drain spacing					
0-15	1.25	32	8	60	3.8	7.98	50.0	25.0
15-30	1.06	12	18	70	4.0	7.81	57.5	34.8
30-60	1.06	12	14	74	4.1	8.20	56.3	37.8
60-90	1.11	24	23	53	4.1	8.20	61.3	44.9
			25 m drain spacing					
0-15	1.23	16	18	66	6.1	7.50	51.3	43.9
15-30	1.11	18	16	66	6.2	7.60	43.8	62.9
30-60	1.04	14	14	72	4.7	7.20	56.3	46.7
60-90	1.00	24	11	65	3.9	7.14	50.0	57.5
			35 m drain spacing					
0-15	1.25	22	18	60	9.2	7.15	48.8	48.7
15-30	1.24	26	15	59	10.5	7.20	52.5	50.0
30-60	1.31	22	33	45	17.1	7.18	47.5	57.9
60-90	1.34	32	27	41	20.1	7.25	52.5	54.8
			55 m drain spacing					
0-15	1.17	36	14	50	16.5	7.24	40.0	62.5
15-30	1.00	20	15	65	21.0	7.25	53.8	48.8
30-60	1.23	38	18	44	25.2	7.25	45.0	66.7
60-90	1.18	56	14	30	28.9	7.28	31.3	68.0

Note : Values given in the table for various parameters are mean of the triplicates.

* Sampling location is at the intersection of the mid-spacing and mid-lateral length lines.

@ ECe of 1:1 of soil:water suspension

4.4.1 Soil-water retentivity equation

The soil water retention curves were estimated through pressure plate assembly for four depths from each drain spacing treatments. Since there was not much variation in the soil water retention characteristics layer-wise, only one relationship was developed for each drain-spacing. Thus four independent retentivity curves were obtained. Each curve, plotted on semi-logarithmic axes, passed through all measured data points i.e. volumetric water content (θ) values at -10, -30, -70, -100, -500 and -1000 kpa. The form of the fitted curve is as proposed by Campbell (1974) and expressed as :

$$\psi = a\ (\theta\ /\ \theta_s)^{-b} \qquad \text{... (4.1)}$$

where, ψ is the pressure potential, bar (100 kPa)

θ is the volumetric water content, fraction

θ_s is the volumetric water content at saturation,

a, b are empirical parameters.

The resulting equations will be used as input in simulation modelling. The parameters of the retentivity equations are given in Table 4.5.

Table 4.5. Saturated water content and empirical parameters of retentivity equations

Area under following drain spacing, m	θ_s	a	b
15	0.98	14.7	7.574
25	0.88	16.0	8.407
35	0.90	13.2	8.801
55	0.85	12.2	7.611

4.4.2 Saturated hydraulic conductivity

In situ, saturated hydraulic conductivity was determined by auger hole method using a grid spacing of 200 metre. The values ranged from 0.02 to 0.90 m d^{-1} with a geometric mean of 0.144 m d^{-1}. Percolation loss from the paddy fields at the project site is 0.012 m d^{-1} (Devadattam and Ramesh Chandra, 1995). In May 1999, the discharges, the hydraulic heads and zone of influence of the existing drains were measured and saturated hydraulic conductivity was determined by using the steady state Hooghoudt's equation. The *in situ* value of saturated hydraulic conductivity by this method was 0.12 m d^{-1}. This value is quite close to the value of 0.144 m d^{-1} reported earlier. The latest value of 0.12 m d^{-1} (0.5 cm hr^{-1}) determined by large scale field method, was adopted as input parameter in the application of ENVIRO-GRO model (Table 3.2).

4.5 Soil sampling and analyses

Soil samples were taken from 0-15, 15-30, 30-60 and 60-90 cm layers for all the 4 drain spacings. The samplings were done both under cropped and saturated as well as dry fallow conditions (Fig. 4.4). The ECe of soil water was determined in three ways. For samples taken under saturated field conditions 1:1 soil:water extract was prepared. When the soil samples were taken in dry fallow conditions 1:2 soil:water extract was prepared. The ECe of oven dried samples was measured in 1:2.5 soil:water extract. The soil water extract in all the three cases was obtained by simply filtering soil solution without using a suction apparatus. The ECe and pH of the extract was measured by digital EC and pH measuring equipment.

In order to study the salinization in 25 m spacing area the soil moisture depletion pattern was estimated by measuring soil moisture content gravimetrically by oven drying at 105^{0}C. The total increase in salt content within the profile during the fallow period was estimated by multiplying the salt concentration in the water table by the cumulative moisture depletion from the 0-15 and 15-30 cm soil layers. All forms of nitrogen, namely, NO_2-N, NO_3-N and NH_4-N, concentration in the soil water extract were calculated assuming that all these forms of nitrogen were dissolved in the water or extracted along with water, including the NH_4-N component.

4.6 Water sampling and analyses

Subsurface drainage water sampling from the central lateral of each drain spacing type i.e. 15, 25, 35 and 55 m began on March 12, 1999 (40 DAT) and continued till March 20, for 15 and 25 m and upto March 22, 1999. Subsurface drainage system with 15 and 25 m drain spacing could not be operated after March 20, 1999 and thus no water sample of subsurface drainage effluent could be collected for further analysis. Also, sub-surface drainage water samples were collected during May 18-22, 1999 to know the salt and nitrogen content in the effluent after the crop growth season. The last dose of urea was applied on March 9, 1999. During the sampling period two irrigations of 5 to 6 cm depth each were applied. Water sampling from the selected central laterals were done from January 24 to February 3, 2000. Drainage system with only 35 and 55 m drain spacing was operational during the crop growth season of 2000. In order to estimate drainage volume, discharge from each lateral was measured on ten occasions, using a stop watch and calibrated bucket of 4.25 litre (Fig. 4.6). The water samples were analysed immediately after collecting from the field and when storage was required beyond 24 hours due to some unavoidable reasons the samples were frozen to prevent microbial activity. The method adopted for estimation of nitrite and nitrate nitrogen both in soil extracts and drainage water was that of Kamphake *et al.* (1967) modified by Downes (1978). Ammonium nitrogen was determined colorimetrically using the modified indophenol blue method (Novozomsky *et al.*, 1974). The digital spectrophotometer used in the analysis is shown in Fig. 4.10. The amount of various forms of nitrogen removed via drainage water was calculated from the volume of the drainage water and their respective concentrations in the representative samples. The average value obtained during the sampling period was then integrated over the crop season to get an approximate value of loss per hectare over the season.

4.7 Plant sampling and analyses

The plant/hill samples were collected from 3 places i.e. just at above the lateral, at 1/4 spacing away from the lateral and at mid-spacing, on 45 DAT when the plant uptake of N is supposedly at its peak. The total nitrogen in plant was determined using an autoanalyser following the procedure outlined in Technicon Monograph I, 1971. The grain yield data were recorded from 1 m square plots of each spacing treatment.

CHAPTER-V

RESULTS AND DISCUSSION

5.1 Experimental Measurements

5.1.1 Soil characteristics vis-a-vis subsurface drainage

Laboratory test revealed that the soil of the study site is highly swelling and shrinking type. In situ, measured values of saturated hydraulic conductivity are reported in section 4.4.2. The areas with 15 and 25 m drain spacing had been under the reclamation influence of subsurface drainage (SSD) for the last one decade and their soil profile salinity was stabilized at 4 to 5 dS m^{-1} till May, 1997 (Ramana Rao, 1998). During the experiment i.e. February to April 1999 the area with 15 m drain spacing was under rice cultivation where as the area with 25 m drain spacing was left fallow with no crop and no irrigation. However, the subsurface drainage system (a decade old) functioned till March 20, 1999, beyond which it could not be operated because the sump, which was receiving the effluents from 15 and 25 m spacings, sank suddenly due to quick sand phenomenon. Bulk densities averaged over four soil depths (0-15, 15-30, 30-60 and 60-90 cm), were 1.12 and 1.10 Mg m^{-3} for profiles of 15 and 25 m drain spacing areas, respectively. The soil salinity (expressed as electrical conductivity of soil extracts) of the four profiles was almost uniform (3.8 to 4.1 dS m^{-1}) in the area with 15 m drain spacing and it ranged from 3.9 to 6.2 dS m^{-1} in the area with 25 m drain spacing (Table 4.4). During the experimental period, the mean EC of the effluent from 15 m drain spacing area was 4.35 dS m^{-1} and from the 25 m drain spacing area was 9.83 dS m^{-1}. Prior to the dry season of 1997 the EC of drainage water remained in the range of 4 to 5 dS m^{-1} under both 15 and 25 m spacing (AICRAD, 1986-1998).

During 1998, 1999 and beyond, the area with 25 m spacing was left fallow and this led to the build up of root zone salinity in the absence of crop cultivation, irrigation, leaching and subsequent drainage. Apart from this, the PET always exceeds the rainfall in the dry months from January through May of any year (Table 4.1). This climatic factor aggravates the chemical degradation of the root zone soil profile. The changes which took place on the land surface over months and over years are depicted in Fig. 4.2 and Fig. 4.3. Under this situation when the drainage system with 15 and 25 m spacing was operated in March 1999, it was found that the EC of the drainage effluent from 25 m spacing had increased by more than two folds as compared to 15 m spacing. This may have happened due to salt build-up in the root zone profile during the fallow period of May 1997 onwards. This observation suggests that such coastal lands are prone to quick secondary salinization in the absence of leaching by subsurface drainage system.

The measured data of salinity of root zone profile i.e. of 0-15 cm and 15-30 cm from February 1997 to February 2000 are presented in Table 5.1. The temporal changes in the salinity of the root zone soil profile are shown graphically in Fig. 5.1. In the figure, the value of soil salinity has been transformed to the salinity of soil water at field saturation. From the Fig. 5.1 it is clear that soil salinity in 0-15 cm layer has increased to 5.76 dS m^{-1} in one year which is almost the upper limit of the safe value (critical value) for rice cultivation. The salinity in 15-30 cm layer in which the maximum root proliferation takes place, increased to 8.08 dS m^{-1} in one

Table 5.1. Statistics of root zone soil salinity measured in the area of 25 m drain spacing

Year	Soil layer (0-15 cm)			Soil Layer (15-30 cm)			Sources/remark
	Mean	S.D.	Range	Mean	S.D.	Range	
1997	1.53	0.03	1.50 - 1.56	2.54	0.17	2.38 - 2.78	Ranaba Rao, 1998
1998	2.88	0.10	2.75 - 3.00	4.04	0.43	3.55 - 4.55	AICRPD, 1999
1999-I	6.24	1.84	3.90 - 8.40	6.42	1.59	4.70 - 8.20	measured in March and May 1999
1999-II	10.70	4.30	6.40 - 14.60	11.60	4.80	6.70 - 15.00	measured in December 1999
2000	11.90	3.40	8.00 - 15.80	12.85	3.60	8.40 - 17.30	measured in February 2000

Footnote : Values given in columns of mean and range represent the ECe in dS m^{-1} of the soil extracts with 1:2 of soil:water ratio.

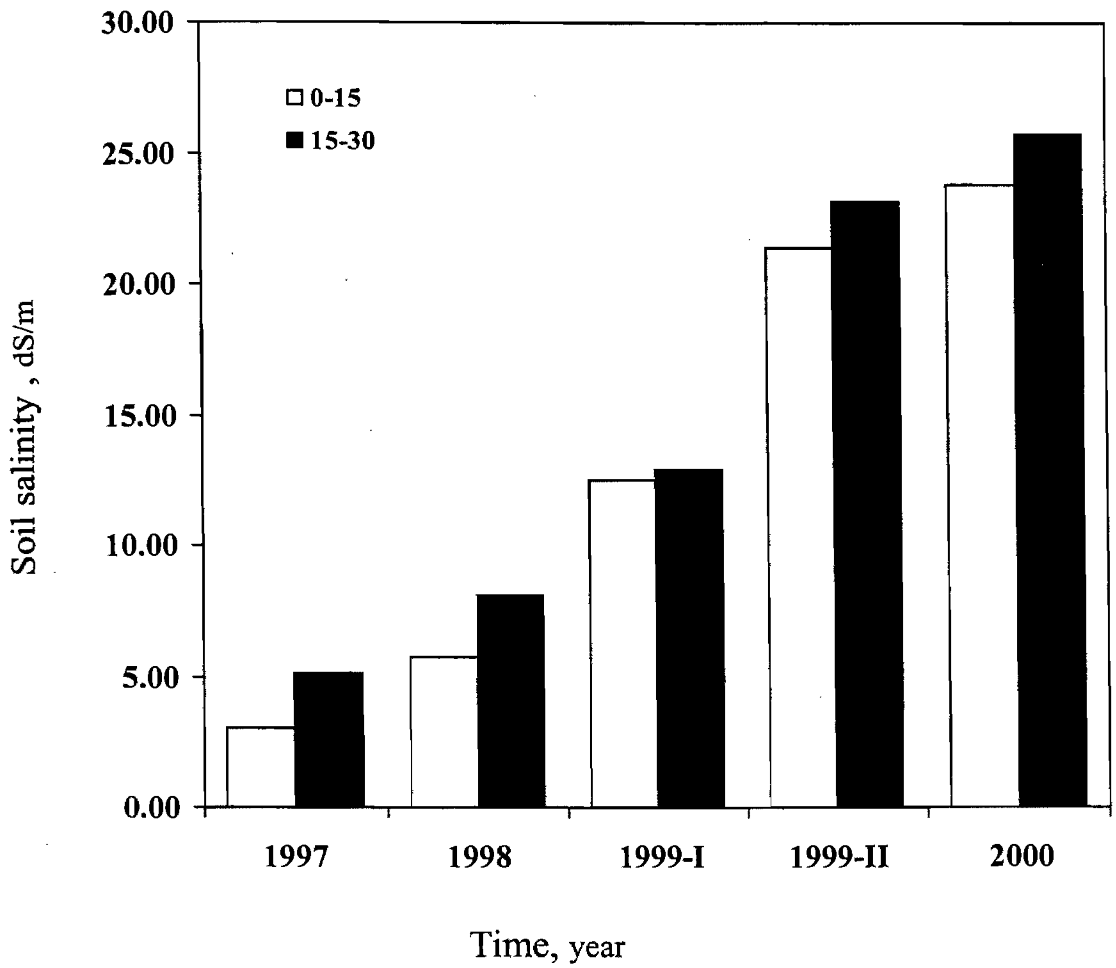

Fig.5.1 Salinization of root zone soil profile in the absence of subsurface drainage

year and it exceeded the critical value of salinity for rice cultivation (Ayers and Westcot, 1985).

Table 5.1 shows that in a span of 3 years, the soil salinity in 0-15 and 15-30 cm layers has increased approximately 8 and 5 folds, respectively, in the absence of leaching and drainage. The increase in soluble salts in the root zone is influenced by climate, soil type, crop cultivation, irrigation water quality and the depth to and salinity of the water table. However, at this specific site the salinization in the coastal clay soils with 25 m drain spacing is primarily caused by capillary flux from saline shallow water table. And the same is corroborated by the highly saline ground water presented in Table 4.2 and and the proximity of water table to the crop root zone given in Table 5.2.

Table 5.2. Location of water table before onset of monsson

Drain spacing (m)	Water table below soil surface (m)
15	0.85
25	0.48
35	0.65
55	0.55

The shallowest water table of 0.48 m was found in case of 25 m drain spacing which was left fallow. The area had the subsurface drainge system which was kept inoperative to study soil salinization. The above observation of water table was taken on May 22, 1999 and EC of the ground water sampled from a pit of 1.5 m depth on that day was found to be 40.4 dS m^{-1}. In another observation, the water table and salinity of the ground water were found to be 0.39 m and 25.2 dS m^{-1}, respectively, in March 1999 when irrigation season was at its peak in the adjoining areas. It may be inferred from the aforementioned observation that land remained waterlogged for almost 10 months of the year and in the remaining two months also the root zone profile remained within the reach of capillary rise. The soil moisture depletion in 0-15 and 15-30 cm layers varied from 1 mm d^{-1} in March to 2.5 mm d^{-1} in May. Based on the field observation it was found that an average salinity of 32.8 dS m^{-1} of ground water would leave 210 kg salt in the root zone soil profile should 1 ha. mm of such ground water through capillary flux evaporates to atmosphere. It was also found that 25.2 Mg ha^{-1} salt would be added to the root zone depth in a year with an average moisture depletion of 2 mm d^{-1} in the 2 months of non-drainage period.

The data on bulk density and soil salinity of the similar profiles from the new experimental area with 35 and 55 m drain spacing are also presented in Table 4.4. The average bulk density of soil of the 35 m spacing area was 1.28 Mg m^{-3} as compared to 1.15 Mg m^{-3} of 55 m spacing area. From the Table 4.4 it is clear that soil of the new experimental area has more sand in most of the layers as compared to the old area with 15 and 25 m drain spacing.

Measured data on cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) of the four profiles in each of the four areas with 15, 25, 35 and 55 m drain spacings are presented in Table 4.4. The CEC of the soil layers above the drainage base for 15 and 25 m spacing areas are similar. In case of 15 m spacing CEC was found to be minimum of 50.0 c.mol (p^+) kg^{-1} in top layer (0-15 cm) and a maximum of 61.3 c.mol (p^+) kg^{-1} in the bottom layer (60-90 cm) (Table 4.4). A gradual increase in ESP was observed from top to bottom layers. The ESP varied from 25 in top layer and 44.9 in the bottom layer. This is due to leaching of salts while irrigating rice crop and discharge of leachate via subsurface drainage. In the process Na^+ was washed from the clay complex. On the contrary the ESP were found to be varying from 43.9 in 0-15 cm and 62.9 in 15-30 cm layers of 25 m spacing area (Table 4.4). Presumably, the ESP would have been the same as was observed in 15 m spacing area because both the areas were under reclamation for a decade. This substantial increase in the ESP in the top 0-30 cm layer of 25 m spacing area is essentially due to salinization, as this area was left fallow and no leaching occurred beyond the dry season of 1997.

The CEC for different soil layers in 35 m spacing area varied with a minimum of 47.5 c.mol (p^+) kg^{-1} in 30-60 cm and a maximum of 52.5 c.mol (p^+) kg^{-1} in 15-30 and 60-90 cm layers (Table 4.4). The range of CEC for different soil layers in 55 m spacing area was 31.3 in 60-90 and 53.8 c.mol (p^+) kg^{-1} in 15-30 cm layer. In both the areas the CEC values are higher. This is due to higher clay content in the soil. Also, very high values of ESP were found in all the layers of new area under both 35 and 55 m drain spacings (Table 4.4). These values suggest that the land under consideration suffers from severe sodicity and drainage of such soils often becomes very difficult. The ESP values with respect to 35 and 55 m spacing areas were observed after one year of operation of the subsurface drainage system. This implies that a very little amount of Na^+ have been washed from the clay complex. The ESP of the soil profile of 25 and 35 m spacing area was found to be similar with an average value of 52.8. The ESP of the soil of 55 m spacing area was still higher as compared to the area with 35 m spacing. These variations are related to the direct effect of drainage density and total drain discharge over a period of time (Table 4.4 and Table 5.5).

5.1.2 Salt removal via subsurface drains

Estimation of salt removal via subsurface drains was done by measuring the EC of the subsurface drainage water. The measurements were done during *rabi* seasons of 1999 and 2000. The measured EC of the subsurface drainage water and its statistical parameters viz. mean, standard duration and coefficient of variations are given in Table 5.3 and Table 5.4 for 1999 and 2000, respectively. The lowest mean salinity of drainage effluent was observed to be 3.86 dS m^{-1} in 15 m drain spacing area with a c.v. of 19% (Table 5.3). The highest mean salinity of the drainage effluent was found to be 44.7 dS m^{-1} in the area which is in its initial stage of reclamation with 35 m drain spacing and its c.v. was more than 6% (Table 5.3). The mean salinity of drainage effluent from 55 m spacing area was 36.72 dS m^{-1} which is lesser than that of 44.70 dS m^{-1} of 35 m spacing. The quality of drainage effluents from 15 and 35 m drain spacings are the two extremes because the former is reclaimed land and the later is unreclaimed. Contrary to these the salinity of drainage effluent from the area with 25 m spacing shows an intermediate value of 11.42 dS m^{-1} and its coeffecient of variation is maximum of 34.72%. The reasons for this high variation possibly are : the land is uncropped and unirrigated. The higher salinity of effluent water as compared to that of 15 m spacing suggest salinization of the soil profile in the 25 m drain spacing. A similar trend of salinity of the drainage effluent of 35 and

Table 5.3. **Measured EC (dS m^{-1}) of subsurface drainage water in 1999**

Date of observation	Drain Spacing 15 m	25 m	35 m	55 m
15 - March	4.3	5.6	43.9	35.1
16 - March	4.2	14.7	45.1	35.3
17 - March	4.4	14.8	46.1	35.4
19 - March	3.8	12.8	41.3	37.4
20 - March	2.6	9.2	46.8	38.4
22 - March	-	-	48.5	38.1
23 - March	-	-	47.8	37.1
19 - May	-	-	40.4	34.8
22 - May	-	-	42.4	38.9
Mean	3.86	11.42	44.70	36.72
S.d.	0.74	3.96	2.88	1.59
c.v. (%)	19.18	34.72	6.45	4.32

'-' Sample could not be taken because of collapse of sump.

Table 5.4. Measured EC (dS m^{-1}) of subsurface drainage water in 2000

Day of observation	Drain spacing	
	35 m	55 m
24 - January	40.4	33.9
26 - January	34.4	27.8
27 - January	37.8	32.1
28 - January	36.6	33.1
29 - January	36.1	30.1
30 - January	35.6	30.5
31 - January	37.5	31.1
1 - February	45.3	36.7
2 - February	44.6	37.4
3 - February	35.1	37.4
Mean	38.11	32.91
S.d.	4.03	3.54
c.v. ((%)	10.57	10.66

55 m drain spacing area was observed in 2000 but EC has reduced by over 6 dSm^{-1} in 35 m and approximately 3 $dS\ m^{-1}$ in 55 m drain spacing area (Table 5.4). Also, the variability in salinity of drainage effluent has increased in the second year but the coefficient of variation in both the spacings were at par with 10.57 and 10.66%.

The pattern of salt removal via subsurface drainage is depicted in Fig. 5.2 and Fig. 5.3 for the reclaimed and unreclaimed land, respectively for the *rabi* season of 1999. Further Fig. 5.4 shows the salt concentration in the subsurface drainage effluents from 35 and 55 m drainage spacing area for the rabi season of 2000. The lateral drain with 15 m spacing washed total dissovled salts on an average of about 2.5 gl^{-1} where as the lateral drain with 25 m spacing discharged on an average of about 7.3 gl^{-1} (Fig. 5.2). It may be noted that the subsurface drainage system with 25 m drainage spacing was operated only to take observation. Contrary to these, the laterals with 35 and 55 m spacing in unreclaimed land washed on an average of 28.6 and 23.5 gl^{-1} of salts, respectively in 1999. Thus, the total dissolved salts in the drainage effluent of unreclaimed area were approximately ten times higher than that of the reclaimed land with 15 m drain spacing. The salt concentration in effluent of the lateral drain of 25 m spacing was three times higher than that of 15 m spacing. This was due to secondary salinization in this area. The salt concentration in the drainage effluents in the next season i.e. in 2000 decreased to 24.4 and 21.1 gl^{-1} from 28.6 and 23.5 gl^{-1} of 1999 in 35 and 55 m drain spacing, respectively. The data on drainage rate, total annual subsurface drainage depth and total salt removal are given in Table 5.5. Two distinct drainage rates were observed in 35 and 55 m drain spacing areas. The drainage

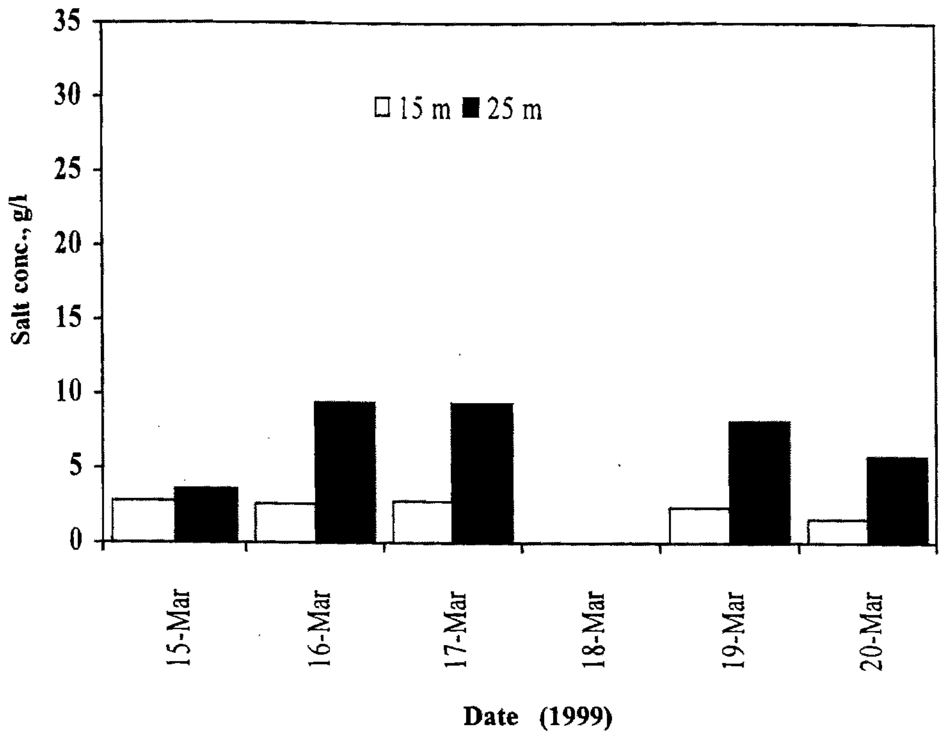

Fig. 5.2 Salt concentration in drainage effluent of the reclaimed area

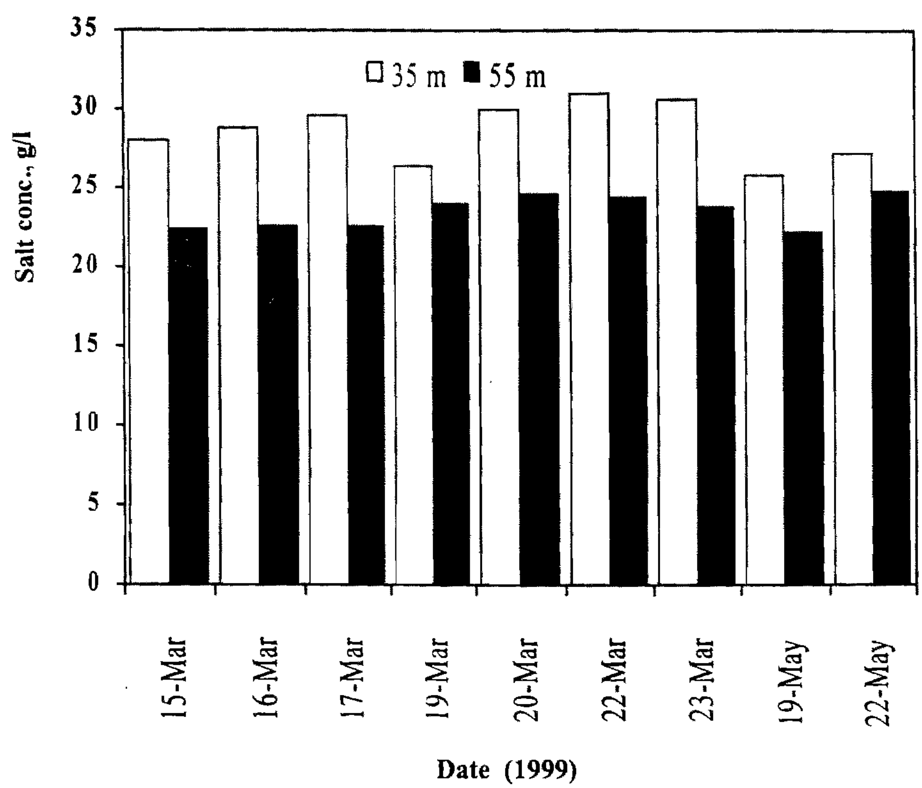

Fig. 5.3 Salt concentration in drainage effluent of the unreclaimed area

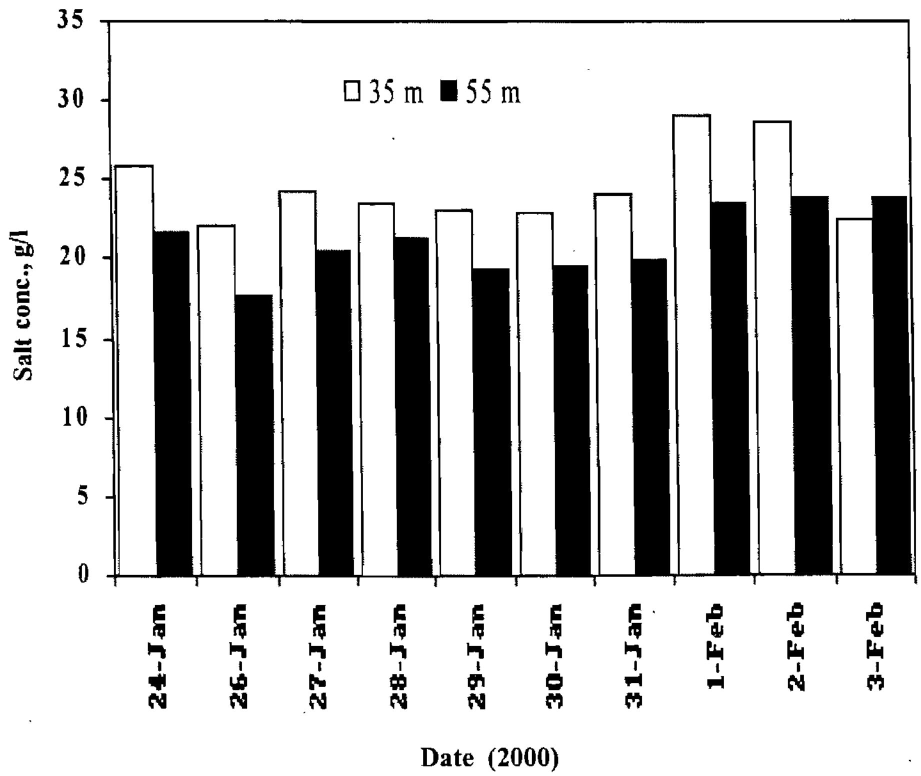

Fig. 5.4 Salt concentration in drainage effluent of the unreclaimed area

rate during the crop season was almost double the drainage rate during the fallow period in both the spacing treatments (Table 5.5). The system produced maximum outflow because atleast 5 to 6 cm ponding were maintained in both *rabi* and *kharif* seasons either by monsoon rain or irrigation during the rice crop growth period. This is the usual practice of the farmers and it facilitates an effective reclamation of coastal clay soils by efficient leaching of salts. Also, it is evident from Table 5.5 that the drainage rate has increased significantly by over 20% in 35 m area in the second year. The increase in drainage rate of 55 m spacing area was marginal i.e. about 10% in the year 2000 (Table 5.5). This observation suggests that improvement in soil physical condition is faster in narrower spacing as compared to the wider one. In the same time period of operation of drainage system more water and salt was removed from the soil profile of 35 m spacing area as compared to 55 m drain spacing area.

In the first year of reclamation i.e. 1999, the lateral drains spaced at 35 and 55 m removed 85.8 and 35.3 Mg ha^{-1} yr^{-1} total dissolved salts respectively. In the year 2000, the rate of removal was decreased marginally in both the spacing areas (Table 5.5). In both the years, the salt removal rates were more than double in case of 35 m spacing if comapred with 55 m drain spacing. From the field measurement it was estimated that the top 1 m layer of soil contained 2 and 1.5% salt in 35 and 55 m drain spacing area, respectively. The data presented in Tables 5.3, 5.4 and 5.5 suggest that salt concentrations in effluents and drainage rate were always much higher in 35 m spacing as compared to 55 m spacing. All these data corroborate the higher pace of reclamation with 35 m drain spacing. Further computation and analysis of data suggest that with the aforementioned

Table 5.5. Subsurface drainage and salt removal rates in unreclaimed area

Year	35 m				55 m			
	Drainage rate, mm d^{-1}		Total drainage mm	Salt removal Mg ha^{-1} yr^{-1}	Drainage rate, mm d^{-1}		Total drainage mm	Salt removal Mg ha^{-1} yr^{-1}
	*Crop season	@Fallow period			*Crop season	@Fallow period		
1999	5.6	3.7	300	85.8	3.0	1.6	150	35.3
2000	6.8	-	325	79.3	3.3	-	160	33.8

'-' not measured; * mean of 15 observation; @ mean of 5 observation

Table 5.6. Nitrogen concentration (mg l^{-1}) in 1 : 1 soil water suspension

Depth (cm)	Subsurface drain spacing (m)											
	Reclaimed area						Area under reclamation					
	15			25			35			55		
	NH_4^+-N	NO_2^-N	NO_3^-N	NH_4^+-N	NO_2^-N	NO_3^-N	NH_4^+-N	NO_2^-N	NO_3^-N	NH_4^+-N	NO_2^-N	NO_3^-N
0 - 15	n.d.	0.052	1.751	n.d.	0.741	0.769	1.987	0.072	1.634	1.788	0.055	3.386
15 - 30	n.d.	0.102	2.044	n.d.	0.358	1.315	1.687	0.067	3.968	1.056	0.075	3.235
30 - 60	n.d.	0.066	2.453	n.d.	0.309	1.555	1.433	0.057	1.734	0.839	0.071	2.773
60 - 90	n.d.	0.048	2.032	n.d.	0.316	1.796	1.298	0.036	2.302	0.717	0.037	3.499

n.d. not detected.

rates of salt removal, the coastal clay soil with the given initial conditions will be reclaimed in 3-4 and 6-7 years with 35 and 55 m drain spacings, respectively provided no additional salts are added to the soil profile of top 1.0 m depth from external sources. The salt balance in the soil profile would have the permissible salinity to raise rice crop after the reclamation period mentioned above.

5.1.3 Nitrogen movement in soil layer

All the three forms namely NH_4-N, NO_2-N and NO_3-N in four layers (0-15, 15-30, 30-60 and 60-90 cm) of soil were measured in the soil samples collected on 40th day of transplanting (DAT) of rice with 1:1 soil water suspension and the results are presented in Table 5.6.

5.1.3.1 Ammonium-nitrogen

The data shown in Table 5.6 indicate that no trace of NH_4-N was found in any of the propfiles of 15 and 25 m drain spacing whereas NH_4-N was present in the soil solutions of all the layers in case of 35 and 55 m drain spacing. The nature of NH_4^+ ion is such that if it is adsorbed on the clay complex it can not be extracted with water. The possibility of having NH_4^+ ion in soil water solution exists only because it remained in diffused double layer rather than getting adsorbed on the clay complex. Data presented in Table 4.4 suggest that the land with 15 m drain spacing is already reclaimed with the least soil salinity and ESP amongst the 4 drain spacing treatments.

The long term influence of drainage might have enhanced the space for NH_4^+ ion adsorption on the clay complex by removing the Na^+ ions. This is why no trace of NH_4-N was detected in the soil samples of 15 m drain spacing. Obviously no trace of NH_4^+ was found in the soil of 25 m drain spacing because this area was kept fallow and no fertilizer was applied in the season. On the contrary, higher concentrations of NH_4-N in the soil samples of all the layers of 35 and 55 m drain spacing were observed (Table 5.6). The areas with 35 and 55 m drain spacing are at the initial stage of reclamation by subsurface drainage system. The average soil salinities (EC_e) of 14.2 and 22.9 dS m^{-1} and ESP 52.8 and 61.5 were observed in 35 and 55 m spacing areas respectively (Table 4.4). The exchange complex of the clay was so much saturated with Na^+ in these cases that it did not allow NH_4^+ ion to get adsorbed on the exchange complex. Also, the NH_4-N concentrations were higher in 35 m spacing as compared to 55 m spacing. The unusual observation of higher concentration of NH_4^+ ion in the soil solution suggests that the soil was over saturated with sodium and the situation has led NH_4^+ to remain in soil solution. The concentration of NH_4-N in soil solution decreased as the depth increased. The maximum concentrations of NH_4-N in soil solution were 1.987 and 1.788 mg l^{-1} in 0-15 cm layer in case of 35 and 55 m drain spacing area, respectively. The decrease in NH_4^+-N concentration with depth may be the result of surface application of urea combined with slow downward movement of NH_4^+ ion unlike anions like NO_3^- which move downwards faster due to anion exclusion.

5.1.3.2 Nitrite-nitrogen

The data of Table 5.6 indicate that traces of nitrite-nitrogen were observed in all the layers of each of the drain spacings. The order of magnitude of the NO_2-N concentrations were similar in cultivated lands regardless of drain spacing and degree of reclamation. A six times higher nitrite-nitrogen concentration was observed in case of 25 m drain spacing which was left fallow.

Nitrite (NO_2^--N) is a biochemical product at the intermediate stage of the nitrification. The nitrification rate is governed by aerobic conditions and the population of active nitrifying bacteria. The reason for higher concentration of nitrite in 25 m spacing area could be anerobic conditions due to waterlogging and nonsurvival of bacteria like nitrobactor due to salt build up in the soil layers. Such developments inhibit further oxidation of nitrite to nitrate. In such a soil and water environment, whatever nitrite is produced from the native nitrogen, does not get further oxidized to nitrate and thus accumulation of nitrite is maintained in the soil layers of fallow land with 25 m drain spacing which is subjected to water logging and salinization due to nonoperation of subsurface drainage system. Contrary to this, nitrite concentration is insignificant in wetland rice fields with 15, 35 and 55 m drain spacings. In cropped fields, the two aerobic sites namely the oxidized surface soil layer and the rhizosphere, under the influence of continuous leaching of salts experience nitrification. Thus nitrite, the intermediate product of nitrification process gets transformed into nitrate, the most stable form of nitrogen. Nitrite concentration in soil layers of cultivated field remained at a very low level which is good for crop (Table 5.6). The increasing trend of the concentration of nitrite in soil layer of 25 m spacing might give rise to nitrite toxicity if it goes above 0.9 mg l^{-1} NO_2-N over the years in the asbence of drainage.

5.1.3.3 Nitrate-nitrogen

Soil NO_3-N were observed to be highest in all the soil layers of 55 m of drain spacing area (Table 5.6). The lowest soil NO_3-N was found in the case of unfertilized area with 25 m drain spacing. The soil NO_3-N were similar in case of 15 and 35 m drain spacing at 0-15, 15-30, 30-60 and 60-90 cm soil layers (Table 5.6). In case of reclaimed area i.e. with 15 and 25 m spacing, soil NO_3-N concentration increased as the depth of soil from surface increases. This indicated the leaching of NO_3-N or the downward movement of NO_3-N due to anion exclusion. No such distinct trend was observed in the first season of cultivation of new area with 35 and 55 m drain spacing which were being reclaimed by subsurface drainage (Table 5.6).

However, the data in Table 5.6 indicate that soil NO_3-N was 3.968 mg l^{-1} in 15-30 cm layer of 35 m spacing and that is the maximum concentration amongst all the values presented in the Table 5.6. This may be due to higher nitrification rate in the proximity of the active root zone, faster removal of salts and no denitrification due to oxidized condition, which is contrary to the area with 55 m drain spacing. The layer wise NO_3-N concentrations in 35 and 55 m spacing do not give any fixed trend. This may have happened due to temporal dynamics of soil NO_3-N which depends upon several factors affecting microbial activity and/or soil physico-chemical processes (Williams *et al.,* 1992). Also, soil NO_3-N concentration at any point of time depends on several processes that occurred concurrently prior to measurement. These processes may include N mineralisation by soil microbes, N immobilisation in soil and microbial biomass, remineralization of immobilised N, nitrification, denitrification, plant uptake, leaching and transformation to gaseous compounds such as NH_3, NO, N_2O and N_2. As suggested by Williams *et al.* (1992) the aforementioned reactions are complex and depend on soil biological, chemical and physical processes. From the Table 5.6 it is evident that there is hardly any difference in soil NO_3-N under 15 and 35 m drain spacing. The reason could be that after hydrolysis of urea the majority of NH_4^+ ions were adsorbed on the clay as this area was reclaimed with the least ESP (Table 4.4) and thus, lesser amount of NH_4^+ ions remained to be transformed into nitrate. The soil NO_3-N in 4 selected layers varied between 1.751 to 2.453 mg l^{-1} in 15 m spacing. A similar range (1.634 to 3.968 mg l^{-1}) was also observed in the 4 soil layers in highly saline sodic soil with 35 m spacing. This is despite the fact that the latter spacing was more than twice of the former and the chemical composition of the soil is entirely different from that of the 15 m spacing (Table 4.4). The two probable reasons are the following. First, because of higher saturation with Na^+, the NH_4^+ resulting from the urea hydrolysis could not get adsorbed on the clay and got drained out through both surface and subsurface drainage. This is corroborated by the highest concentration of NH_4-N in the subsurface drainage effluent (Fig. 5.7 and Fig. 5.9) and faster surface run off from 35 m spacing area to the adjacent area with 55 m drain spacing. And the second reason is that lesser NH_4^+ ion remained in the soil water medium to be transformed into nitrate. The second reason is the direct consequence of the first. On the contrary, lesser concentration of NH_4^+-N in subsurface drainage effluent were observed from 55 m spacing drains as compared with 35 m spacing. The former being a lowland, led to accumulation of flood water with with NH_4^+-N for longer duration. This situation might have allowed more loss of nitrogen through ammonia volatilization. Several other factors from the soil-water and crop environment might have allowed more nitrification and then more release and accumulation of NO_3-N in the soil water medium. This resulted into higher nitrate leaching in 55 m spacing as compared to 35 m spacing. A further support to this argument can be obtained by critically examining and comparing the nitrate histograms in Fig. 5.7 through 5.10.

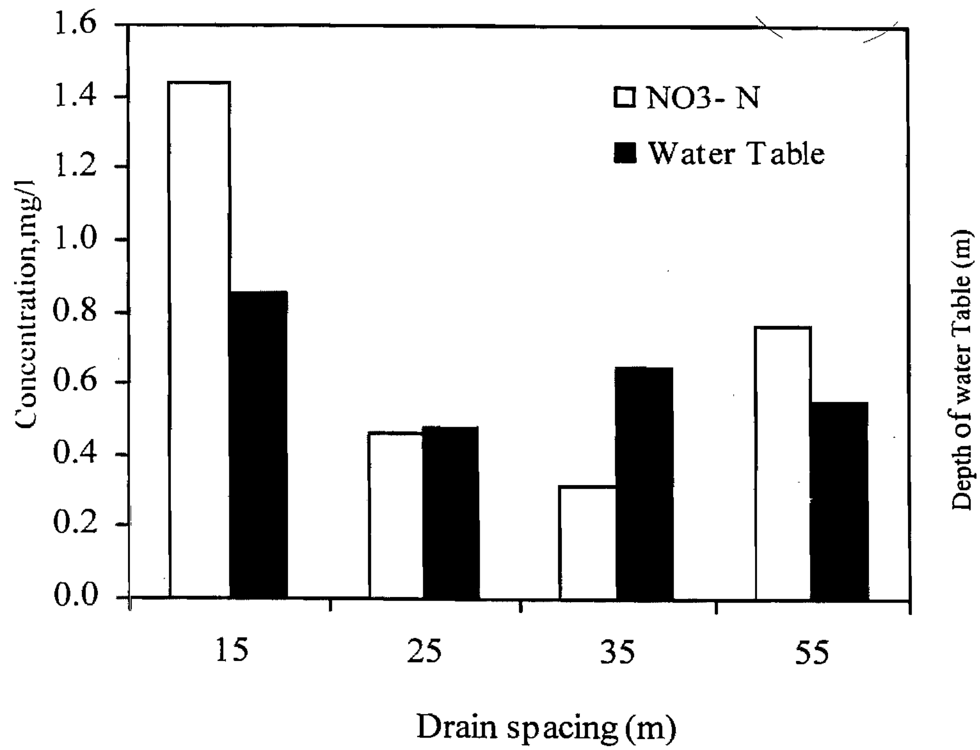

Fig.5.5 Nitrate-nitrogen in groundwater of various spacing areas

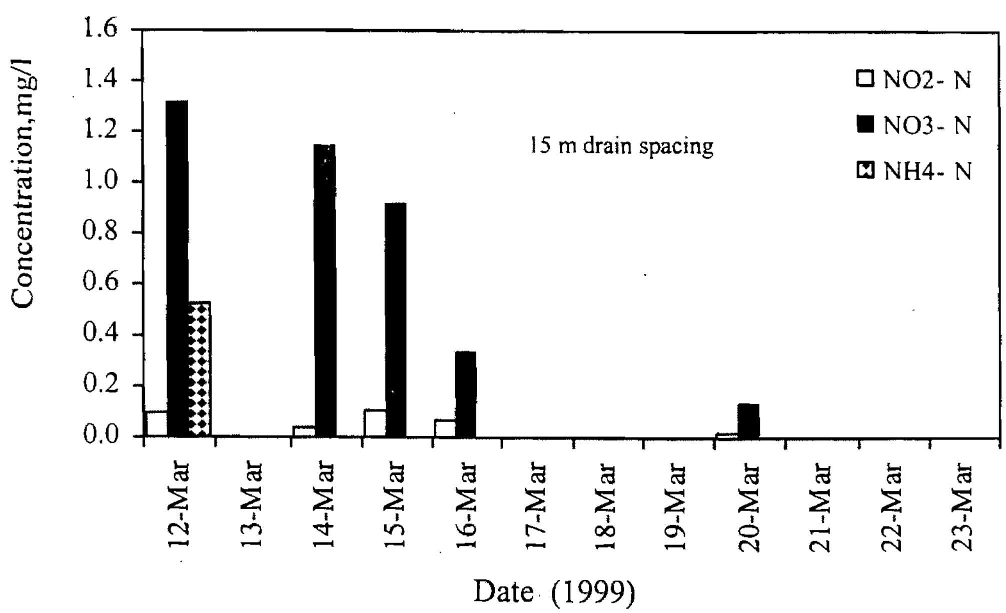

Fig.5.6 Nitrogen concentration in drainage effluent of 15 m spacing

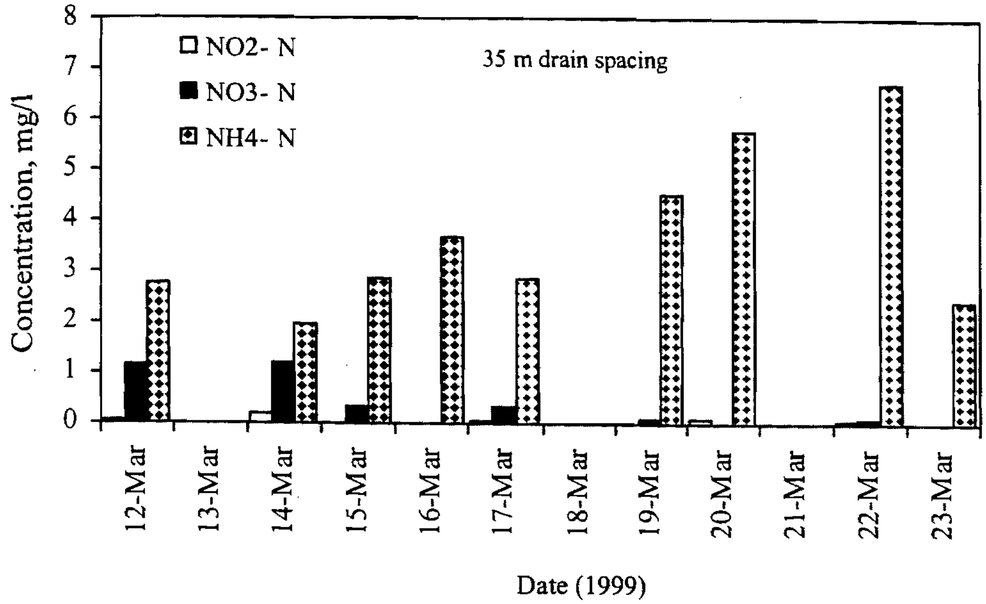

Fig.5.7 Nitrogen concentration in drainage effluent of 35 m spacing

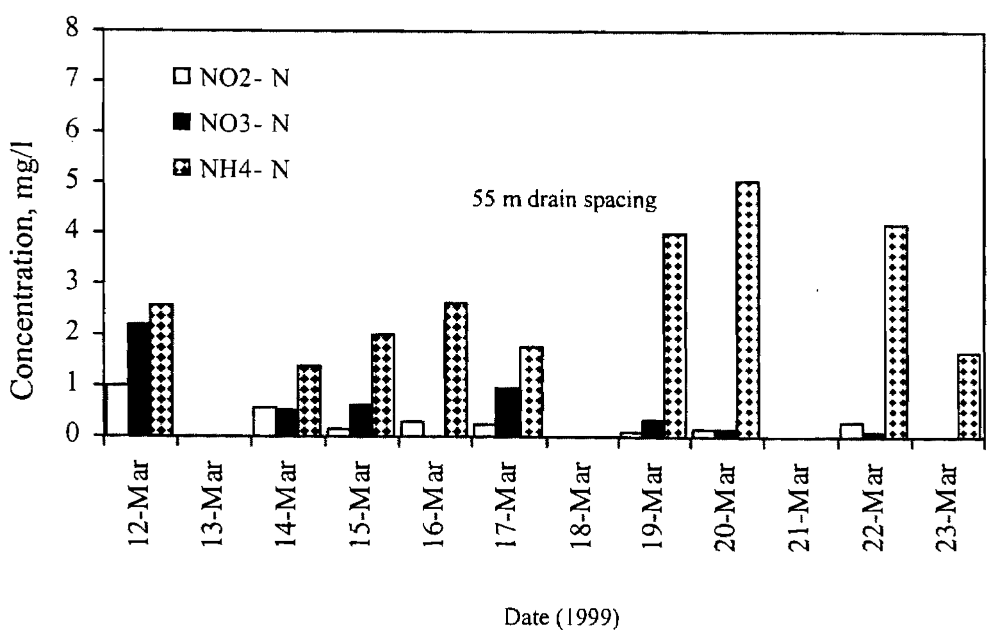

Fig.5.8 Nitrogen concentration in drainage effluent of 55 m spacing

5.1.4 Nitrogen losses through subsurface drainage effluent

For the two successive years, the concentration of three forms of nitrogen namely, NH_4-N, NO_2-N and NO_3-N in the subsurface drainage effluent from 15, 35 and 55 m drain spacing areas were measured. In 1999, the sampling of effluent began on 40 days after transplanting (DAT) i.e. on March 12; three days after the third dose of urea (@ 30 kg N ha^{-1}) was applied in all the three drain spacing areas. The sampling continued for consecutive 10 days during which two irrigations were applied following the local practice.

The measured concentration of various nitrogen forms in the drainage effluent are presented in Fig. 5.6, Fig. 5.7 and Fig. 5.8 for 15, 35 and 55 drain spacing area, respectively, for the year 1999. From the figures it is evident that the form of nitrogen losses in reclaimed land with 15 m drain spacing and in unreclaimed land with 35 and 55 m drain spacing were opposite to each other. NO_3-N loss dominated in 15 m drain spacing (Fig 5.6) where as NH_4-N losses dominated in 35 and 55 m drain spacing areas (Fig. 5.7 and Fig. 5.8). From Fig 5.6 it may be seen that a peak of 1.32 mg l^{-1} NO_3-N in effluent was observed on March 12 i.e. 3 days after fertilizer application and it gradually decreased to one tenth of peak value after 8 days. In these eight days, the observation on March 13, 17, 18 and 19 were not taken. Fig 5.6 suggests an exponential decrease of NO_3-N concentration over time in drainage effluent to a certain minimum value. NO_2-N losses were observed to be negligible. NH_4-N loss was observed only on the first day of sampling i.e. on march 12. Beyond 3 days after the fertilizer application NH_4-N was not found in any of the samples taken from 15 m spacing. Later on, after the harvest of rice crop in April, 1999, the subsurface water was analysed and traces of NO_3-N were detected but NO_2-N and NH_4-N were absent.

It may be recalled that the area under 15 m spacing was under reclamation for a decade. This treatment did improve the soil condition i.e. soil salinity from 35 to 4.0 dS m^{-1} and ESP from 55 to 35.6. This might have allowed NH_4-N adsorption on clay complexes of the soil.

From Fig. 5.7 and 5.8 it is clear that NO_2-N was almost absent in 35 m spacing area and negligibly small in 55 m spacing area. No samples were collected on March 13, 18 and 21, 1999.

NO_3-N concentration in the effluent varied from nil to 1.2 mg l^{-1} and nil to 2.2 mg l^{-1} in 35 and 55 m drain spacing, respectively. Majority of the nitrogen loss occurred from these two spacing areas were of the NH_4-N form. NH_4-N concentration in the sample varied from almost 1.98 to 6.70 mg l^{-1} and 1.65 to 5.1 mg l^{-1} in 35 and 55 m spacing area, respectively. Also, it was observed that the effluent from 35 and 55 m drain spacing areas contained 6.704 and 4.205 mg l^{-1} of NH_4-N, respectively, before irrigation, and 2.438 and 1.650 mg l^{-1}, after irrigation. The dilution effect was due to irrigation. At this stage, the new finding of significant concentration of NH_4-N in subsurface drainage effluent was too startling to be reconciled with by the panel of experts supervising the study. During the discussion the argument which came up most often was why should there be NH_4-N in the water which was sampled 1 m below the soil surface. Normally, NH_4^+ ion which is generated by hydrolysis of urea should get adsorbed on clay complex and/or nitrified into nitrite and finally to nitrate. And thus, these measurements, on the advice of the experts were repeated at the time of transplanting when the urea (@ 60 Kg N ha^{-1}) was applied as a basal dose. In 2000, the basal dose was applied on January 25. First sampling was done on January 24 a day before the fertilizer application and next sampling began on January 26 and continued daily till February 3. The NH_4-N concentration in drainage effluent in 35 and 55 m spacing area over time is presented in Fig. 5.9 and 5.10, respectively. The finding of 1999 was confirmed in 2000. From this set of observation, it may be seen that the peak concentration of NH_4-N in drainage effluent was found after 1 to 2 days after fertilizer application whereas such a peak concentration in 1999 was observed after 10 to 12 days in both 35 and 55 m drain spacing areas. In 1999, when leaching of the salts and its removal was initiated, the soil was highly saline and sodic with very poor hydraulic conductivity. These factors might have hampered the urease activity and thus the release of NH_4^+ ions got delayed and subsequent transport to the drain was slower due to sealing of soil pores due to hydrodynamic dispersion and swelling nature of the clays. On the contrary, in the later case (i.e. in the year 2000), the peak concentration of NH_4-N was observed much earlier. This implies the influence of the subsurface drainage which helped improving the soil physico-chemical properties and enhanced the urease activity.

Also the pH of soil water solution during the observation period varied between 7.8 to 8.3 which is ideal for the release of NH_4^+ after the hydrolysis of urea. This led to higher losses of nitrogen in ammonical form. In fact, the exchange complex of the clay was so much saturated with Na^+ in unreclaimed area that it did not allow NH_4^+ ion to get adsorbed on the clay complex. Although the ammonification follows the first order reaction kinetics but in the presence of rice plants in wet lands, it could be modified

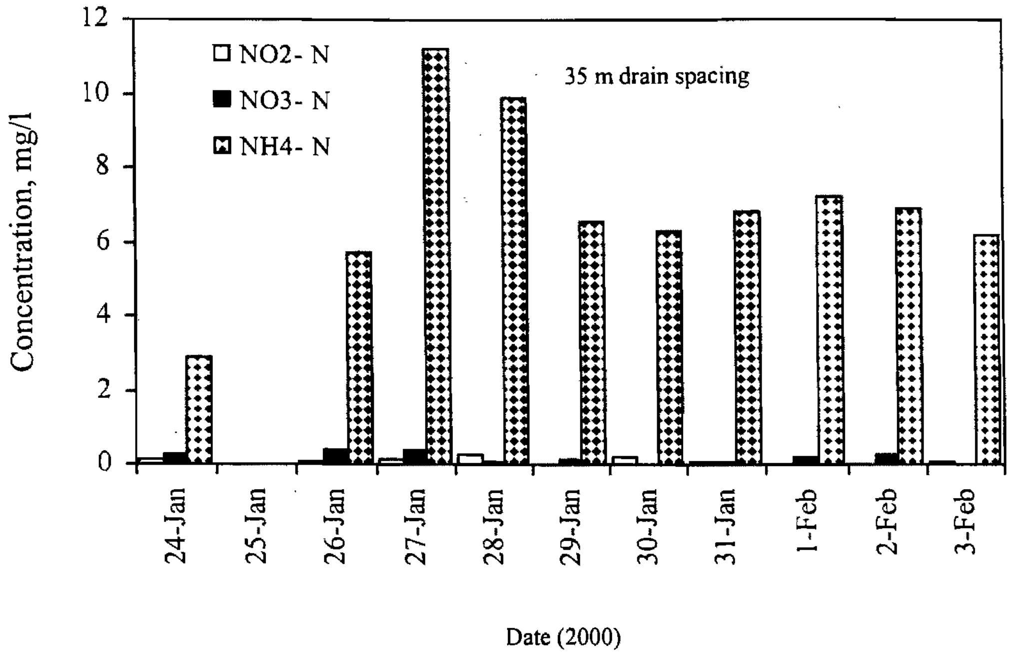

Fig.5.9 Nitrogen concentration in drainage effluent of 35 m spacing

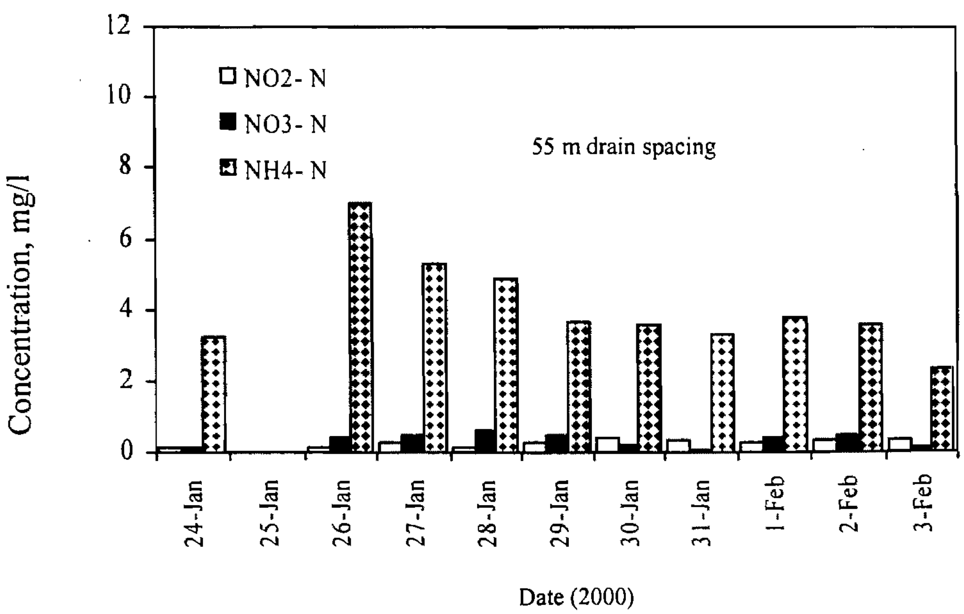

Fig.5.10 Nitrogen concentration in drainage effluent of 55 m spacing

(Savant and De Datta, 1982). Kinetic data on ammonia release in soil solution collected by Manguiat and Broadbent (1977) showed (i) an initial increase in NH_4-N in soil solution, attaining a maximum of 14 mg l^{-1} in 2 weeks time under submergence followed by a reduction to 1 mg l^{-1} after 8 weeks, and (ii) increased salinity created by varying amounts of sodium chloride remarkably increased NH_4-N concentration from 10 to 22 mg l^{-1} in the quasi-equilibrium soil solution. This could have been due to NH_4^+ replacement from the soil exchange complex by added Na^+. This could have happened in our experiment too. In the specific situation like the one in our study, since the exchange complex of the clay is saturated with Na^+ and as the salinity of soil water is very high, NH_4^+ ion may have remained in diffused double layer and moved slowly downward alongwith the continuously percolating water, ultimately finding its way to subsurface drainage effluent. Vlek *et al.* (1980) suggested that the leaching loss of NH_4-N in wet land soils could be very serious if the percolation rate exceeds 5 mm d^{-1}. In our expariment also, higher loss of ammonium was observed in the drainage effluent of 35 m spacing laterals which was dewatering the soil profile at the rate of 5.6 and 6.8 mm d^{-1} in the crop seasons of 1999 and 2000, respectively (Table 5.5). Thus, a substantial loss of NH_4-N via subsurface drainage effluent was observed. These losses would be in addition to the loss via ammonia volatilization (Aulakh and Singh, 1997). In this experiment however, no attempts were made to estimate the ammonium losses above the ground surface as the main focus was an estimation of losses via subsurface drainage system.

A summary of the measured total nitrogen losses for three drainage spacings for 1999 and 2000 are given in Table 5.7.

Table 5.7 Summary of total nitrogen losses via subsurface drainage effluent

Nitrogen loss ($kg\ ha^{-1}\ yr^{-1}$)	1999			2000		
	15 m	35 m	55 m	15 m	35 m	55 m
NO_2-N	0.256	0.132	0.465	-	0.319	0.429
NO_3-N	3.068	1.059	0.801	-	0.582	0.562
NH_4-N	0.420	11.184	4.205	-	22.630	6.494
Total-N	3.744	12.375	5.471	-	23.531	7.485

'-' no sampling was done, due to system collapse.

From the Table 5.7 it is amply clear that the soil environment and the intensity of drainage did play an important role in removal of nitrogen from the soil-water system via subsurface drainage discharge. In case of 15 m drain spacing, the loss was minimum of 3.744 kg ha^{-1} yr^{-1}. Out of the total nitrogen losses the NO_3-N contributed the maximum of 82% and NH_4-N and NO_2-N contributed 11 and 7%, respectively. The total nitrogen losses was 12.375 and 23.531 kg ha^{-1} yr^{-1} in 35 m drain spacing area in 1999 and 2000, respectively. In this particular spacing treatment the NH_4-N losses contributed 90 to 96% of the total loss. Where as the losses in the form of NO_2-N and NO_3-N remained negligible in both the years. Due to wider spacing and poor drainage condition in 55 m drain spacing area the loss of nitrogen were lesser as compared to the 35 m drain spacing. In this case NH_4-N form of loss varied from 77 to 87% of the total N loss and No_3-N did contribute to the tune of 8 to 15% and NO_2-N contributed 5 to 8% of the total N loss.

5.1.5 Effect of drain spacing on N-uptake and crop yield

Total nitrogen uptake data were obtained from the analysis of rice hills sampled at three points; at above the drain, one fourth of spacing and mid of spacing on 45 DAT. The results of the plant analysis and the mean values of the triplicates are depicted in Fig. 5.11. In all cases the total nitrogen uptake by rice hill was observed highest for those which grew at above the drains. The reasons for such variations in plant uptake is directly related with the impact of reclamation, better exchange of oxygen and better availability of nutrients. Maximum uptake of approximately 0.585 g/hill was observed in 15 m drain spacing area with an average nitrogen uptake of 0.412 g/hill across the lteral drain. The grain yield from this area was 6.5 t ha^{-1} in 1999. The maximum total nitrogen uptake in 35 and 55 m drain spacing areas were 0.371 and 0.267 g/hill, respectively for the hills which grew just above the drains and 0.157 and 0.155 g/hill for the hills which grew at mid point of the drain spacing. The mean total-N uptake by plants in 55 m spacing area, which was practically unreclaimed in 1999 was just half of that observed in the area with 15 m drain spacing. The plant N uptake in the samples of 35 m drain spacing area followed the same trend but higher N-uptake was observed as compared to 55 m drain spacing area (Fig. 5.11). The grain yields were also very low at 1.9 t ha^{-1} and 1.8 t ha^{-1} in 35 and 55 m spacing areas, respectively. Such a low yield was attributed to low availability of nitrogen in extremely saline to saline sodic soils on one hand and significant losses of nitrogen through subsurface drainage on the other.

5.1.6 Nitrate load in ground water

In order to study the spatial variation of nitrate load in ground water under various subsurface drain spacings namely 15, 25, 35 and 55 m, and the temporal variation of various forms viz., NH_4-N, NO_2-N and NO_3-N in 15 m spacing, ground water was sampled and analysed in the end of

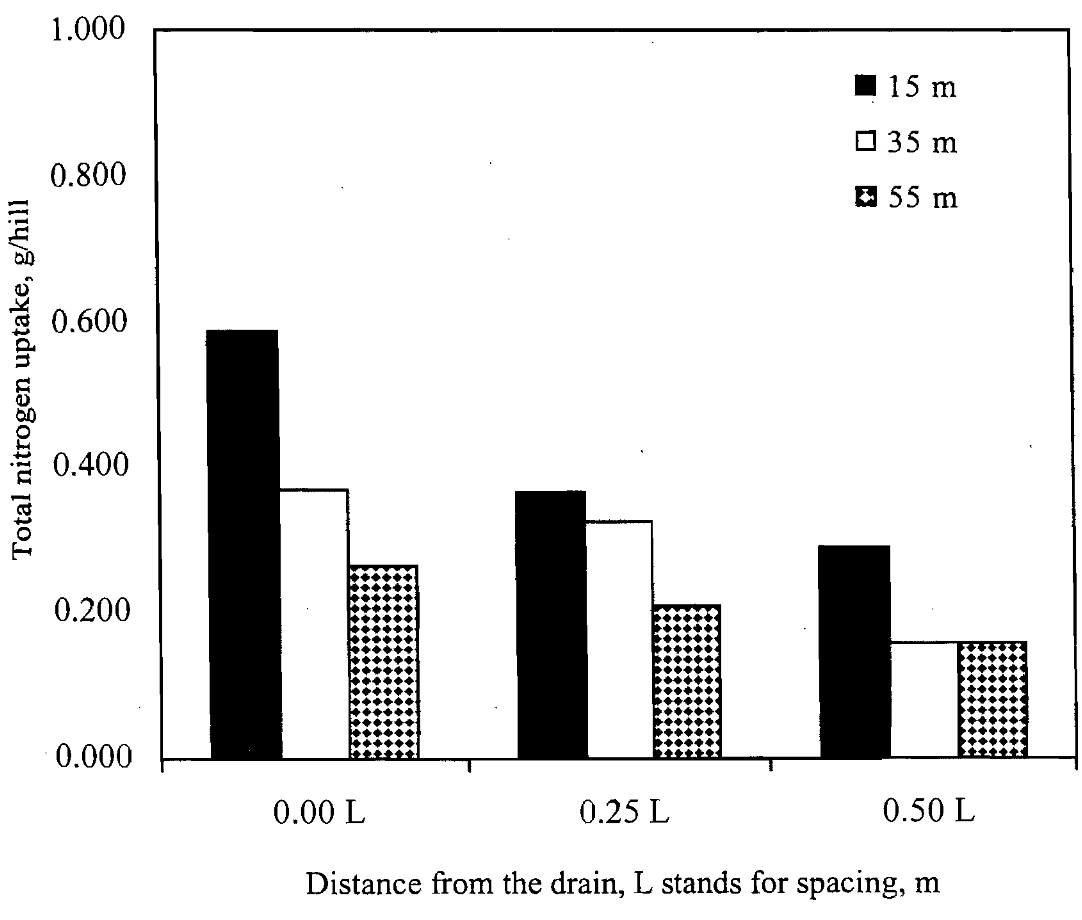

Fig. 5.11 Effect of reclamation with various drain spacings on nitrogen uptake

May, 1999 i.e. the month after the harvest of the crop. The results are given in Fig. 5.5 to 5.6. NH_4-N and NO_2-N were not found in any of the ground water samples collected from 1.5 m deep bore hole. Only the most stable form of nitrogen i.e. NO_3-N were found in all the ground water samples analysed (Fig. 5.5). The highest accumulation of NO_3-N in ground water of 15 m drain spacing area was found to be 1.44 mg l^{-1} in May 1999. This land was under *rabi* rice followed by *kharif* rice with 120 kg - N application per hectare per season for the last one decade. The cumulative accumulation of NO_3-N after long term usage of land and fertilizer is not very high. The reasons for very low concentration of NO_3-N in ground water essentially were two. The first is high water table situation and the second is effective interception of major NO_3-N load by the subsurface drainage system. This finding suggests that besides land reclamation, the subsurface drainage system does prevent ground water from nitrate pollution by intercepting it at a depth of 1 m below from ground surface and discharging it into an outlet or large surface water bodies without any negative environmental consequences. The lowest concentration of NO_3-N was found to be 0.32 mg l^{-1} in case of 35 m drain spacing area. This is in accordance to the reasons explained in section 5.1.4. In fact, in this specific case of 35 m spacing nitrification was hampered to a great extent and not much NO_3 was released rather the excess of NH_4-N was lost through subsurface drainage discharge. And moreover, this observation is just after one year of usage of fertilizer and the land which is salt affected and being reclaimed by subsurface drainage technology. In this case insignificant amount of leaching of NO_3-N was observed thorugh out the crop season.

Contrary to the case of 35 m drain spacing, the NO_3-N was found to be 0.76 mg l^{-1} in the ground water of the area with 55 m drain spacing. Thus, the nitrate load in ground water of 55 m spacing is approximately two and half times of what was observed in the case of 35 m spacing area. It may be noted that the agronomic practices and the environmental factors remained the same in both the treatments of drain spacing. This observation suggests that wider drain spacing in highly saline clay soils under wet land rice cultivation enhances high-risk of nitrate leaching and contamination of ground water as compared to the narrower drain spacing. The measured average drainage rate over the season in 35 m drains spacing was twice of the drainage rate of 55 m drain spacing (Table 5.5). This observation was also in agreement with the theory by Kirkham (1957) for drain spacing equation for ponded water condition. According to this theory, the drain spacing and drainage rate are inversely proportional. This held true in our experiment too. The faster rate of drainage implies faster rate of removal of nitrogen load outside the system and thus resulting in low net addition of NO_3-N in the ground water and the slower rate of drainage means slow pace of nitrogen removal from the soil and thus more time is available for nitrate to percolate down to the ground water and more addition of net nitrate in ground water.

5.2 Simulation modelling

5.2.1 Calibration and runs of SALTMOD

In order to obtain the initial values for model parameters the calibration of the SALTMOD was conducted on computer through simulation runs using the input given in Table 3.1. It was done against three factors : the soil salinity in the root zone, the salt concentrtion of the subsurface drainage water and the depth of the water table. The match between the model output and the observed data by varying the surface drainage and leaching efficiency of the rootzone of the bunded rice field until the best possible agreement was found. However, the effects of different leaching efficiencies and surface drainage values are not presented here. Neither of these two factors could be measured in the field whereas other input data needed by SALTMOD were fixed for the calibration process because majority of them were measured (Table 3.1).

From the calibration process, the leaching efficiency was found to be 0.60 and surface drainage of 0.350 and 0.250 m for the season 1 (*rabi*) and season 2 (*kharif*), respectively and given in Table 3.1. Simulation modelling was done considering two approaches and two drain spacings (35 and 55 m) assuming similar soil and water regimes at the beginning of the simulation. The first approach (simulation-I) was adopted to predict the soil salinity in the root zone, the salt concentration of the subsurface drainage water and the depth of water table on a long term basis with a seasonal time step with the same initial values for the entire simulation period. In the second approach (simulation II) the computations were performed year by year, giving each year a separate input. Bhattacharya (1999) reported that the value of saturated hydraulic conductivity increased from 0.14 m d^{-1} to 1.5 m d^{-1} in subsurface drained coastal clay soils in 8 years from the same site with 10, 15, 25 and 35 m drain spacing till 1995. The rate of annual increment of saturated hydraulic conductivity was derived from the above reference and revised values of saturated hydraulic conductivity were used every year in the simulation run. The results found in simulation I and simulation II were different from each other. Separate sections for each identified factors are devoted to discuss the results in detail and these are presented hereafter.

5.2.2 Soil salinity in the root zone

The results of simulation of the root zone salinity by SALTMOD, using the parameters listed in Table 3.1 together with the observed data for first year (i.e. 1999) and the next year (i.e. 2000) for the season 1 are given in Table 5.8. The results indicated that the model performed well and the deviation between the model output and the observed rootzone salinity varied from 5.3 to 8.9% in 35 m drain spacing and from 2.6 to 15.3% in 55 m drain spacing. The model overestimated the root zone salinity in both 35 m and 55 m drain spacing except in 55 m drain spacing where the model over-estimated the root zone salinity just after one year of operation of the subsurface drainage system. A better agreement between the observed and the simulated II was noticed in both the spacings (Table 5.8). The simulation further suggested that the root zone salinity were significantly higher in the 55 m spacing as compared to the 35 m spacing. In both the cases the simulated values of root zone salinity was found to be stabilized after six years and hence, the simulated root zone salinities are reported upto 6 years in Table 5.8. Simulation II indicates that the root zone salinity got reduced to approximately 8 dS m^{-1} at field saturation in 4 and 6 years period from 35 to 55 m drain spacing, respectively. Thus, the projections made by the model suggest that the land with 35 m and 55 m drain spacing, for existing soil, water and climatic parameters, may be reclaimed for rice-rice cultivation within 4 to 6 years. The inference drawn from the simulation is in good agreement with what was inferred in section 5.1.2.

Table 5.8 Simulated effect of different drain spacings on the root zone salinity

Year	Season 1 (January-May)			Season 2 (June-December)		
	Obser ved	Simula-ted I	Simula-ted II	Obser-ved	Simula-ted I	Simula-ted II
	Root zone salinity (dS m^{-1}) in 35 m drain spacing					
1	21.40	23.30	23.30	—	21.80	21.80
2	15.00	16.20	15.80	—	14.90	14.00
3	—	12.70	11.60	—	11.70	9.78
4	—	11.20	9.55	—	10.30	7.76
5	—	10.60	8.92	—	9.78	7.09
6	—	10.40	8.68	—	9.63	6.73
	Root zone salinity (dS m^{-1}) in 55 m drain spacing					
1	28.15	27.40	27.40	—	29.60	29.60
2	20.90	24.10	22.60	—	25.80	21.30
3	—	21.90	17.00	—	23.30	15.00
4	—	20.20	13.30	—	21.40	11.40
5	—	19.10	11.30	—	20.10	9.58
6	—	18.30	10.60	—	19.20	8.71

— Simulated effects are shown only upto 6 years because the rootzone salinity stabilized after 6 years.

— Simulated I represents the results obtained with the initial input parameters based on field measurements and the calibrated parameters.

— Simulated II represents the results obtained by performing computations year by year, giving each year a separate input based on changed values of saturated hydraulic conductivity suggested by Bhattacharya (1999).

5.2.3 Simulation of subsurface drainage water quality

The simulated salinity of subsurface drainage water along with two years observed values are presented in Table 5.9. The Table 5.9 shows that the agreement between the observed and the simulated values is not perfect. The deviation ranged from 21 to 27% in 35 m spacing and 1.5 to 25% in 55 m spacing. The best agreement was found in season 1 of the first year of operation of drainage system for 55 m spacing area with only 1.5% deviation. In general, simulation II offered better agreement for both the spacings. An interesting conclusion may be drawn from the Table 5.8 and 5.9 that the salt concentration of the drainage water is relatively independent of the salt concentration of the root zone soil salinity. The main reason for this is that the water percolating from the root zone does not go directly to the drains, but passes through the transition zone which has a considerable large buffering effect. The probable other reasons could be contribution of highly saline ground water to the subsurface drainage water which otherwise is assumed to be zero in input parameters (Table 3.1) which may not be true in real situation. The latter reason is further confirmed by Table 5.9 that in all cases the observed values were significantly higher than the simulated ones. Also, the leaching efficiency might have got improved over the years which was not considered in the model.

5.2.4 Depth of water table

The water table depths were observed to be 0.65 and 0.55 m below soil surface in the end of May, 1999 (end of season 1 after one year) of operation of SSD systems, in 35 and 55 m drain spacing areas, respectively (Table 5.10). Simulated values of water table did not match with the

Table 5.9 **Simulated effect of different drain spacings on the quality of drainage effluent**

Year	Season 1 (January-May)			Season 2 (June-December)		
	Observed	Simulated I	Simulated II	Observed	Simulated I	Simulated II
Average salinity of subsurface drainage water (dS m^{-1}) in 35 m drain spacing						
1	39.6	30.90	30.90	—	29.10	29.10
2	38.12	27.70	30.00	—	26.40	27.80
3	—	24.50	29.40	—	22.70	26.70
4	—	20.70	29.30	—	18.80	26.30
5	—	17.10	29.10	—	15.50	26.00
6	—	14.00	29.00	—	12.70	25.70
Average salinity of subsurface drainage water (dS m^{-1}) in 55 m drain spacing						
1	33.72	33.20	33.20	—	33.70	33.70
2	35.67	26.60	30.80	—	27.60	28.80
3	—	21.70	29.80	—	22.70	27.40
4	—	17.90	29.50	—	18.60	26.80
5	—	15.00	29.40	—	15.30	26.40
6	—	12.70	29.10	—	12.70	26.00

observed ones. Generally, the land with rice crop in both *rabi* and *kharif* seasons remains saturated either with irrigation water or with rain water to sustain the rice crop. Thus the water table fluctuates from 5 to 6 cm above the soil surface (when surface ponding is maintained) to 20 to 30 cm below soil surface, when lateral drains discharge free flow in the inspection chamber (Fig. 4.5 and 4.7) during the active crop growth season. A meticulous field observation suggests that although, the rice fields are saturated and a few centimeters of water stands on the soil surface but the piezometers indicate a lower hydraulic head. This indicates that there may not be a continuity between the ponded water above soil surface and the ground water. Moreover, it was observed that there are always about 30 and 45 days period, left after season 2 and season 1, respectively during which the water table goes below the root zone. Another reason for disagreement of water table could be that SALTMOD computation method does not account for ponded water case. Rather, it always assumes the location of water table below the soil surace and solves with Hooghondt's steady state formula which is not the case in reality in wetland rice cultivation. Over and above, accurate prediction of water table is not relevant for rice cultivation, moreover, the objective of SSD system in this experimental area was not for water table control but for salinity control. Also, the topographic observation suggests that the area with 55 m drain spacing is 5-10 cm lower as compared to the area with 35 m drain spacing. In case of 55 m drain spacing the seasonal average simulated water table was found to be at the soil surface in season 1 (Table 5.10). This may not be true in the presence of a subsurface drainage system.

Table 5.10 Observed and simulated water table depth over the years

Year	Season 1 (January-May)			Season 2 (June-December)		
	Observed	Simulated I	Simulated II	Observed	Simulated I	Simulated II
	Water table depth (from soil surface in metre) of 35 m drain spacing area					
1	0.65	0.38	0.38	—	0.66	0.66
2	—	0.46	0.53	—	0.68	0.72
3	—	0.46	0.66	—	0.68	0.77
4	—	0.46	0.72	—	0.68	0.81
5	—	0.46	0.77	—	0.68	0.83
6	—	0.46	0.81	—	0.68	0.86
	Water table depth (from soil surface in metre) of 55 m drain spacing area					
1	0.55	0.00	0.00	—	0.55	0.55
2	—	0.00	0.38	—	0.55	0.66
3	—	0.00	0.59	—	0.55	0.75
4	—	0.00	0.68	—	0.55	0.79
5	—	0.00	0.71	—	0.55	0.80
6	—	0.00	0.71	—	0.55	0.83

Note : Observed water table is at the end of the season and the simulated water tables are the seasonal averages.

5.2.5 Validation of ENVIRO-GRO in the study area

ENVIRO-GRO model simulated the interaction of water, salinity, subsurface drainage and nitrogen on rice yield and nitrogen leaching. Designated parameters for prediction of various scenarios were taken from Table 3.2. The model did not use a calibration or parameter fitting approach because all of the input data were obtained through field measurement or derived from the standard sources of literature. The results of simulation by ENVIRO-GRO, using the parameters listed in Table 3.2 in terms of root zone salinity, nitrogen uptake and nitrogen leaching together with the observed yield of *rabi* rice for 1999 and 2000 are given in Table 5.11.

5.2.6 Soil salinity

The simulation began with the initial root zone soil salinity of 35 dS m^{-1} in both 35 and 55 m drain spacing areas. The simulation suggested that the salinity in 0-15 and 15-30 cm layer would be reduced to 6.07 and 7.06 dS m^{-1}, respectively in 35 m drain spacing and 11.58 and 12.19 dS m^{-1}, respectively in 55 m draining spacing areas in the end of the simulation period i.e. crop season of 80-85 days (Table 5.11). These model simulated soil salinities are too low as compared to the observed ones and the values simulated by SALTMOD (Table 5.8). This suggests that ENVIRO-GRO over-estimated desalinization. No agreement was found between the observed and the simulated soil salinity. Four important reasons for poor prediction of soil salinity by ENVIRO-GRO are : (i) the model considers the piston flow in soil medium, (ii) the model does not account for location of water-table in soil profile and leaching efficiency of the soil root zone, (iii) the model does not account for the ground water salinity and (iv) the model assumes that a constant drainage rate holds throughout

Table 5.11. Observed and simulated output of ENVIRO-GRO

Output parameter	1999				2000			
	35 m		55 m		35 m		55 m	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Soil salinity* (dS m^{-1})								
(0-15 cm)		6.07		11.58		5.88		9.70
(15-30 cm)	—	7.06	—	12.19	—	6.69	—	11.15
Water stress factor	N.A.	0.660	N.A.	0.519	N.A.	0.654	N.A.	0.592
Nitrogen stress factor	N.A.	0.574	N.A.	0.494	N.A.	0.578	N.A.	0.554
Nitrogen uptake kg N ha^{-1}	—	51.0	—	42.0	—	51.0	—	48.0
N-leaching losses, kg ha^{-1}	—	84.0	—	72.0	—	85.0	—	76.0
Grain yield, t ha^{-1}	1.945	2.462	1.875	1.667	2.100	2.457	2.084	2.132

* Soil salinity in the end of the season; N.A. Not applicable; '—' not observed.

the season. In real life situation these may not have been true. Thus, it may be inferred that ENVIRO-GRO has limitations for the prediction of root zone soil salinity.

5.2.7 Simulated nitrogen loss through ENVIRO-GRO

The model simulates nitrogen leaching at the bottom of the root zone i.e. 30 to 35 cm below the soil surface. In the experiment the nitrogen losses were measured at the outlet of drain laterals which are 1.0 m below soil surface (Fig. 4.6). There were no measured data on leaching below the root zone and hence the simulated results of nitrogen leaching given in Table 5.11 may not be strictly comparable to the observed values. Therefore, evaluation of model against seasonal nitrogen leaching was not done. Also, the location of water table during the crop growth season remained well within the root zone and most of the times almost at the soil surface due to frequent surface ponding. This situation did not permit estimation of the net nitrogen leaching at the bottom of the root zone. Pang and Letey (1998) observed that the model estimated the maximum potential of nitrogen leaching. In Table 5.11, the N-leaching losses were obtained by multiplying drainage volume with the N concentration at the layer i.e. 35 cm below soil surface. The magnitude of nitrogen leaching at this layer may not be the same as what was observed below 1.0 m from ground surface, at the drain outlet. The simulated N leaching was found to be 84 and 85 kg ha^{-1}, respectively in 1999 and 2000 in case of 35 m spacing and 72 and 76 kg ha^{-1}, respectively in case of 55 m drain spacing area. These projections are approximately 70 and 60 % of the applied nitrogen for the 35 and 55 m drain spacing areas, respectively. These simulated figure of nitrogen losses are similar to the measured data from wetland rice fields by Savant and De Datta (1982). But these losses are very high as compared to the measured data presented in Table 5.7. Along the vertical path beyond the root zone to the depth of drains i.e. about 65-70 cm, there might have been ammonia volatilization, immobilization, adsorption and denitrification in surface ponded and highly reduced conditions of wetland rice fields. All these nitrogen balance components were not accounted in the model except the plant uptake. Also the model assumes that all nitrogen leaching is of the form of nitrate which is not the case in highly saline sodic soil. The main shortcomings of the model is the assumption of no denitrification and ignoring the other process as enumerated above in the soil-water-chemical and subsurface drainage system. This is why the model over predicted the nitrogen leaching under conditions conducive to ammonia volatilization and denitrification.

5.2.8 Nitrogen uptake and grain yield

The model simulates nitrogen uptake directly based upon the rate of N uptake as a function of time, for the crop under consideration and predicts the grain yield indirectly. The model computes both water stress and nitrogen stress for a given soil-water-plant environment. The results are presented in Table 5.11. The relative yield was assumed to be equal to the product of both the stresses. At the experimental site, the maximum yield of rice in subsurface drained field was observed to be 6.5 t ha^{-1} and in undrained field 1.5 t ha^{-1} (not shown in the tables). These yields were considered to be the extremes for this study. The resulting relative yield was used in prediction of the crop yield. The potential yield of rice crop was assumed to be 6.5 t ha^{-1}. Thus, the simulated and observed grain yields are presented in Table 5.11. The grain yield from the experimental field suggests that an increase of 30 and 25 per cent was observed in first year of the operation of the subsurface drainage system in 35 and 55 m drain spacing areas. The performance of the model in predicting the yield was good. The deviation between the observed and the simultaed yield was maximum of 26 % in the first year (1999) in case of 35 m drain spacing area and 17% in 55 m drain spacing area. In the next year the deviations decreased to 11.0 and 2.3 % in 35 and 55 m drain spacing areas, respectively. In fact, in both the years the model over predicted the crop yield due to over estimation of nitrogen uptake in 35 m drain spacing area. The area with 35 m drain spacing is upland as compared to the area with 55 m drain spacing. This leads to recession of ponded water towards the area with 55 m drain spacing and thus reclamation process was observed to be more uniform due to uniform submergence and leaching in 55 m drain spacing area as compared to the 35 m drain spacing area. This caused more patchy growth pattern of crop in 35 m spacing area as compared to the latter. Moreover leaching loss of nitrogen in the former was high as compared to the 55 m drain spacing area. This might have resulted in a lesser availability of nitrogen in 35 m drain spacing area. However, the model could not replicate the real situation and assumed similar nitrogen availability in the soil-water system and over predicted the grain yield. In the subsequent year, variability of soil salinity with respect to spacing was reduced and a more uniform growth of crop was observed over the entire area. Under this situation the prediction by ENVIRO-GRO was very good. The overall mean deviation between the observed and simulated crop yield was 14% which is within acceptable limit. Further, the simulated ranges of crop nitrogen uptake and the corresponding grain yield presented in Table 5.11 are in agreement with the argument given by Yoshida (1981). He suggested that grain yield is determined by soil fertility level, amount of nitrogen applied and per cent of nitrogen recovery and reported that the nitrogen uptake by rice crop in the order of 160 kg N ha^{-1} may produce 6 t ha^{-1} rice grain and an average rice uptake of 50 kg N ha^{-1} must produce the rice grain in the range of 2.75 to 3.25 t ha^{-1}. The agreement between the simulated and measured grain yield was good, particularly for wider drain spacing and in the second year of the land reclamation process. It is further believed that the greatest utility of the model is to account for, and compute the effects of interactions and feed back mechanisms between the plant and the soil-water-chemical and subsurface drainage system. Salinity leads to reduced plant growth, which leads to reduced evapo-transpiration and hence, more leaching loss of salts and other chemicals such as nitrogen and pesticides from the root zone, under a subsurface drainage system. Under this situation, reduced availability of nitrogen in the root zone is apparent. The ENVIRO-GRO model permits the studies of interaction of numerous variables on a temporal basis, which would be virtually impossible in the case of a field experiment.

The present study conducted through field experiments and by adopting a modelling approach gave a better insight into the interaction of soil-water-plant(rice)-nitrogen in coastal saline, sodic, waterlogged and heavy clay soils. The study revealed the positive impact of subsurface drainage in such a soil-water-environment and also gives clues to proper nitrogen management in the rice fields.

CHAPTER-VI

SUMMARY AND CONCLUSIONS

Salinization of heavy textured coastal soils is primarily caused by long term evaporation from shallow and brackish water table and tidal backwater flow. To combat the twin problems of salinization and waterlogging, drainage is needed.

The present study was carried out in the farmers' fields located at the Endakuduru village near Machilipatnam in Krishna district of Andhra Pradesh. The soils of experimental area are clayey, saline and waterlogged. Rice is the major crop grown by the farmers. The rice yields under the existing condition are poor and at times, the plant mortality is very high under extreme saline condition.

Subsurface tile drainage system with drain spacings of 15 m in 0.4 ha and 25 m in 3.2 ha were installed at the farmers' field in 1986 and 1987, respectively. The system's performance in terms of the changing physical and chemical properties of the soil and rice yield was continuously monitored for a decade. Field data suggested the possibility of adopting wider spacings and thus, drainage system with 35 and 55 m spacings was laid in 1997 in a 4 ha area. Thus, the experimental site was equipped with four drain spacings namely, 15, 25, 35 and 55 m. The experiments were conducted with rice crop on 15, 35 and 55 m spacing plots whereas the 25 m spacing plot was left fallow for the studies on salinization.

As a subsurface drainage system continuously removes dissolved chemicals from the salt affected and waterlogged soil profile, it is apprehended that some amount of nutrients applied to the cropped land may also be lost through subsurface drainage effluent. Keeping the future needs in mind, a scientific study pertaining to the rate of salinization in the absence of subsurface drainage system and quantification of nitrogen losses under the influence of subsurface drainage system was conducted. The goal of this study was to investigate the impact of subsurface drainage on salinization and nitrogen loss scenario and rice yield in the saline coastal clay soil.

The findings of the present study are based on modelling as well as experimental approaches to assess salinization in the absence of adequate drainage, desalinization in the presence of subsurface drainage, water quality monitoring of drainage effluents, root zone salinity distribution over time and nitrogen losses via subsurface drainage effluents.

Several models, which simulate the transport of solutes in soil-water-plant system have been reviewed. Considering the merits and limitations of various models and the data collected at the experimental site, the two models namely SALTMOD (Oosterbaan, 1998) and ENVIRO-GRO (Pang and Letey, 1998) were used in the present study. SALTMOD used the measured data from the field experiment and simulated soil salinity in the root zone, subsurface drainage water quality and depth of water table. ENVIRO-GRO also used the field data and simulated the interaction of soil-water-salinity-plant and nitrogen system.

Based on the results of the study undertaken, the following conclusions are drawn :

1. Coastal clay soils are prone to quick secondary salinization in the absence of leaching by subsurface drainage system. In a span of 3 years, the soil salinity in 0-15 and 15-30 cm layers had increased approximately 8 and 5 folds, respectively in the absence of leaching by subsurface drainage. The salinity in 15-30 cm layer in which the maximum root activity of rice crop takes place, increased to over 8 dS m^{-1} in one year and exceeded the critical value of salinity for rice cultivation when the subsurface drainage system was made inoperative (Fig. 5.1, Table 5.1). It was further found that 25.2 Mg ha^{-1} salt will be left behind in the root zone with an average moisture depletion of 2 mm d^{-1} in 2 to 3 months of non-drainage period. In the process of salinization an annual increase of 38% in ESP of root zone layer was estimated (Section 5.1.1).

2. Based on two years of observation, it was found that the subsurface drainage system removed approximately 82.5 and 34.5 Mg ha^{-1} yr^{-1} of total dissolved salts from a soil layer of 1 m depth, respectively, from 35 and 55 m drain spacing areas. The rate of salt removal was approximately two and half times higher in case of 35 m spacing than that of 55 m spacing. Further computations and analyses of the field data suggest that with the aforementioned rates of salt removal, the coastal clay soil with the given initial conditions will be reclaimed in 3-4 and 6-7 years with 35 and 55 m drain spacings, respectively, provided no salts are added to the soil profile of top 1 m depth from external sources (Fig. 5.3 and 5.4, Table 5.5).

3. Application of SALTMOD revealed that the land with 35 and 55 m drain spacing for the existing agro-climatic condition may be reclaimed for rice-rice cultivation within 4 to 6 years. The inference drawn from the simulation is in good agreement of what was inferred in section 5.1.2, which was based on field monitoring.

4. An interesting conclusion may be drawn from Table 5.8 and Table 5.9 that the salt concentration of the drainage water is relatively independent of the root zone soil salinity. This conclusion may be justified from the fact that the root zone considered in the study extended from surface down to 30 to 35 cm. The remaining of 65 to 70 cm, before reaching the drain depth acted as temporary storage for salts. This zone being highly saline, the contribution of salts from the upper zone perhaps does not bear much relevance in further increasing its salinity. The influence of this transitiion zone is more in contributing to the effluent salinity.

5. Subsurface drainage in highly saline sodic soils will cause loss of ammonium form of nitrogen due to its weak adsorption on the clay complex. This conclusion is corroborated by the results reported in Fig. 5.7 through Fig. 5.10. The loss of nitrogen in ammonium form varied from 4.2 to 22.6 kg ha^{-1} yr^{-1} and correspondingly to 90 to 96 per cent of total nitrogen loss through subsurface drainage. These results pertain to 35 and 55 m drain spacing areas which had a high ESP of greater than 35. As a consequence of high ammonium loss, the nitrate loss was very low in the drainage effluent. The nitrate-nitrogen loss dominated in 15 m spacing

whereas ammonium-nitrogen loss dominated in 35 and 55 m drain spacing areas.

6. To help a better utilization of applied nitrogen, it will be appropriate to split the basal dose of 60 kg N ha^{-1} into 3 doses of 20 kg N ha^{-1} each separated by an interval of 10 days. This is based on the observation that the peak concentration of NH_4-N in drainage effluent was found after 1 to 2 days after the basal dose of 60 kg N ha^{-1} was applied and similar peak was observed after 10 to 12 days when the dose of 30 kg N ha^{-1} was applied.

7. Subsurface drainage helps in controlling nitrite-nitrogen concentration in the root zone. A six times higher nitrite-nitrogen concentration (0.31 to 0.75 mg l^{-1}) was observed in root zone soil layer of 25 m drain spacing area where the subsurface drainage system was operated only at some fixed times for sampling purpose. The increasing trend of the concentration of nitrite-nitrogen in soil layers might give rise to nitrite-nitrogen toxicity should it exceed the threshold limit of 0.9 mg l^{-1} over the years in the absence of subsurface drainage system.

8. The risk of nitrate contamination in ground water can be reduced by adopting the subsurface drainage technology. Results discussed in Section 5.1.6 reveal that wider drain spacing in salt affected coastal clay soils enhances high risk of nitrate leaching and contamination of ground water as compared to the narrower drain spacing. The narrower drain spacing helps in faster removal of excess nitrate from soil water system and thus resulting in low net addition of nitrate in ground water.

9. Subsurface drainage has a profound influence in nitrogen uptake by the field crops and hence the crop production. This conclusion is based on the following observations. The total nitrogen uptake by rice hill was observed highest for those hills which grew at above the drains. This was the direct consequence of the reclamation by subsurface drainage. Also, the mean total nitrogen uptake by rice hills planted in unreclaimed area was just half of what was observed in the area reclaimed by subsurface drainage. As a result of poor nitrogen uptake in unreclaimed area the grain yield was only 30% of the maximum yield observed in reclaimed area.

10. ENVIRO-GRO model has the ability to predict crop yield from two stress factors namely, water stress factor and nitrogen stress factor without any calibration process. These stress factors are the output from the model. The model performed well in predicting the grain yield. The deviation between the observed and the simulated yield varied from 2.3 to 11%. The model, however overestimated the pace of desalinization. The model predicted the potential of nitrogen leaching to be approximately 60 to 70% of the applied nitrogen.

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SAMPLE INPUT AND OUTPUT FILES FOR SALTMOD

Input file : SSDE 3500

Endakuduru_SSDE New Area with 35 m drain spacing and surface runoff
Additional Explanatory text :

Basic data of the experimental site of the new area under reclamation

1.	Area	Ns	Kd	Kf	Kr	
	4.0	2	1	0	3	
2.	Ny	Ky				
	10	0				
3.	Ts1	Ts2				
	5.0	7.0				
4.	A1	B1	A2	B2		
	0.000	1.000	0.000	1.000		
5.	Lc1	Io1	Lc2	Io2		
	0.000	0.000	0.000	0.000		
6.	IaA1	EpA1	IaA2	EpB2		
	0.000	0.000	0.000	0.000		
7.	IaB1	EpB1	IaB2	EpB2		
	1.250	0.766	0.000	0.888		
8.	Pp1	EpU1	Pp2	EpU2		
	0.040	0.000	1.007	0.000		
9.	FsA	FsB	FsU			
	0.650	0.650	0.650			
10.	Gil	Co1	Gi2	Go2		
	0.000	0.000	0.000	0.000		
11.	SiU1	SoU1	SiU2	SoU2		
	0.000	0.000	0.000	0.000		
12.	SoA1	SoB1	SoA2	SoB2		
	0.000	0.350	0.000	0.250		
13.	Gw1	Fw1	Gw2	Fw2		
	0.000	0.000	0.000	0.000		
14.	Dr	Ptr	Dx	Ptx	Dq	Ptq
	0.300	0.600	1.600	0.450	5.000	0.350
15.	Per	Flr	Pex	Flx	Peq	Flq
	0.050	0.600	0.080	0.800	0.250	1.000
16.	Cx0	Cq0	Cic	Ch	Cp	
	40.000	40.000	1.500	50.000	0.000	
17.	CA0	CB0	CU0	Dw0	Dc	
	0.000	35.000	0.000	0.000	1.500	
18.	Dd	QH1	QH2	Gu1	Gu2	
	1.000	0.003	0.000	0.000	0.000	
19.	Cxa0	Cxb0	Frd1	Frd2		
	40.000	40.000	0.200	0.800		

Definition of the symbols of Input data

Row 1	:	**Contains Area, Ns, Kd, Kf and Kr**
Area	:	Total area considered for simulation, ha
Ns	:	Number of seasons per year, Ns=1,2,3 or 4
Kd	:	Key for the presence of a subsurface drainage system : for yes - Kd=1, for no - Kd=0
Kf	:	Key for farmers' responses to waterlogging, salinization or irrigation scarcity : Yes - Kf = 1; For no - Kf = 0
Kr	:	Key for rotational type of land use. Kr = 1, 2, 3 and 4
Row 2	:	**Contains Ny and Ky**
Ny	:	Number of years for simultion run
Ky	:	Key for yearly changes of input data, for yes Ky=1, for no - Ky=0
Row 3	:	**Contains Ts_1 and Ts_2**
Ts_1 & Ts_2	:	Duration of the season 1 and season 2, respectively, months
Row 4	:	**Contains A_1, B_1 and A_2, B_2**
A_1 & A_2	:	Fraction of the total area under irrigated crop of group A in season 1 and season 2, respectively. Group A crop refers to the crops other than rice and sugarcane.
B_1 and B_2	:	Fraction of the total area under irrigated crop of group B in season 1 and season 2, respectively. Group B crop refers to rice and/or sugarcane.
Row 5	:	**Lc_1, Io_1 and Lc_2, Io_2**
Lc_1 & Lc_2	:	Percolation from the canal system in season 1 and season 2, respectively, m
Io_1 & Io_2	:	Water leaving the area through the irrigation canal system in season 1 and season 2, respectively, m.
Row 6	:	**Contains IaA_1, IpA_1, IaA_2 and EpA_2**
IaA_1 & IaA_1	:	irrigation water applied to the irrigated fields under group A crop in season 1 and season 2 respectively, m
EpA_1 & EpA_2	:	Potential evapotranspiration of group A crop in season 1 and season 2, respectively, m
Row 7	:	**Contains IaB_1, EpB_1 and IaB_2, EpB_2**
IaB_1 & IaB_2	:	Irrigation water applied to the irrigated fields under group B crops in season 1 and season 2, respectively, m
EpB_1 & EpB_2	:	Potential evapotranspitation of group B crops in season 1 and season 2, respectively, m
Row 8	:	**Contains Pp_1, EpU_1, Pp_2 and EpU_2**
Pp_1& Pp_2	:	percipitation in season 1 and season 2 respectively, m.
EpU_1 & EpU_2	:	Potential evapotranspiration of unirrigated area in season 1 and season 2, respectively, m
Row 9	:	**Contains FsA, FsB and FsU**
FsA	:	Fraction of irrigation and rain water stored in root zone of A crops - $0 < FsA < 1$.
FsB	:	Fraction of irrigation water stored in root zone of B crops $0 < FsB < 1$

FsU	Fraction of rain water stored in the root zone of unirrigated lands $0 < FsU < 1$
Row 10	**Contains Gi_1, o_1, Gi_2 and Go_2**
Gi_1 & Gi_2	Horizontally incoming groundwater through the aquifer in season 1 and season 2, respectively, m
Go_1 & Go_2	Horizontally outgoing groundwater through the aquifer in season 1 and season 2, respectively, m
Row 11	**Contains SiU_1, SoU_1, SiU_2 and SoU_2**
SiU_1 & SiU_2	Surface inflow of water from surrounding areas in the unirrigated area in season 1 and season 2, respectively, m
SoU_2 & SoU_2	Outgoing surface run off water from the unirrigated area in season 1 and season 2, respectively, m
Row 12	**SoA_1, SoB_1, SoA_2 and SoB_2**
SoA_1 & SoA_2	Surface drainage water outgoing from irrigated land with respect to Crop A in season 1 and season 2, respectivley, m.
SoB_1 & SoB_2	Surface drainage water outgoing from irrigated land with respect to Crop B in season 1 and season 2, respectivley, m.
Row 13	**Contains Gw_1, Fw_1, Gw_2 and Fw_2**
Gw_1 and Gw_2	Ground water pumped from wells in the aquifer in season 1 and season 2, respectively, m
Fw_1 and Fw_2	Fraction of pumped from wells in the aquifer in season 1 and season 2, $0 \leq Fw \leq 1$
Row 14	**Dr, Ptr, Dx, Ptx, Dq and Ptq**
Dr	Thickness of root zone, m
Ptr	Total porosity of the root zone (dimensionless)
Dr	Thickness of the transition zone between root zone and aqrifer, m
Ptx	Total porosity of the transition zone (dimensionless)
Dq	Thickness of the aquifer, m
Ptq	Total porosity of the aquifer (dimensionless).
Row 15	**Contains Per, Flr, Pcx, Flx, Peq and Flq**
Per	Drainable porosity of the root zone, dimensionless
Flr	Leaching efficiency of root zone, dimensionless, $Flr > 0$.
Pcx	Drainable porosity of the transition zone, dimensionless
Flx	Leaching efficiency of the transision zone, dimensionless, $Flx > 0$
Peq	Drainable porosity of the aquifer, dimensionless
Flq	Leaching efficiency of the aquifer dimensionless, $Flq > 0$.
Row 16	**Contains CxO, CqO, Cic, Ch and Cp**
Cxo	Initial salt concentration of the groundwater in the upper part of the transition zone, dS m^{-1}
Cqo	Initial salt concentration of the groundwater in the aquifer, dS m^{-1}
Cic	Salt concentration of the income canal water, dS m^{-1}
Ch	Salt concentration of incoming groundwater, dS m^{-1}
Cp	Salt concentration of rain water, dS m^{-1}

Row 17	**:**	**Contains CAo, CBo, CUo, DWo and Dc**
CAo	:	Initial salt concentration of the soil moisture at field saturation in the root zone of irrigated land with crops (s) A, dS m^{-1}
CBo	:	Initial salt concentration of the soil moisture of field saturation in the root zone of irrigated land with crops B, dS m^{-1}
CVo	:	Initial salt concentration of the soil moisture at field saturation in the root zone of the unirrigated land dS m^{-1}
DWo	:	Initial depth of water table, m
Dc	:	Critical depth of water table for capillary rise, m.
Row 18	**:**	**Contains Dd, QH_1 - QH_2, Gu_1 and Gu_2**
Dd	:	Depth of subsurface drain, m
QH_1	:	Ratio of drain discharge and height of the watertable above drain level, m d^{-1} m^{-1}
QH_2	:	Ratio of drain discharge and required height of the water level above the drainage level, m d^{-1} m^{-2}
Gu_1 and Gu_2	:	Subsurface drainage water used for irrigation in season 1 and season 2, respectively, m
Row 19	**:**	**Contains Cxao, Cxbo, Frd_1 and Frd_2**
Cxao	:	Initial salt concentration of the groundwater in upper part of the transition zone, dS m^{-1}
Cxbo	:	Initial salt concentration of the ground water in lower part of the transition zone, dS m^{-1}
Frd_1 and Frd_2	:	Reduction factor of the drainage operaton for water table control, in season 1 and season 2, respectively dimensionless.

SALTMOD

Output from file : SSDE 3500

Soil Salinities root zone (dS/m)

Year	Season	CrA	CrB	CrU	Cr4	C1*	C2*	C3*
0	1	n.a.	35.00	n.a.	n.a.	n.a.	n.a.	0.00
0	2	n.a.	35.00	n.a.	n.a.	n.a.	n.an	0.00
1	1	n.a.	23.30	n.a.	n.a.	n.a.	n.a.	0.00
1	2	n.a.	21.80	n.a.	n.a.	n.a.	n.a.	0.00
1	1	n.a.	16.20	n.a.	n.a.	n.a.	n.a.	0.00
2	2	n.a.	14.90	n.a.	n.a.	n.a.	n.a.	0.00
3	1	n.a.	12.70	n.a.	n.a.	n.a.	n.a.	0.00
3	2	n.a.	11.70	n.a.	n.a.	n.a.	n.a.	0.00
4	1	n.a.	11.20	n.a.	n.a.	n.a.	n.a.	0.00
4	2	n.a.	10.30	n.a.	n.a.	n.a.	n.a.	0.00
5	1	n.a.	10.60	n.a.	n.a.	n.a.	n.a.	0.00
5	2	n.a.	9.78	n.a.	n.a.	n.a.	n.a.	0.00
6	1	n.a.	10.40	n.a.	n.a.	n.a.	n.a.	0.00
6	2	n.a.	9.63	n.a.	n.a.	n.a.	n.a.	0.00
7	1	n.a.	10.40	n.a.	n.a.	n.a.	n.a.	0.00
7	2	n.a.	9.59	n.a.	n.a.	n.a.	n.a.	0.00
8	1	n.a.	10.40	n.a.	n.a.	n.a.	n.a.	0.00
8	2	n.a.	9.57	n.a.	n.a.	n.a.	n.a.	0.00
9	1	n.a.	10.40	n.a.	n.a.	n.a.	n.a.	0.00
9	2	n.a.	9.57	n.a.	n.a.	n.a.	n.a.	0.00
10	1	n.a.	10.40	n.a.	n.a.	n.a.	n.a.	0.00
10	2	n.a.	9.57	n.a.	n.a.	n.a.	n.a.	0.00

n.a. not applicable

Definition of the symbols used above. The units for all of them is dS m^{-1}

CrA : Salt concentration of the soil moisture in the root zone at field saturation for the permanently irrigated land under group A crop(s) at the end of a particular season.

CrB : Salt concentration of the soil moisture in the root zone at field saturation for the permanently irrigated land under group B crop(s) at the end of a particular season.

Cru_1 : Salt concnetration of the soil moisture in the root zone at field saturation for permanently unirrigated land at the end of the particular season.

Cr_4 : Salt concentration of the soil moisture in the root zone, when saturated in the fully rotated land at the end of the season.

C_1 : Salt concentration of soil moisture in the root zone, when saturated, for the land outside the permanently unirrigated area at the end of the season, applicable when rotation key Kr = 1. Kr is already defined in input file.

C_2 : Salt concentration of the land outside of the irrigated land under group A crop(s) when the rotation key Kr = 2

C_3 : Salt concentration of the land outside of the irrigated land under group B crop(s) when the rotation key Kr = 3

Other salinites (dS/m)

Year	Season	Cxf	Cxa	Cxb	Cqf	Ci	Cd	Cw
0	1	n.a.	40.00	40.00	40.00	0.00	0.00	n.a.
0	2	n.a.	40.00	40.00	40.00	0.00	0.00	n.a.
1	1	n.a.	32.50	37.30	40.00	1.50	30.90	n.a.
1	2	n.a.	31.80	35.50	40.00	0.00	29.10	n.a.
2	1	n.a.	24.40	33.70	40.00	1.50	27.70	n.a.
2	2	n.a.	23.60	32.20	40.00	0.00	26.40	n.a.
3	1	n.a.	18.10	29.10	40.00	1.50	24.50	n.a.
3	2	n.a.	17.50	27.60	40.00	0.00	22.70	n.a.
4	1	n.a.	13.80	24.20	40.00	1.50	20.70	n.a.
4	2	n.a.	13.50	22.90	40.00	0.00	18.80	n.a.
5	1	n.a.	11.10	19.90	40.00	1.50	17.10	n.a.
5	2	n.a.	10.90	18.80	40.00	0.00	15.50	n.a.
6	1	n.a.	9.47	16.30	40.00	1.50	14.00	n.a.
6	2	n.a.	9.36	15.50	40.00	0.00	12.70	n.a.
7	1	n.a.	8.57	13.60	40.00	1.50	11.60	n.a.
7	2	n.a.	8.50	13.00	40.00	0.00	10.60	n.a.
8	1	n.a.	8.05	11.70	40.00	1.50	9.86	n.a.
8	2	n.a.	8.02	11.20	40.00	0.00	9.15	n.a.
9	1	n.a.	7.77	10.30	40.00	1.50	8.58	n.a.
9	2	n.a.	7.75	9.87	40.00	0.00	8.07	n.a.
10	1	n.a.	7.61	9.37	40.00	1.50	7.69	n.a.
10	2	n.a.	7.60	8.99	40.00	0.00	7.34	n.a.

n.a. not applicable

Definition of the symbols used above. The units for all of them is dS m^{-1}

Cxf : Salt concentration of the soil moisture in the transition zone, applicable only when no subsurface drainage syste is present.

Cxa : Salt concnetration of the soil moisture in the transition zone above the drain level

Cxb : Salt concentration of the soil moisture in the transition zone below drain level

Cqf : Salt concentration of the soil moisture in the aquifer.

Ci : Salt concentration of the irrigation water

Cd : Salt concentration of the subsurface drainage water

Cw : Salt concentration of the pumped well.

Drain/well flow, water table (m)

Year	Season	Gd	Ga	Gb	Gw	Dw
0	1	0.00	0.000	0.000	0.000	0.00
0	2	0.000	0.000	0.000	0.000	0.00
1	1	0.222	0.000	0.222	0.000	0.38
1	2	0.042	0.000	0.042	0.000	0.66
2	1	0.194	0.000	0.194	0.000	0.46
2	2	0.041	0.000	0.041	0.000	0.68
3	1	0.193	0.000	0.193	0.000	0.46
3	2	0.041	0.000	0.041	0.000	0.68
4	1	0.193	0.000	0.193	0.000	0.46
4	2	0.041	0.000	0.041	0.000	0.68
5	1	0.193	0.000	0.193	0.000	0.46
5	2	0.041	0.000	0.041	0.000	0.68
6	1	0.193	0.000	0.193	0.000	0.46
6	2	0.041	0.000	0.041	0.000	0.68
7	1	0.193	0.000	0.193	0.000	0.46
7	2	0.041	0.000	0.041	0.000	0.68
8	1	0.193	0.000	0.193	0.000	0.46
8	2	0.041	0.000	0.041	0.000	0.68
9	1	0.193	0.000	0.193	0.000	0.46
9	2	0.041	0.000	0.041	0.000	0.68
10	1	0.193	0.000	0.193	0.000	0.46
10	2	0.041	0.000	0.041	0.000	0.68

n.a. not applicable

Definition of the symbols used above.

Gd : Total amout of subsurface drinage water, m

Ga : Amount of subsurface drainage water through ground water flow above drain level, m

Gb : Amount of subsurface drainage water through ground water below drain level, m

Gw : Amount of water through pumped well, m

Dw : Depth of waer table in the end of the season, m.

APPENDIX II

SAMPLE INPUT AND OUTPUT FILES FOR ENVIRO-GRO

The input data are read from a set of three non-formatted ASC II files. The samples of input and output files and explanation of different notations are shown below :

Data file # 1 : Main.dat (Basic information)

s_deP k IER Krd trt_max yrmax switchN(Switch_N = 0=no N eff. 1=with N eff.)

100 20 80 7 1 1 1 1

conds TSAT psin thin ata bata bhb Bulb_d OMN min rate 1yr min rate 2yr

0.5 0.85 -13.2 0.85 -13.2 8.801 20.602 1.29 100 0.00020 0.0000065 0.00000300

rdfday RDFDEL ESTART ESTOP cropend gg5 hhr h_trhres salt_thres

1 24 1 55 82 -8592 -1100 -360 -1836

t_simul redis_t wini_h wini_BC salt_in (ds/m)

1990 24 -100 -100 35.0

HDRY HWET WATL HLOW

-.1E5 0 0.44 -0.7E4

OL 1/8L 2/8L 3/8L 4/8L 5/8L 6/8L 7/8L L(Bot.R.Z)

x0 x1 x2 x3 x4 x5 x6 x7 x8

0 4.0 8.0 12.0 16 20 24 28 32

f0 f1 f2 f3 f4 f5 f6 f7 f8

0 4 5 6 5 4 3 3 0.0

KRAIN KDRAI (KDRAIN : 0= head, 2=free drain)

0 1

DRAIN DELT DELMINDELMAX TOL1 TOL2

0.023 0.01 0.001 1.0000 0.001 0.001

Linewise Explanation of the symbols :

Line 1	:	**File Name and/or identification of problem area and short description**
Line 2	:	**Comment line of control parameters**
Line 3	:	**Control parameters (Values)**
S-dep	:	Soil depth of calculation domain, cm
k	:	number of layers, it is obtained by deviding s-dep by thickness of each layer.
IER	:	Total number of data entries in V array. The v array is found in data file No. 2 i.e. Irriga.dat.

krd	:	The node at which drainage and N leaching are calculated
Trt_MAX	:	Number of treatments to be simulated.
Yr_MAX	:	Number of years to be simulated for each treatment
Switch_N	:	O, for no N effect (assuming N not limiting); 1, when N effect is included
Line 4	**:**	**Comment line of soil hydraulic parameters**
Line 5	**:**	**Soil hydraulic parameters (values)**
CONDS	:	Saturated hydraulic conductivity, cm hr^{-1}
TSAT	:	Saturated volumetric water content, cm^3cm^{-3}
PSIN	:	Matric potential at the inflection point where the two parts of the hydraulic properties function of Hutson and cass join, cm
THIN	:	Water content at the inflection point, cm^3 cm^{-3}
ATA	:	Air entry matric potential for the soil under consideration, cm
BATA	:	Exponent from the equation relating matric potential to water content as developed by campbell.
BHB	:	Exponent from the equation relating hydraulic conductivity to water content as developed by campbell
Bulk_D	:	Bulk density of soil, g cm^{-3}
OMN	:	Organic mineralized nitrogen contribution from soil per season, Kg-N/ha.
minrate 1 yr	:	Rate constant in organic nitrogen mineralization during the first year.
minrate 2yr	:	Rate constant in organic nitrogen mineralization during the second year
minrate 3yr	:	Rate constant in organic nitrogen mineralization during the third year
Line 6	**:**	**Comment line of crop information**
Line 7	**:**	**Crop information (values) :**
rdfday	:	Time when root reached its maximum root depth, day
RDFDEL	:	Number of hours before depth of root changes (usually 24), hour.
ESTART	:	Time when vegetative growth starts at soil surface, day
ESTOP	:	When plant cover is fully developed, day
Cropend	:	Time when crop matured, day
gg5	:	Osmotic head at which transpiration is reduced by 50%, cm
hh5	:	Matric potential at which transpiration is reduced by 50% cm.
h_thres	:	Threshold value of matric potential below which plants feel stressed, cm
salt_thres	:	Threshold value of osmotic potential below which plants feel stressed, cm
Line 8	**:**	**Comment line of run control variables and initial conditions.**
t_simul	:	time period for simulation, hour

redis_t : time period for water redistribution started uniformaly at wini_h, hour

wini_h : initial matric potential head uniformaly through soil profile, cm.

wini_BC : initial matric potential head at bottom boundary, cm

salt_in : initial salt concentration in soil profile, dSm^{-1}

Line 10 : Comment line of water constants

Line 11 : Values of water constant :

HDRY : Matric head corresponding to WATL, cm

HWET : Matric head of saturated water control (usually O), cm

WATL : air dry (lowest) water content, cm^3cm^{-3}

HLOW : Matric potential at wilting point, cm

Line 12 : Comment line of root distribution

Line 13 : Comment line of rooting depths

Line 14 : rooting depth at which root amount is defined

Line 15 : Comment line of "amounts' of roots

Line 16 : root amounts at the depth given on line 14. They can be any number supplied by the user and the model normalizes them to unity.

Line 17 to Line 20 are used for van Genuchten model.

KRAIN : Rainfall code for the soil surface boundary condition:

= 0 if pressure head is specified; = 1 if information is specified

KDRAIN : Drainage code for lower boundary :

= 0 if pressure head is specified

= 1 if drainage rate is specified

= 2 if the pressure head gradient is zero (free drainage)

Drain : Drainge rate, cm/hr

DELT : Time increment, hour

DELMIN : Minimum value of DELT permitted during execution, hour

DEH MAX : Maximum value of DELT permitted during execution, hour

TOL 1 : Relative error criterion, dimension less

TOL 2 : Absolute error criterion, cm

Date file # 2 : Irrig.dat

This file contains information in two parts. The first part of the file keeps the information irrigation and potential evapotranspiration. Values of upper boundary fluxes and cumulative ending time is called v-array. The second part this file contains value of crop water use coefficient, hourly N uptake rate of the crop considered, salt concentration of irrigation water and schedule of nitrogen application with irrigation water. The sample file given below, has 80 entries (IER = 80) in both parts.

1.00	10.00	-0.017	72.0
1.00	78.00	-0.017	120.0
1.00	126.00	-0.017	168.0
1.00	174.00	-0.017	240.0
1.00	246.00	-0.017	336.0
1.00	342.00	-0.017	408.0
1.00	414.00	-0.017	480.0
1.00	486.00	-0.017	552.0
1.00	558.00	-0.017	648.0
1.00	654.00	-0.021	744.0
1.00	750.0	-0.021	816.0
1.00	822.00	-0.021	912.0
1.00	918.00	-0.021	984.0
1.00	990.00	-0.021	1056.0
1.00	1062.00	-0.021	1200.0
1.00	1206.00	-0.021	1320.0
1.00	1326.00	-0.023	1440.0
1.00	1446.00	-0.023	1536.0
1.00	1542.00	-0.023	1632.0
1.00	1638.00	-0.023	1992.0
0.90	0.03	1.10	60.0
0.90	0.03	1.10	0.0
1.00	0.03	1.10	0.0
1.00	0.03	1.20	0.0
1.10	0.04	1.20	0.0
1.10	0.04	1.20	0.0
1.10	0.04	1.20	30.0
1.20	0.05	1.30	0.0
1.20	0.0613	1.30	0.0
1.20	0.0613	1.30	0.0
1.20	0.1125	1.40	0.0
1.20	0.1125	1.40	30.0

1.20	0.1375	1.50	0.0
1.50	0.1375	1.50	0.0
1.50	0.15	1.60	0.0
1.50	0.15	1.60	0.0
1.50	0.15	1.70	0.0
1.20	0.04	1.80	0.0
1.20	0.02	1.90	0.0
1.00	0.01	1.90	0.0

Explanation

The V-array has 40 rows and 4 columns. The first 20 rows and 4 columns represent first part and remaining 20 rows and 4 columns report the second part of the file.

[1,1] : Irrigation or rainfall rate (cm/hr) (+ve)

[1,2] : Cumulative ending time of irrigation application or rainfall, hr

[1,3] : Evapotranspiration rate, cm hr^{-1} (-ve)

[1,4] : Cumulative ending time of ET.

Part - I

Simulation started at t=0, then having an irrigation (or could be rainfall) at the rate of 1.0 cm hr^{-1} for 10 hours, irrigatio or rain stopped at 10.0 hrs at ET started at this moment (t = 10.0 hrs) with a rate of 0.021 cm hr^{-1} (minus sign indicates water is going out of profile), this ET happening with (t = 72.0 hrs. then again irrigation or rain occurs at a rate of 1 cm hr^{-1} until t = 78.0 hrs irrigation period) is (78-72 = 6 hrs), then ET occurs with a rate of 0.021 cm hr^{-1} until 120 hrs. This pattern continues to until the total simulation period is reached.

Part - II

[21,1] : crop water use coefficient (diversion less)

[21,2] : hourly N uptake rate by rice crop, kg/hr/ha.

[21,3] : Salt concentration of water, dSm^{-1}

[21,4] : nitrogen amount applied with irrigation water, kg-N/ha

This part also must have 80 entries. In the last column, there are all zeros except three entries. The first one refers to 60 kg-N applied as a basal dose at the time of transplanting, the next two doses of 30 kg-N each according to the schedule.

Data file # 3 : Mgt_N.dat

This file has one row matrix. It contains management information. These parameters are DRLQA, SENOA, SENO_APPLICA.

DRLQA : factor to control how many folds of ET is applied as irrigation water (e.g. 0.6ET, 1.0ET or 1.4ET etc.)

SENDA : Initial amount of N in soil profile (assumed that it was uniformally distributed throughout soil profile); kg-N/ha.

SENO_APPLICA : N application in top soil layer before transplanting, kg-N/ha.

Sample file :

DRLQA	SENDA	SENDA_APPLICA
1.00	100	60

OUTPUT FILES FOR ENVIRO-GRO MODEL

File Name : YIELD.OUT

Simulation started : 20:56:58 7/05/2000

# Year	Irri cm	Tr_a cm	Nup kg N/ha	Dr(krd) cm	Dr(b.b) cm	NL (krd) kgN/ha	RET	RYN
Water redistribution time = 24.000								
1	118	29	51	32	40	84	.660	.574

Rain=6 cm N applied=120 kgN/ha, Root Zone = 35 cm

Simulation ended : 20 : 57 : 12

7/05/2000

year : Number of the year (1=first year, 2 = second year etc. for multi-year simulation only).

Irri : crop season irrigation and rainfall amount (cm)

Tr_a : crop season actual ET amount (cm)

Nup : crop season actual N uptake amount (kg N/ha)

Dr (krd) : drainage amount that passed the simulation depth of krd (cm)

Dr (b.b) ; drainage amount that passed the bottom boundary (cm)

NL: (krd) : N leached the simulation depth of krd (kg N/ha)

RET : relative yield based on water stress

RYN : relative yield based on N stress.

Water redistribution time : water was initially uniformly distributed through soil profile, then allowed to drain freely. Water redistribution time is the length of time (hrs) at which the water content (or matric potential) distribution is used as the beginning condition of the simulation.

Rain : amount of rainfall occurred between the end of crop season and the end of simulation (cm)

N-applied : total N applied (kg N/ha)

Root Zone : total rooting depth (cm)

File Name : HYDR_TAB.OUT

Simulation started : 19:59:49 7/05/2000

w.c. cm^3/cm^3	h (w.c.) cm	k (w.c.) cm/hr
.4400	-4338.7327	.0000
.4452	-3913.2979	.0000
.4504	-3533.8037	.0000
.4556	-3194.8428	.0000
.4608	-2891.6961	.0000
.4659	-2620.2382	.0000
.4711	-2376.8573	.0000
.4763	-2158.3868	.0000
.4815	-1962.0461	.0000
.4867	-1785.3904	.0000
.4919	-1626.2669	.0000
.4971	-1482.7773	.0000
.5023	-1353.2459	.0000
.5075	-1236.1911	.0000
.5127	-1130.3014	.0000
.5178	-1034.4147	.0000
.5230	-947.4996	.0000
.5282	-868.6397	.0000
.5334	-797.0203	.0000
.5386	-731.9154	.0000
.5438	-672.6781	.0001
.5490	-618.7309	.0001
.5542	-569.5580	.0001
.5594	-524.6980	.0001
.5646	-483.7376	.0001
.5697	-446.3066	.0001
.5749	-412.0728	.0002
.5801	-380.7378	.0002
.5853	-352.0335	.0002
.5905	-325.7186	.0003
.5957	-301.5757	.0003
.6009	-279.4089	.0004

.6061	-259.0415	.0005
.6113	-240.3138	.0006
.6165	-223.0815	.0007
.6216	-207.2141	.0008
.6268	-192.5935	.0009
.6320	-179.1125	.0011
.6372	-166.6740	.0013
.6424	-155.1898	.0016
.6476	-144.5800	.0018
.6528	-134.7717	.0022
.6580	-125.6987	.0026
.6632	-117.3007	.0030
.6684	-109.5229	.0035
.6735	-102.3150	.0041
.6787	-95.6314	.0049
.6839	-89.4305	.0057
.6891	-83.6740	.0066
.6943	-78.3272	.0077
.6995	-73.3580	.0090
.7047	-68.7375	.0105
.7099	-64.4387	.0122
.7151	-60.4372	.0142
.7203	-56.7104	.0165
.7254	-53.2378	.0191
.7306	-50.0003	.0221
.7358	-46.9806	.0256
.7410	-44.1626	.0296
.7462	-41.5315	.0342
.7514	-39.0738	.0394
.7566	-36.7770	.0454
.7618	-34.6296	.0523
.7670	-32.6208	.0601
.7722	-30.7410	.0691
.7773	-28.9810	.0793
.7825	-27.3325	.0910
.7877	-25.7878	.1043
.7929	-24.3396	.1194
.7981	-22.9815	.1365
.8033	-21.7072	.1561
.8085	-20.5110	.1782
.8137	-19.3879	.2033

.8189	-18.3328	.2318
.8241	-17.3412	.2640
.8292	-16.4090	.3004
.8344	-15.5323	.3416
.8396	-14.7074	.3882
.8448	-13.9310	.4407
.8500	-13.2000	.5000

Simulation ended : 20 : 00 : 58 7/05/2000

W.C. : Water content (cm^3/cm^3)

h (w.c.) : Soil water matric potential (cm)

k (w.c.) : hydraulic conductivity (cm/hr)

File Name : Profile.out

Simlation started : 19:59:49 7/05/2000

z cm	h(z) cm	wc(z) cm^3/cm^3	salt_conc. dS/m	N_Amnt kg/ha/cm
TIME = 24.00				
.0	-112.953	.666	35.003	.000
5.0	-108.649	.669	34.998	.000
10.0	-105.549	.671	34.997	.000
15.0	-103.410	.673	34.999	.000
20.0	-102.002	.674	35.001	.000
25.0	-101.121	.674	35.001	.000
30.0	-100.598	.675	35.001	.000
35.0	-100.304	.675	35.000	.000
40.0	-100.148	.675	35.000	.000
45.0	-100.069	.675	35.000	.000
50.0	-100.030	.675	35.000	.000
55.0	-100.013	.675	35.000	.000
60.0	-100.005	.675	35.000	.000
65.0	-100.002	.675	35.000	.000
70.0	-100.001	.675	35.000	.000
75.0	-100.000	.675	35.000	.000
80.0	-100.000	.675	35.000	.000
85.0	-100.000	.675	35.000	.000
90.0	-100.000	.675	35.000	.000
95.0	-100.000	.675	35.000	.000
100.0	-100.000	.675	35.000	.000

TIME = 72.000

.0	-82.480	.690	20.254	19.863
5.0	-77.814	.695	21.484	19.729
10.0	-73.075	.700	24.236	19.423
15.0	-69.136	.704	27.209	18.815
20.0	-66.058	.708	29.768	17.858
25.0	-63.663	.711	31.729	16.341
30.0	-61.816	.713	33.130	14.074
35.0	-60.402	.715	34.072	11.130
40.0	-59.305	.717	34.650	7.890
45.0	-58.381	.718	34.952	4.890
50.0	-57.443	.719	35.064	2.641
55.0	-56.236	.721	.35.065	1.236
60.0	-54.451	.724	35.012	.4E96
65.0	-51.781	.728	34.931	.168
70.0	-48.032	.734	34.815	.048
75.0	-43.232	.743	34.566	.011
80.0	-37.642	.755	33.877	.003
85.0	-31.643	.770	32.163	.001
90.0	-25.587	.788	28.765	.000
95.0	-19.709	.812	23.559	.000
100.0	-14.119	.844	17.309	.000

time 120.000

.0	-70.029	.703	14.168	10.720
5.0	-65.358	.709	15.669	11.802
10.0	-60.560	.715	18.769	13.981
15.0	-56.536	.721	22.043	15.671
20.0	-53.312	.725	25.060	16.444
25.0	-50.685	.730	27.722	16.290
30.0	-48.514	.733	29.984	15.264
35.0	-46.694	.736	31.805	13.465
40.0	-45.143	.739	33.159	11.061
45.0	-43.787	.742	34.070	8.341

time = 1992.000

.0	-329.942	.590	5.714	4.090
5.0	-318.889	.592	5.770	4.165
10.0	-296.297	.597	5.916	4.349
15.0	-266.563	.604	6.107	4.596
20.0	-236.438	.612	6.316	4e.863
25.0	-210.239	.621	6.540	5.120
30.0	-189.289	.628	6.793	5.344
35.0	-173.317	.634	7.098	5.522
40.0	-161.558	.639	7.475	5.637
45.0	-153.269	.643	7.917	5.695
50.0	-147.919	.646	8.407	5.803
55.0	-145.234	.647	8.919	5.960
60.0	-145.225	.647	9.433	6.134
65.0	-148.260	.646	9.930	6.301
70.0	-155.259	.642	10.390	6.435
75.0	-168.204	.637	10.786	6.514
80.0	-191.576	.627	11.092	6.511
85.0	-237.287	.612	11.293	6.401
90.0	-347.523	.586	11.421	6.151
95.0	-760.702	.536	11.469	5.628
100.0	-4626.819	.437	11.469	4.584

Simulation ended : 20 : 00 : 58 7/05/2000

z	:	Soil depth (cm)
h(z)	:	matric potential at depth of z, (cm)
wc(z)	:	water content at depth of z, (cm^3/cm^3)
Salt Conc.	:	Salt concentration (dS/m)
N_Amnt	:	amount of N at depth of z (kg/ha/cm)
Time	:	at which the simulation results were taken (hrs.).

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