



LIBRARY
New Delhi

Call No.

Acc. No.

7 030

ASSESSMENT OF NON-POINT SOURCE POLLUTION OF GROUNDWATER IN IRRIGATION PROJECT AREAS

VEMURI MUTHAYYA CHOWDARY

T6303



IARI

DIVISION OF AGRICULTURAL ENGINEERING
INDIAN AGRICULTURAL RESEARCH INSTITUTE
NEW DELHI-110 012

1998

ASSESSMENT OF NON-POINT SOURCE POLLUTION OF GROUNDWATER IN IRRIGATION PROJECT AREAS

By

VEMURI MUTHAYYA CHOWDARY

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

1 9 9 8

Approved by :

Chairman : Dr. P.B.S. Sarma

Members : Dr. A.K. Bhattacharya

Dr. N.H. Rao

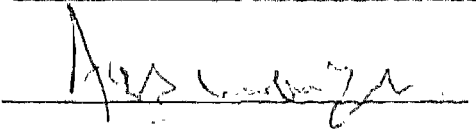
Dr. K.S. Sundara Sarma

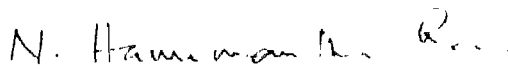
Dr. R. Srivastava

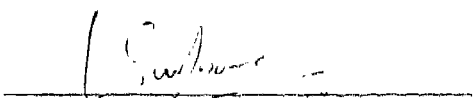
Shri S.N. Mathur

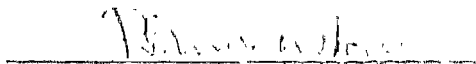
Dr. K.S. Uppal

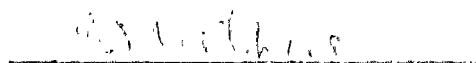


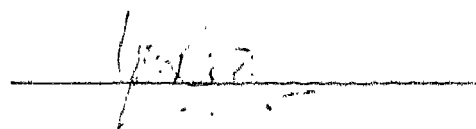












1-6'35'2.

DIVISION OF AGRICULTURAL ENGINEERING
INDIAN AGRICULTURAL RESEARCH INSTITUTE
NEW DELHI-110012, INDIA

DR. P.B.S. SARMA

Project Director

Water Technology Centre

Indian Agricultural Research Institute

New Delhi - 110 012

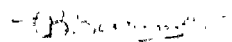
CERTIFICATE

This is to certify that the thesis entitled "**Assessment of Non-Point Source Pollution of Groundwater in Irrigation Project Areas**", 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**, is a record of *bonafide* research work carried out by **Shri V. MUTHAYYA CHOWDARY**, under my supervision and guidance. No part of the thesis has been submitted for any other degree or diploma.

It is further certified that such help or source of information, as has been availed of in this connection has been duly acknowledged by him.

Place : New Delhi

Date : 17 March, 1998



(Dr. P.B.S. Sarma)

Chairman

Advisory committee

ACKNOWLEDGEMENT

I, with everlasting enthusiasm, pride and pleasure, in expressing my deep sense of gratitude and indebtedness to Dr. P.B.S. Sarma, Chairman of my advisory committee and project director, Water Technology Centre, Indian Agricultural Research Institute, New Delhi, for his adept guidance, constructive criticism, valuable suggestions and constant encouragement during my course work, research investigation and preparation of thesis.

With immense pleasure and overwhelming sense of respect, I express my earnest thanks from my heart of hearts to Dr. N.H.Rao, Senior Scientist, member of my advisory committee, for his learned counsel, unstinted attention, timely help, constant encouragement, arduous and meticulous guidance throughout the period of study. Ineffable is my gratitude to him without whose incessant and untiring help, it would not have been possible for me to complete this manuscript. I have been fortunate to be inspired by his affectionate behaviour, dynamic innovative and ever helping nature throughout the period of my study.

I place on record my thanks and indebtedness to Dr. A.K. Bhattacharya, Principal Scientist, Water Technology Centre, Dr. K.S. Sundara Sarma, Senior Scientist, Division of Agricultural Physics, Dr. R. Srivastava, I.A.S.R.I., New Delhi, Shri S.N. Mathur, Computer Centre, I.A.S.R.I., New Delhi and Dr. K.S. Uppal, Senior Scientist, Division of Soil Science and Agricultural Chemistry, who are members of my advisory committee, for their helpful criticism and useful suggestions for improvements in the presentation of the thesis.

My deep sense of gratitude is recorded to Dr. O.P. Singhal, Professor, Division of Agricultural Engineering, and Dr. J.S. Panwar, Head, Division of Agricultural Engineering for their kind help during the course of this investigation.

A special word of thanks I owe to Dr. D.K. Singh, Dr. A.K. Singh, Dr. H. Chandrasekharan, Dr. T.B.S. Rajput, Dr. A. Singh, Dr. S.K.

Bandhyopadhyay and Dr. I.M. Mishra for their spontaneous help on different demanding occasions.

The kind hospitality and help received from Dr. U. Sridhar, Dr. S. Krishna Reddy, Sri Sri Rama Murthy, Sri Ram Mohan, Sri. S. Vijay and Smt. Seshasri during my stay at Rajahmundry as part of my research work is gratefully acknowledged.

It is quite beyond my expression to say a word for moral encouragement, staunch support and selfless help rendered to me by my dearest friends, class mates and well wishers throughout my study period.

I sincerely acknowledge the staff of decision support system lab, Ms. Sheena Browne, Ms. Smita and Mr. Ashok Kumar, for their cordiality and friendliness.

I am thankful to the authorities of Godavari Delta Central Canal Irrigation Project, Rajahmundry, for cooperation rendered during the study. My special thanks are due to the officials of Andhra Pradesh State Groundwater Board, Rajahmundry and concerned mandal officials for providing necessary data for this study. Thanks are also due to Dr. K.V. Ramana, Scientist, NRSA, Hyderabad for providing necessary data for this study.

I am personally thankful to all the staff of W.T.C. especially Julfiram and Ghanshyam for their help in the preparation of thesis.

I am grateful to the Dean and Director of IARI and CSIR for the award of senior research fellowship to pursue this study.

My beloved parents, sister and brother-in-law also boosted my moral at many testing times. Finally the affection and understanding of my wife and in-laws have been all through an assest in my endeavour

Finally I must thank Shri P.K. Garg and Shri Ashwani Kumar for their patient and efficient help in the typing of manuscript.

New Delhi
March 12th, 1998


(V. MUTHAYYA CHOWDARY)

CONTENTS

Chapter	Page No.
1. INTRODUCTION	1
1.1 Sources of groundwater pollution	1
1.1.1 Agricultural pollution	2
1.1.2 Agricultural pollution in India	3
1.2 Effects of nitrate pollution	4
1.3 Assessment of non point source pollution of groundwater in irrigation project areas	5
1.4 Objectives of the study	7
1.5 Organisation of the thesis	8
2 REVIEW OF LITERATURE	10
2.1 Estimation of groundwater recharge	12
2.1.1 Estimation of percolation losses by soil water balance	14
2.1.2 Percolation losses from rice fields	16
2.1.3 Estimation of seepage losses in conveyance system	17
2.2 Simulation of groundwater flow	19
2.3 Prediction of pollutant loads to groundwater from rice fields	21
2.3.1 Urea hydrolysis	22
2.3.2 Ammonia volatilization	24
2.3.3 Mineralization and immobilization	27
2.3.4 Nitrification process	29
2.3.5 Denitrification	30
2.3.6 Leaching of nitrate	31
2.3.7 Nitrogen uptake by rice plants	33
2.4 Simulation of pollutant transport in groundwater	37
2.5 Linking spatially distributed inputs and outputs to simulation models	39
2.5.1 Geographical Information System (GIS)	39
2.5.2 Interfacing GIS with simulation models	40
2.6 Critique	41

	Chapter	Page No.
3.	THE CASE STUDY AREA	44
3.1	Climate	44
3.2	Topography and soils	45
3.3	Cropping pattern	45
3.4	Irrigation	47
	3.4.1 Canal irrigation	47
	3.4.2 Groundwater	47
3.5	Groundwater quality	49
3.6	Aquifer parameters	49
3.7	Generation of Basic Simulation Units (BSU) using GIS	51
4	ESTIMATION OF GROUNDWATER RECHARGE	53
4.1	Canal flow model to estimate seepage losses	53
	4.1.1 Model development	54
	4.1.2 Estimation of irrigation depth	57
	4.1.3 Computer program	58
	4.1.4 Data input for the model	58
4.2	Estimation of deep percolation by soil water balance	59
	4.2.1 Water balance in rice field	59
4.3	Soil water balance for non paddy crops	63
	4.3.1 Estimation of components of soil water balance	65
4.4	Soil water balance for uncultivated lands	70
	4.4.1 Estimation of evaporation from uncultivated lands	71
4.5	Soil water balance from rice fallow lands	72
4.6	Computer program	72
4.7	Interface between soil water balance model and GIS	72
4.8	Application to study area	73
	4.8.1 Estimation of seepage losses in the study area	73
	4.8.2 Estimation of percolation losses from fields in the study area	76
4.9	Assessment of spatial distribution of recharge in the study area	80
4.10	Discussion	85

Chapter	Page No.
5. ESTIMATING NITRATE POLLUTANT LOADS TO GROUNDWATER	94
5.1 Development of a model for quantifying nitrogen transformation processes	95
5.1.1 Modelling individual components of N-balance equation	96
5.2 Selection of model parameters	102
5.3 Computer program	102
5.4 Validation of the nitrogen balance model	102
5.5 Estimation of nitrate pollutant loads to groundwater in the case study area	112
5.5.1 Input data and model parameters	115
5.5.2 Interface between the nitrogen balance model and GIS	117
5.6 Discussion	118
6. SIMULATION OF GROUNDWATER FLOW AND POLLUTANT TRANSPORT IN THE STUDY AREA	127
6.1 Development of groundwater basin simulation model	127
6.1.1 Solution to the equation of groundwater flow	129
6.2 Computer program	130
6.2.1 Program structure	130
6.3 Evaluation of performance of the groundwater model	133
6.4 Application of groundwater basin simulation model to the study area	134
6.4.1 Organization of input data	134
6.4.2 Spatial distribution of pumping rates	137
6.4.3 Simulation of groundwater levels	140
6.4.4 Regional water balance of the study area	142
6.4.5 Annual water balance	145
6.5 Sensitivity analysis and validation of the simulation model	146
6.6 Development of the Groundwater Transport Model	151
6.6.1 General equation of solute transport in groundwater	152
6.7 Computer program	157
6.7.1 Program structure	158

Chapter		Page No.	
6.8	Application of groundwater transport model to the study area		162
6.8.1	Input data organization		162
6.8.2	Validation of the groundwater transport model		164
6.9	Discussion		166
7.	ASSESSMENT OF IMPACTS OF NITRATE POLLUTION ON GROUNDWATER UNDER DIFFERENT SCENARIOS		172
7.1	Discussion		180
8	SUMMARY AND CONCLUSIONS		184
	REFERENCES	I	XX
	APPENDICES		
Appendix A	Aquifer pumping data for two locations within the study area		
	- Canal discharge data for the year, 1995 for all the four canals	A1	A11
	- Daily rainfall data for the year 1995, for all the raingauge stations		
Appendix B	- Fortran program listing for canal flow model	B1	B16
	Estimated irrigation depths for all four canals using canal flow model		
Appendix C	- Fortran program listing for soil water balance model	C1	C31
Appendix D	- Fortran program listing for nitrogen balance model	D1	D11
Appendix E	- Finite element method description	E1	E12
Appendix F	- Fortran program listing for groundwater flow model		
	Sample input file for the year 1995	F1	F22
	Sample output file for the year 1995		
Appendix G	Fortran program listing for groundwater transport model		
	Sample input file for the year 1995	G1	G21
	Sample output file for the year 1995		

LIST OF TABLES

Table No.	Title	Page No.
1 1	Nitrate standards for potable water prescribed by different countries/organisations	3
2.1	Rate constants for different N-transformation processes	23
2 2	Reported volatilization losses from flooded soils in India	26
2.3	Reported leaching losses from flooded paddy fields in India	32
2.4	Reported uptake of nitrogen by rice from flooded fields in India	35
3.1	Hydro-physical properties of soils in the case study area	45
3 2	Cropping pattern in Godavari delta central canal irrigation project	46
3 3	Cross sectional details of canals in Central Godavari Delta Irrigation Project	48
3 4	Rice cropped areas under each canal during <i>Khurif</i> and <i>Rabi</i> seasons in the study area, ha	49
3 5	Nitrate concentration of groundwater at different observation wells in the study area, ppm	50
3.6	Polygon Attribute Table (PAT) for the resulted Basic Simulation Units (BSU)	52
4.1	Representative value of 'a' for estimation of evaporation from uncultivated soils, mm/day ^{1/2}	72
4 2	Monthly seepage rates from the canal distribution system, cumec	75
4.3	Statistical parameters for rating curves obtained for estimation of seepage losses	77
4.4	Weekly average reference evaporation values	78
4 5	Details of crop characteristics adopted for the soil water balance model	79
4.6	K _r values adopted for various crops of study area	79

Table No.	Title	Page No.
4.7	Soil water depletion factor (p) for crop groups at different potential evaporation (PET) values	80
4.8	Daily water balance in the rice fields for one BSU of the study area (<i>Kharif</i> season, 1995), mm	81
4.9	Monthly percolation rates during <i>Kharif</i> season (1995), mm	83
4.10	Cropping pattern in all BSU's of Godavari Delta Central Canal Irrigation Project	84
4.11	Recharge rates (m ³ /sec) for basic simulation units (BSU), 1992-93	86
4.12	Recharge rates (m ³ /sec) for basic simulation units (BSU), 1993-94	87
4.13	Recharge rates (m ³ /sec) for basic simulation units (BSU), 1994-95	88
4.14	Recharge rates (m ³ /sec) for basic simulation units (BSU), 1995, Monsoon season	89
5.1	Rate constants for N-transformation processes in flooded rice fields	103
5.2	Weekly average reference evapotranspiration values, mm/day at Pantnagar	105
5.3	Final values of model parameters for different N-transformation processes in rice at Pantnagar	106
5.4	Daily nitrogen balance in rice fields at Pantnagar	107
5.5	Seasonal nitrogen balance values at Pantnagar	109
5.6	N-uptake pattern for Pantnagar location	110
5.7	Daily pan evaporation values measured at IARI meteorological observatory, New Delhi for the year, 1989	111
5.8	Model parameters for different N-transformation processes at IARI, New Delhi	112
5.9	Daily nitrogen balance in rice fields at IARI, New Delhi	113
5.10	Seasonal nitrogen balance values at IARI, New Delhi	115
5.11	Sensitivity analysis of the rate constants on N transformation processes	116

Table No.	Title	Page No.
5.12	Model parameters for different N-transformation processes in rice for the soils of Central Godavari Delta Irrigation Project	117
5.13	Daily nitrogen balance for BSU 1 of the study area	119
5.14	Seasonal nitrogen balance from all the BSU's in the study area	121
5.15	Monthly and seasonal nitrate loads from all the BSU's, ppm	122
6.1	Distribution of nodes within each basic simulation unit	138
6.2	Norms adopted in derivation of pumping rate coefficients	139
6.3	Simulated water table levels for the year 1992-93, m	141
6.4	Observed and simulated water table levels, m	143
6.5	Monthly outflow rates from the study area, m ³ /sec	144
6.6	Annual water balance of the study area	146
6.7	Sensitivity analysis of predicted water table levels with changes in specific yield	148
6.8	Sensitivity analysis of predicted water table levels with changes in hydraulic conductivity	149
6.9	Simulated water table levels for the year (Nov., 1995)	150
6.10	Annual (June-May) rainfall, 1992-1995	151
6.11	Observed and simulated nitrate concentration levels in the ground water, ppm (Nov., 1995)	165
7.1	Projected nitrate concentrations in the ground water, ppm	174
7.2	Annual nitrate loadings to groundwater for all Basic Simulation Units, ppm	177
7.3	Simulated nitrate concentration under different management practices, ppm (May, 1996)	178

LIST OF FIGURES

Fig. No.	Title	After Page
1.1	Integrated framework for assessment of non-point source pollution of groundwater in irrigation project areas	7
2.1	Schematic representation of the N-transformations in flooded rice field	22
3.1	Location map of Godavari Delta Central Canal Irrigation Project	44
3.2	Raingauge thiesen polygons	45
3.3	Topographical map	45
3.4	Soil map	45
3.5	Command areas of the branch canals	47
3.6	Administrative blocks (<i>mandals</i>)	51
3.7	Basic simulation units	51
4.1	Schematic representation of canal section for seepage estimation	54
4.2	Waterbalance components of rice field	60
4.3	Relationship between soil moisture availability and AET	62
4.4	Components of soil water balance model	63
4.5	GIS Model linkages for generating thematic maps	72
4.6	Rating curve for estimation of seepage losses (Cannavaram Canal)	76
4.7	Rating curve for estimation of seepage losses (Amalapuram Canal)	76
4.8	Rating curve for estimation of seepage losses (Bank Canal)	76
4.9	Thematic map of average recharge for the study area	85
5.1	Zoning of ideal paddy field for N balance studies	95
5.2	Schematic diagram of the nitrogen balance model	96
5.3	Schematic representation of simulated nitrogen transformation processes in rice at Pantnagar	104

Fig. No.	Title	After Page
5.4	Nitrogen uptake in rice at Pantnagar	109
5.5	Nitrogen uptake in rice at Pantnagar	109
5.6	Schematic representation of simulated nitrogen transformation processes in rice at IARI	110
5.7	Schematic representation of simulated nitrogen transformation processes in rice at study area	117
5.8	Seasonal percolation losses from rice fields, mm (Kharif, 1995)	118
5.9	Seasonal nitrate pollution loads to groundwater in rice fields at study area, ppm (Kharif, 1995)	118
6.1	General configuration of finite element program	132
6.2	Generalized flow diagram for subroutine FMODEL	132
6.3	Finite element grid of the study area	134
6.4	Observed ground water levels, m (May, 1992)	135
6.5	Observed and simulated groundwater levels, m (May, 1993)	147
6.6	Observed and simulated groundwater levels, m (May, 1994)	147
6.7	Observed and simulated groundwater levels, m (May, 1995)	147
6.8	Observed and simulated groundwater levels, m (Nov, 1995)	147
6.9	Observed and simulated groundwater levels in the study area, m (May, 1993)	147
6.10	Observed and simulated groundwater levels, m (May, 1993)	147
6.11	Observed and simulated groundwater levels, m (May, 1994)	147
6.12	Observed and simulated groundwater levels with pumping factor 1.0, m (Nov, 1995)	147
6.13	Observed and simulated groundwater levels with pumping factor 0.75, m (Nov, 1995)	147

Fig. No.	Title	After Page
6.14	General configuration of finite element program	160
6.15	Generalized flow diagram for subroutine TMODEL	160
6.16	Observed nitrate concentration levels in the groundwater, ppm (May, 1995)	163
6.17	Observed and simulated nitrate concentration levels in the groundwater, ppm (Nov., 1995)	164
6.18	Observed and simulated groundwater nitrate concentrations in the study area, ppm (Nov., 1995)	165
7.1	Projected nitrate concentration levels in the ground water, ppm	175
7.2	Comparison of simulated nitrate concentration levels obtained for the conditions of current practices and Scenario II (doubled fertilizer use), ppm	176
7.3	Comparison of simulated nitrate concentration levels obtained for the conditions of current practices and Scenario III (reduced percolation losses), ppm	179
7.4	Comparison of simulated nitrate concentration levels obtained for the conditions of current practices and Scenario IV (increased paddy area), ppm	180

1. INTRODUCTION

Groundwater forms more than 90% of the total fresh water available and it has become an important source of water for meeting the demands of ever growing population. Pollution from agricultural, industrial and domestic wastes is increasingly inhibiting the use of groundwater. The growing concern over acute or chronic health hazards resulting from contaminants in drinking water has brought the degradation of the quality of groundwater to public attention. Groundwater quality is a primary environmental concern not only for health reasons, but also for its effect on crop production.

1.1 SOURCES OF GROUNDWATER POLLUTION

Contamination of groundwater is mainly from the following four sources

a) Industrial sources

- * Industrial effluents contain large quantities of chemical substances which may find their way into the groundwater
- * Rain infiltrating through waste disposal sites
- * Accidents like breaking of pipe lines, overturning of trucks carrying hazardous chemicals, etc.

b) Sources originating from domestic and personal habits

- * Leakage from septic tanks and toilets
- * Leaching from garbage disposal sites
- * decaying corpses

c) Agricultural sources

- * Fertilizers, salts and pesticides infiltrate through the ground surface to reach the aquifers
- * Wastes from live-stocks

d) Environmental sources

- * Sea water intrusion in coastal aquifers
- * Seepage from polluted streams or canals
- * Diffusion into groundwater from adjacent surface water sources

Pollution by activities other than agriculture is mainly point source pollution. Agricultural pollution is essentially non-point source pollution as it results from widespread use of fertilizers and other agricultural chemicals over a large area. Point source pollution is generally highly toxic and it is relatively easily located and controlled. Non-point source pollutants are relatively low in concentration, but because of their scale and variability, pose a far greater threat to soil and groundwater resources than point source pollutants. This is because of the areal extent of the contamination and the difficulty of effective remediation once soils and groundwater are contaminated.

The present study is concerned with non-point source pollution from agricultural sources. More specifically it is directed towards assessing non point source pollution of groundwater resulting from the excessive use of nitrogen fertilizers in the command areas of major irrigation projects.

1.1.1 Agricultural Pollution

As the world's population continues to grow, the foremost nonparochial problem facing humans is meeting the requirement of food with a sustainable

agriculture. However, sustainable agriculture requires a delicate balance between crop production, natural resource conservation and utilization, environmental impacts and economics. It strives to optimise food production while maintaining economic stability, minimizing the utilization of finite natural resources, and avoiding adverse impacts on the environment. Yet, agriculture remains the single greatest contributor of NPS pollutants to soil and water resources (Humenik *et al.*, 1987). In particular, nitrogen fertilizers are highly water soluble and more likely to be leached out of the root zone in the form of nitrate. Nitrate concentrations beyond 45 mg/l in the groundwater is considered to be carcinogenic and detrimental to healthy crop growth. The consequences of excessive levels of nitrate in potable water are widely recognised and nitrate standards for potable water prescribed by different countries are given in table 1.1.

1.1.2 Agricultural Pollution in India

Our national priorities demand fertilizer use to be enhanced for increasing food production. At the same time, environmental concerns have been expressed

Table 1.1 Nitrate standards for potable water prescribed by different countries/organisations

S.No.	Country/Organisation	Concentration as NO ₃ -N, ppm	Concentration as NO ₃ , ppm
1.	W.H.O	10	45
2.	U.S. Environmental protection agency	10	45
3.	India	10	45
4.	Canada	10	45
5.	Poland	10	45
6.	EEC	11.3	50
7.	Bulgaria	6.7	30

(Source : Lunkad, 1994)

on pollution and other hazards associated with accelerated use of fertilizers. The increase in food production from 50 million tonnes in 1950 to 194 million tonnes in 1995-96 was accompanied by corresponding increase in $N + P_2O_5 + K_2O$ consumption from 0.65 million tonnes in 1951-52 to 13.9 million tonnes during 1995-96. Out of this, the contribution of N alone is 9.8 million tonnes. Consumption of N, P_2O_5 and K_2O has increased from 0.44, 0.05 and 0.06 kg/ha in 1951-52 to 52.7, 15.5 and 6.2 kg/ha in 1995-96 respectively. Numerous studies have indicated that nitrogen fertilizers are leached beyond the crop rootzone by excessive irrigation.

Very few studies attempted to relate the nitrate pollution of groundwater in India with the non point source contribution such as the use of nitrogenous fertilizers. Particularly worth mentioning is the study by C.G.W.B. (Mehta *et al.*, 1990) attributing high nitrate in dug well waters of Ganjam district (Orissa) to high N fertilizer use. Gupta (1992) also suggested that high nitrate in groundwater of Udaipur District (Rajasthan) could be due to a five fold increase in the use of N-fertilizers in the district during the decade 1979-89. In a study by NEERI (Bulusu and Panda, 1990) high nitrate concentrations in 41% samples from villages around Nagpur metropolitan city and 49% samples from Gulbarga district (Karnataka) also reflect contributions from agricultural sources. The high nitrate concentrations reported in some groundwater samples from Haryana, Punjab and U.P. in north, Tamilnadu and Karnataka in south, Orissa (Ganjam district) and Bihar in east and Gujarat in the west was attributed to high N-fertilizer consumption.

1.2 EFFECTS OF NITRATE POLLUTION

Although nitrate is low in normal water, its concentration beyond 45 ppm is considered carcinogenic and produces blue baby syndrome

(Methaemoglobinaemia). The disease is caused when oxygen carrying haemoglobin reacts with NO_2 (derived from biochemical reduction of NO_3) to form methaemoglobin hampering oxygen transport. Even higher nitrate concentration may cause gastric cancer. The functioning of central nervous system (CNS) and cardiovascular system (CVS) may also be adversely affected by nitrate rich water. In addition to these effects on the biological system high nitrate is undesirable in fermenting and dyeing industries as it reacts readily with organic compounds. While some amount of NO_3 may be considered desirable in irrigation water, its excess reduces soil permeability and may thus have adverse effects on soil fertility.

1.3 ASSESSMENT OF NON-POINT SOURCE POLLUTION OF GROUNDWATER IN IRRIGATION PROJECT AREAS

Assessing the environmental impacts of NPS pollutants at a global, regional and localized scale is a key component in achieving sustainability of agriculture, as well as preserving the environment. Assessment of groundwater pollution from agricultural sources involves the estimation of non-point source pollutant loading into the aquifer and its movement in the aquifer system. The pollutant loading occurs along with the recharge water. Recharge represents the primary contaminant transport mechanism into the aquifer. It describes the fraction of water available at the surface that infiltrates into the soil and percolates through the vadose zone into the ground water. Recharge can be from different sources . rainfall, seepage from canals, percolation losses from irrigated fields.

The Central Groundwater Board, the nodal agency for development of groundwater in India, has developed empirical norms for estimating groundwater recharge from each source. These norms are based on the amount of rainfall and irrigation supplies and some correction factors are applied based on the type of soils and aquifers etc. However, in real field conditions, recharge varies with

the soils, weather, crop and water use. A reliable estimate of groundwater recharge can be obtained only after these physical conditions are taken into account. Recharge therefore, varies both spatially and temporally. In addition to the aquifer conditions such as basin boundaries, depth to water table and other aquifer properties will also control the pollutant levels in the groundwater.

Since the vadose zone is an integral part of the hydrological cycle it is essential to understand the physical and chemical processes in the zone for groundwater protection and management. The various mechanisms that facilitate the transport of nitrate from the surface through the vadose zone towards the water table and methods of simulating these processes have been the subject of considerable review in recent years. In general, these assessments rest on soil, climatic conditions, irrigation supplies and fertilizer use pattern. Water and chemical balance models are the primary means of estimating the spatially distributed pollutant loading into the aquifer.

Once reliable estimates of pollutant loadings into the groundwater are available, the fate of pollutant in the aquifer system can be predicted. This can be carried out by groundwater transport models. A pre-requisite for this, is the simulation of groundwater levels using the available information of recharge. With the advent of computers and simultaneous developments in numerical models, the ability to predict the groundwater system behaviour has improved considerably (Prickett and Lonquist, 1971, Rushton and Redshaw, 1979; Sondhi, *et al* .1989; Rao, 1992).

As agricultural pollution largely dependent on spatially distributed attributes, a frame work for manipulating and analysing large amounts of spatial input data is needed. Geographical Information Systems (GIS) can make significant contributions to modelling by facilitating the treatment of spatial

variations and in manipulating large volumes of data. It is probably true that the factor limiting the use of existing distributed parameter models is not the ability to characterise hydrologic processes at the regional scale, but rather the ability to manipulate the large volume of model input parameters. The linkage of GIS with simulation models can overcome some of the limitations by providing an effective data management and analysis tool.

1.4 OBJECTIVES OF THE STUDY

This study aims at developing an integrated framework for the mathematical formulation and solution of the problem of non point source pollution of groundwater in canal irrigation projects. Simulation models of recharge, nitrogen transformations, groundwater flow, groundwater transport and GIS form the major components of the framework of the study (Fig. 1.1). Specific objectives of the present study are :

1. Development of a mathematical model for estimating the spatially and temporally variable recharge rates in irrigation project areas using GIS.
2. Development of a mathematical model to predict the spatial distribution of the dissolved pollutant load from agricultural non-point pollution sources in the groundwater recharge.
3. Simulation of groundwater flow and movement of the dissolved pollutant in the groundwater aquifer of an irrigation project area.
4. Assessment of impacts of nitrate pollution on groundwater quality under different scenarios.

The various procedures are developed and validated using data from the the Godavari Delta Central Canal Irrigation Project as a case study area. Rice

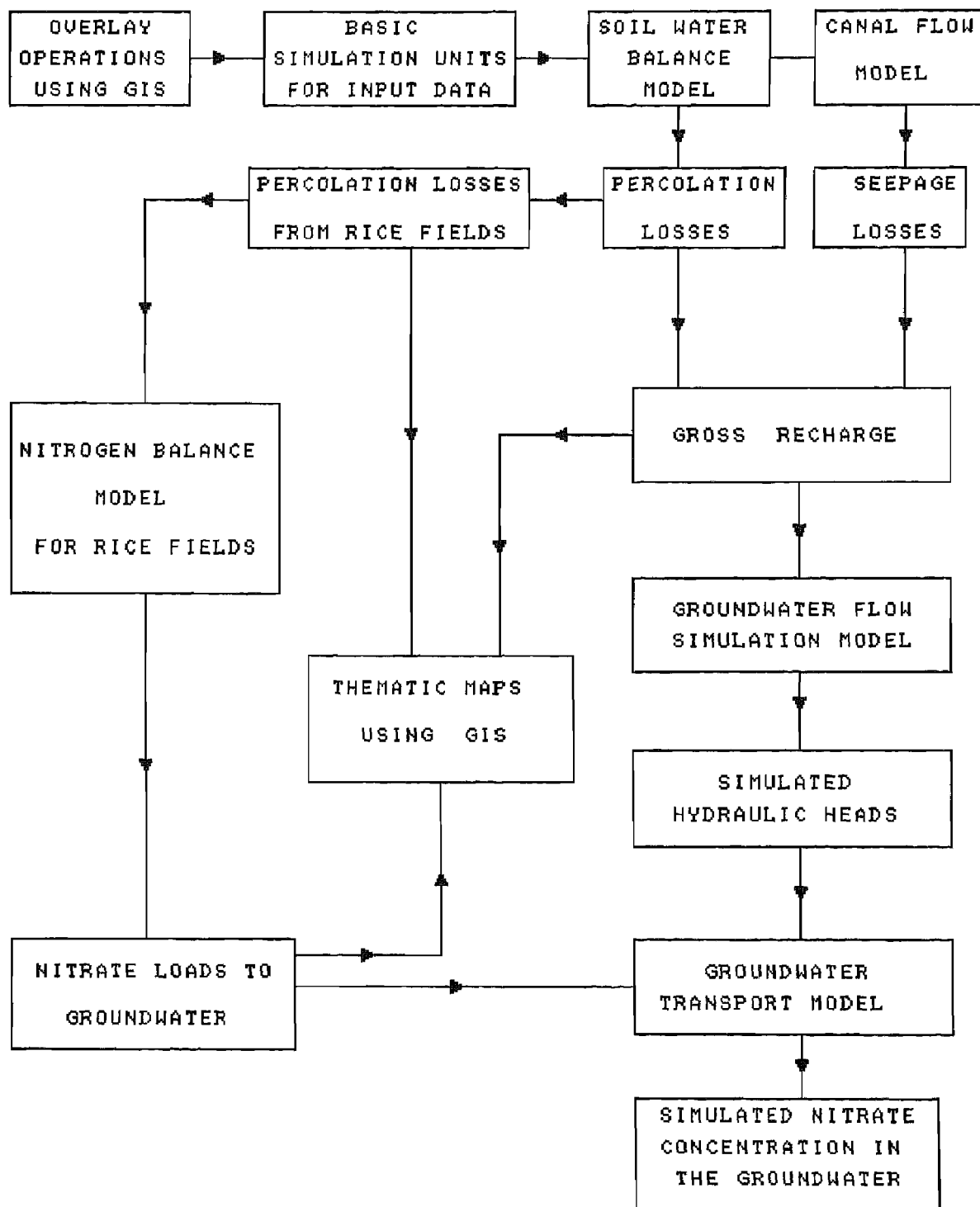


FIG 1.1 Scheme of Integrated Framework for Assessment of Non-Point Source Pollution of Groundwater in Irrigation Project Areas

is the dominant crop in the study area and commands the bulk of the fertilizer used in the area.

1.5 ORGANISATION OF THE THESIS

A detailed review of the literature relevant for the study is presented in Chapter 2. The concepts of GIS and application of GIS in water resources management are also reviewed in this chapter. The detailed description of the study area is given in chapter 3. Rainfall, recharge, return flow from irrigated areas and seepage from canals and distributaries form the major components for aquifer recharge. Estimation of these components is done based on the existing physical conditions in the command area instead of using empirical methods proposed by the Central Groundwater Board. A two layer root zone soil water balance model is used for estimation of recharge to groundwater from rainfall and return flow from irrigated areas. Seepage losses are estimated using a canal flow model. Geographical Information systems (GIS) is interfaced with soil water balance model for estimation of spatially and temporally distributed recharge. These procedures for estimation of recharge are described in chapter 4.

Estimation of pollutant loads into groundwater is done by developing a simple nitrogen balance model. The development of such a model which includes all the important nitrogen transformation processes in the soil root zone (urea hydrolysis, volatilization, nitrification, mineralization, immobilization, denitrification, uptake and leaching) is presented in chapter 5. The output of the soil water balance model (percolation losses, standing water depths) of chapter 4 serve as input to the nitrogen balance model described in this chapter.

Once the recharge and the pollutant loadings into the groundwater system are estimated, it is necessary to predict the rate of movement of pollutant in the groundwater. Simulation of pollutant transport in the aquifer system is

accomplished by solving the groundwater flow equation and groundwater transport equation sequentially. The simulation models of groundwater flow and transport are described in chapter 6. The values of water table at all the nodes are provided by the solution of the groundwater basin simulation model and are used as inputs to the groundwater transport model. The input data of pollutant loads is provided by the output from the nitrogen balance model described in Chapter 5.

The integrated frame work developed in the earlier chapters (4,5 and 6) is used to predict the future behaviour of the system in a case study area in chapter 7. The impacts of pollution and possible mitigation measures are discussed in this chapter. A summary of the study and conclusions are presented in chapter 8.

2. REVIEW OF LITERATURE

Groundwater is an important component of the total water resource for meeting the demands of the ever growing population. The growing concern over acute or chronic health hazards resulting from contaminants in drinking water has brought the degradation of the quality of groundwater to public attention. The quality of groundwater is a primary environmental concern not only for health reasons, but also for crop productivity. Excessive use of fertilizers and improper water management are the main reasons for pollution and degradation of groundwater in the irrigated areas. In particular, nitrogen fertilizers are water soluble and more likely to be leached out of the root zone in the form of nitrate. Concentration of $\text{NO}_3\text{-N}$ beyond 10 mg/l is considered detrimental to healthy crop growth. Numerous studies reported that such levels of $\text{NO}_3\text{-N}$ concentrations in groundwater are associated with use of fertilizers in agricultural area (Edmunds *et al.*, 1982; Hill, 1982; Spalding *et al.*, 1982; Kanwar *et al.*, 1985; Hubbard, *et al.*, 1986; Spalding and Exner 1993).

Quantification of the processes involved in groundwater recharge, groundwater flow and pollutant transport can help in prediction of pollution loads and movement of pollutants under different fertilizer application rates and water management strategies. The sources of recharge to groundwater in the command area of an irrigation project are seepage from rivers, reservoirs, canals, drains and percolation from cropped areas. In addition to this recharge, there could also be net subsurface inflow from outside the command area. The effect of recharge from all these sources is usually an increase in the groundwater storage and consequent rise of the groundwater levels at various locations in the command area. The changes in the groundwater levels can be simulated by development

of appropriate seepage and percolation models and linking them to a groundwater basin flow model. The pollutant enters the groundwater along with the recharge flows. Its subsequent dispersal within the aquifer can be simulated by a groundwater transport model.

The fertilizer use efficiency of rice is low ranging from 20% to 40%. Further, a standing water depth of 5 to 7 cm is always maintained in paddy fields. Leaching of nitrogen fertilizer beyond the root zone occurs along with the percolating water. Just as the percolation losses are governed by the soil water balance, the pollutant loads from applied fertilizer to groundwater are governed by the chemical balance in the root zone of crop. Thus nitrate pollution loads from rice fields will be governed by the fertilizer and irrigation applied.

The root zone of a crop determines the depth of soil from which the plants extract water and nutrients. The soil water regime within the crop root zone is determined by the daily soil water balance. The nitrogen budget is based on the different N-transformations in the crop root zone. There are significant practical difficulties in developing groundwater basin pollution simulation models because of complex nature of the processes involved. These include difficulties related to the spatial modelling of the hydrologic processes in the soil (runoff, infiltration, seepage, percolation and groundwater flow) and the determination of parameters responsible for groundwater movement and pollutant movement in the groundwater. A major problem is the selection of rate constants for various N-transformations. These difficulties need to be addressed before developing a groundwater basin pollution simulation model. Newer techniques like GIS are increasingly being used with the simulation models to address some of the key problems of spatial variation of the parameters and inputs to groundwater flow and transport models. GIS also facilitates display of spatial recharge and pollution loads and results of model simulations.

Literature related to the above issues is reviewed in this chapter. Specifically the review covers the following aspects:

- 2.1 Estimation of groundwater recharge,
- 2.2 Simulation of groundwater flow,
- 2.3 Prediction of pollutant loads to groundwater from rice fields,
- 2.4 Simulation of pollutant transport in groundwater, and
- 2.5 Linking spatially distributed inputs and outputs to simulation models using GIS.

2.1 ESTIMATION OF GROUNDWATER RECHARGE

Recharge to groundwater aquifers depends on the source and the process of recharge, the conditions of top soil, aquifer etc. The sources of recharge in irrigation project command areas are percolation from rainfall, percolation losses from irrigated fields and seepage losses from canals and distributaries. Both physical and chemical tracer methods can be used to estimate recharge from different sources. Physical methods are subdivided into indirect and direct methods. These methods assume more importance in wet areas and for estimating artificial recharge where the fluxes are higher and the inputs are more constant with time (Allison *et al.*, 1994).

Among the direct methods, lysimetry has long been used to estimate percolation losses from fields. Gee *et al.*, (1993) successfully used lysimeters to estimate recharge at arid sites in the western USA. Tracer methods use natural tracers for estimation of recharge. Natural tracers most commonly used in recharge studies are ^3H , ^{14}C , ^{36}Cl , ^{18}O , ^2H , ^{13}C and Cl . Of the tracers mentioned above ^3H , ^2H and ^{18}O are known to most accurately simulate the movement of

water because they integrate well with the water molecules (Gritzman and Margaritz, 1986; Taylor and Howard, 1996). Tracer methods are likely to be more successful than physical methods when the recharge rates are low, of the order of few millimeters or less per year (Allison *et al.*, 1994). Direct methods are cumbersome if recharge estimates are required over a large area with different crops, soils and weather etc.

The indirect methods for estimating percolation losses rely on either the soil water balance or calculation of water fluxes beneath the root zone using Darcy law or Richards equation. The soil water balance is essentially the principle of conservation of mass applied to the soil reservoir and is one of the widely used methods to estimate recharge from agricultural areas (Howard and Lloyd, 1979; Rushton and Ward, 1979; Sarma *et al.*, 1980). Several studies have involved the use of unsaturated hydraulic conductivity and hydraulic potential data to solve either Darcy's law or Richard's equation in the unsaturated zone and to estimate soil water flux for periods ranging from a month to several years (Sophocleous and Pary, 1985; Stephens and Knowlton, 1986). The water flux is calculated at such a depth in the profile that no further extraction by roots occurs from that depth, so that the downward flux will be equal to the groundwater recharge. Because of the difficulty in obtaining the relationships between hydraulic conductivity and moisture content, slight differences in sample measurement of water content can translate into large differences in unsaturated hydraulic conductivity (Stephens and Knowlton, 1986). This is particularly true when applied over a large region.

In India, the Central Groundwater Board provided broad empirical guidelines for estimating various quantities involved in groundwater recharge from different sources on a regional scale (CGWB, 1984). These norms which are

basically empirical in nature, are known as “New Norms” of groundwater evaluation and development and were proposed by Agricultural Refinance Development Corporation (Charlu and Dutt, 1982). These norms are purely empirical and do not consider the actual field conditions like crops, soils, depth to water table etc. This review is concerned with the estimation of different recharge components, percolation losses from fields and seepage losses from conveyance system by indirect methods using simulation models.

2.1.1 Estimation of Percolation Losses by Soil Water Balance

The soil water balance has been used to monitor the moisture status to arrive at actual evapotranspiration or irrigation scheduling decisions (Howards and Lloyd, 1979; Sarma *et al.*, 1980; Rao, 1985, Doraiswamy, 1992; Hajilal *et al.*, 1993, 1997; Arora and Gajri, 1996; Xevi *et al.*, 1996) for many crops other than rice. It can also be used to calculate percolation out of root zone which recharges the underlying aquifer.

The soil water balance equation defined for any specified time period is given by,

$$\Delta S = (R + I + U) - (Q + DP + ET) \quad (2.1)$$

Where R = rainfall, mm

I = irrigation, mm

U = Upward capillary flux, mm

ΔS = Change in storage, mm

Q = runoff, mm

DP = Deep percolation, mm and

ET = Evapotranspiration, mm

The choice of time period over which the soil water balance is carried out mainly depends on the purpose. Daily soil water balance is a norm for irrigation management applications. The same is also recommended for estimation

of deep percolation or recharge to groundwater bodies (Howard and Lloyd, 1979). Larger time durations like a month or an year are usually adopted for making gross estimates and assessing long term trends. Rainfall and irrigation are measured inputs, and all other terms of equation 2.1 need to be calculated. Methods for daily soil water balance range from simple book keeping to complex numerical solution of equations describing the dynamics of unsaturated flow in the soil plant systems. The dynamic models have been reviewed by Feddes *et al.* (1988). The book keeping procedure involves estimating each component of equation separately. Methods for estimating runoff, ET, U, DP etc. have been reviewed by Rao (1991). These procedures are now routinely employed in several well known watershed models such as CREAMS (Knisel, 1980), SWRRB (1990), AGNPS (Young *et al.*, 1987). They have also been used as irrigation scheduling models (Rao *et al.*, 1990; Hajilal, 1997). Calculations of soil water balance have also been made using the SWATRER model for irrigation scheduling purposes (Wesseling and Van den Broek, 1988). The English MORECS service method is based on a two part soil reservoir with differing rates of water release, corresponding to soil and subsoil (Thompson *et al.*, 1981). The Canadian service method is based on a soil water Budget model (Boisvert *et al.*, 1992a) which estimates changes for up to six zones identified by percentages of the overall available water for the root zone. Simple conceptual models of soil water balance have been proposed by Rao (1987), Sarma and Mani (1992) and Hajilal *et al.* (1998). These models were applied over a large irrigation project areas and were validated with field data.

Modelling the different physical processes making up the soil water balance like, infiltration, evapotranspiration, runoff, redistribution of infiltrated water, capillary rise and percolation have been reviewed extensively component wise by several researchers (Rao, 1991; Pereira *et al.*, 1995)

2.1.2 Percolation Losses from Rice Fields

The procedure for computation of water balance of rice fields is different from that of other crops because of the ponded conditions on these fields during most of the growing period. Rice field water balance has been analysed by Kampen (1970) and Brown *et al.* (1978). The specific aspects of water movement through and below the root zone of rice fields have been studied by Wickham and Singh (1978). Different water balance components of paddy fields were quantified by Shimura (1987); Mizutani *et al.* (1989); Yukuma (1989); Murayama (1989) and Watanabe (1992). Tabbal *et al.* (1992) indicated how each component of the water balance influences management aspects in paddy fields. The relation between field layout and field water balance conditions can be seen from three view points . effect of layout on field surface flow, seepage and percolation and water management. These effects are interrelated. Rao and Rees (1992) modelled the water balance in the paddy fields for scheduling of irrigations in the Kaudulla irrigation scheme area of Sri Lanka.

Smith (1992) introduced water balance of rice fields into the computations of the FAO's CROPWAT program, adopting a specific procedure including the nursery period, the period of land preparation and inundation prior to transplanting, and the various growth stages. Percolation is not modelled, but is input as a daily percolation rate, covering both vertical and horizontal water losses. The model IRRICEP (Pereira, 1989) uses the main concepts developed in earlier studies, treating separately each component of the water balance, in relation to crop growth stages. It computes the vertical and horizontal seepage assuming Darcy flow conditions. Extensive review on water balance in paddy fields was given by Murthy and Koga (1992). Rao (1995) carried out water balance studies in paddy fields of MRBC area, Gujarat. Odhiambo and Murthy

(1996) developed a water balance model for lowland paddy fields. The model inputs were irrigation supply, climatic data, soil parameters and layout dimensions. This model was formulated to simulate various processes such as evapotranspiration, seepage and percolation and surface runoff as they occur in the field water balance system. Vertical and horizontal movement of water was considered using Darcy's law. The governing equations were solved numerically using finite differences.

2.1.3 Estimation of Seepage Losses in Conveyance System

A significant proportion of the irrigation water released from the source is lost as seepage through canals, distributaries etc., and recharges the aquifer. Quantitative knowledge of seepage rates is required for determining seepage losses from canals or streams. Such knowledge can be obtained by direct measurement or estimation using mathematical models. Seepage losses from flowing channels can be determined directly by measuring discharge at various points (inflow-outflow techniques) or by measuring the rate of water movement through the bottom or bank of the channel using a seepage meter or tracer techniques. Ahmad (1974) reviewed a large number of measurements of canal losses in the Indus basin. The seepage rates were estimated to be 0.25 m/day and 0.2 m/day for main canals and water courses respectively. Mathematical models of seepage are based on knowledge of both flow processes in the canals and distributaries as well as in the aquifer. Extensive reviews on seepage losses in canals were given by Deacon (1984).

Several attempts have been made to simulate accurately the unsteady gradually varied flow conditions in canals, using Saint-Venant equations of one-dimensional flow that are derived from the conservation of mass and momentum (Chow, 1959; Strelkoff, 1969, Mahmood and Yevjevich, 1975; Joliffe, 1984; Walker and Skogerboe, 1987). These equations are hyperbolic and non-linear

with no closed form solutions. The numerical solutions of these equations form the base of several canal hydraulics models such as dynamic wave operational model (Fread, 1978); Stream Hydraulic package (Smith, 1979) and Branched network flow package (Schaffraner *et al.*, 1981). A review of mathematical models available for hydraulic transient studies was given by Mandavia and Acharya (1995). Most of these mathematical models have been developed for specific projects to examine the system response. A major difficulty in adapting these models is the availability of the precise engineering data of the canals and the flow control structures and their calibrations, as they exist on date.

Vyas and Sarma (1992) developed a simple analytical model for the estimation of flows and associated seepage losses in various reaches of a canal network. In this model, the entire length of the canal is divided into a number of reaches, the distance between the two consecutive off-take points being treated as a reach. As the flow in a reach varies spatially, the depths of flow at the upstream and downstream ends will be different. An iterative procedure together with uniform flow equation is used to estimate the flows at different locations. The applicability of this model was demonstrated to estimate the flows at different locations of Sihol minor of Mahi Right Bank Canal Command area, Gujarat (Vyas and Sarma, 1992). Hajilal *et al.* (1997,1998) developed a relationship between seepage losses and flow in a reach for use in estimating the discharges at different reaches of the canal system. Rao and Maurer (1996) proposed a simplified approach for modelling transmission losses in a stream. A theory relating seepage from a channel with the depth of flow is simplified to a one-parameter relationship. A power relationship is then utilised for the stage discharge relationship, which is coupled with the seepage relationship. This combined equation is integrated over the channel reach to arrive at a general model for seepage loss through a reach, with only one parameter needing calibration.

Other studies require measurement or estimation of data other than stream flow such as seepage rate (U.S. Bureau of Reclamation, 1967) or water table elevation (Mishra and Seth, 1988). All the models require information about seepage rates. Representative values of seepage rates are assumed based on condition of flow (Canal lining, soil medium etc.). The seepage rate however, depends on the condition in the aquifer, depth to water table, soil permeability etc. (Rao, 1990; Rao, 1993).

2.2 SIMULATION OF GROUNDWATER FLOW

Flow of groundwater in the aquifer is governed by two dimensional or three dimensional partial differential equation of flow subject to different boundary conditions and type of aquifer. The widespread availability of computers and concurrent development of efficient numerical methods for the solution of partial differential equations of groundwater flow have enabled the development of complex groundwater flow models. The differential equations are generally solved either by Finite Difference Method (FDM) or Finite Element Method (FEM). The basic principle behind both these methods is to replace the true solution by an approximate one constructed from a suitable set of basic functions. Extensive reviews of groundwater models are available in literature (Prickett, 1976; Pinder and Gray, 1977; Rushton, 1988; Stoertz and Bradbury, 1989, Krabbenhoft and Babiarz, 1992).

In the finite difference methods, the governing partial differential equation of flow is approximated using finite difference equations and the resulting set of simultaneous linear or nonlinear algebraic equations is solved using direct or indirect techniques (Tyson and Webber, 1964; Bredehoeft and Pinder, 1970, Prickett and Lonquist, 1971 and Trescott and Larson, 1977). The commonly used numerical algorithms are Iterative Alternating Direction Implicit Method

(IADI), (Prickett and Lonquist, 1971) and standard backward difference scheme (Rushton and Redshaw, 1979). McDonald and Harbaugh (1988) developed three dimensional finite difference groundwater flow model called “MODFLOW” which is extensively used.

The finite element method is based on an integral approach. The fundamental idea of the method is to replace the exact continuous solution of the original partial differential equation by an approximate piecewise continuous function. The piecewise continuous function is specified by a set of coefficients defined at a finite number of discrete points called nodes. Functional values between these points are calculated using the piecewise continuous interpolating functions defined over a finite number of sub-domains called elements. Certain advantages of this approach include

- (i) Ability to handle complex heterogeneities and anisotropy
- (ii) The boundaries can be more adequately defined when rapid changes occur at these boundaries, by reducing the element size, as it facilitates the approximate numerical solution becoming closer to true solution, and
- (iii) The method derives its power from the fact that it uses a very general technique for the evaluation of spatial gradients in any direction at any point within the flow domain.

The finite element method has developed into a very powerful numerical tool for analysing a variety of groundwater flow problems since its introduction into groundwater hydrology in the mid 1960's. By early 1970's with the advent of mini computers, the finite element method became an every day tool for the practising engineer (Narasimhan and Witherspoon, 1982).

The concept adopted in the FEM is to use a set of non-collinear points to define the spatial variation of a piecewise continuous function. Depending on the number of points used (Minimum three for two dimensions and four for three dimensions), simple triangular and tetrahedral elements in two and three dimensions respectively are formed. These elements permit first degree approximation to the variation of the desired spatial variable. Then isoparametric elements are introduced which lead to higher order approximations to define the spatial variability of function of interest by increasing the number of non collinear points to define the element (Ergatoudis *et al.*, 1968).

The capabilities of finite element method was amply demonstrated by Sreenivasulu *et al.* (1984) by developing a Digital model for the aquifer of Korata basin in Karimnagar district, Andhra Pradesh. This model was used to predict the future water levels due to contemplated pumping activity. Rao and Sarma (1993) used the finite element groundwater flow model for the command area of 53L canal of Sri Ram Sagar Project.

2.3 PREDICTION OF POLLUTANT LOADS TO GROUNDWATER FROM RICE FIELDS

Leaching of $\text{NO}_3\text{-N}$ from nitrogenous fertilizers and other N sources applied to crops plays an important role in the $\text{NO}_3\text{-N}$ contamination of unconfined aquifers (Gormly and Spalding, 1979; Spalding *et al.*, 1982; Hallberg, 1989, Spalding and Exner, 1993). The transport and transformations of fertilizers and pesticides in soils constitute major components in predicting pollution loads to groundwater. Efficiency of use of N-fertilizer is low in rice and usually ranges from 20 to 40% recovery by the crop, depending on N source, management practices and agroecological conditions (Craswell and Vlek, 1979; Sahrawat, 1979a; De Datta, 1987). The standing water depth of 5 to 7 cm maintained in paddy fields during the entire crop season, helps in leaching of applied N

beyond root zone along with percolating water and eventually it reaches the groundwater body. Nitrogen fertilizer when applied to flooded rice, enters a unique soil-plant-water atmosphere system and is subjected to a complex set of transformation processes that occur in the different zones of an idealized flooded soil-water system. Nitrogen transformations in submerged conditions are markedly different from those taking place in drained soils and affect not only the amount of N available for biological activity, but also influence global N budgets.

To effectively address $\text{NO}_3\text{-N}$ leaching and groundwater contamination from rice fields, an understanding of various processes of N-transformations is essential. The various processes involved are urea hydrolysis, ammonia volatilization, mineralization and immobilization process, nitrification, denitrification, leaching and uptake. The sequence of occurrence of these processes and their inter-relationships are shown in Fig. 2.1. These processes are characterized and quantified by their respective rate constants (Table 2.1). The individual processes are briefly discussed in the following paragraphs.

2.3.1 Urea Hydrolysis

Urea is widely used N fertilizer for rice in India due to its high analysis and greater subsidized market value. Hydrolysis is the first step of urea transformation which converts it into inorganic ammonium form. This is brought about by the enzyme urease and releases ammonium and carbon dioxide under both flooded and nonflooded conditions. However, rapidity of urea hydrolysis is responsible for different kinds of losses, which may take place during its subsequent transformations. The reaction of urea hydrolysis process is given as follows:

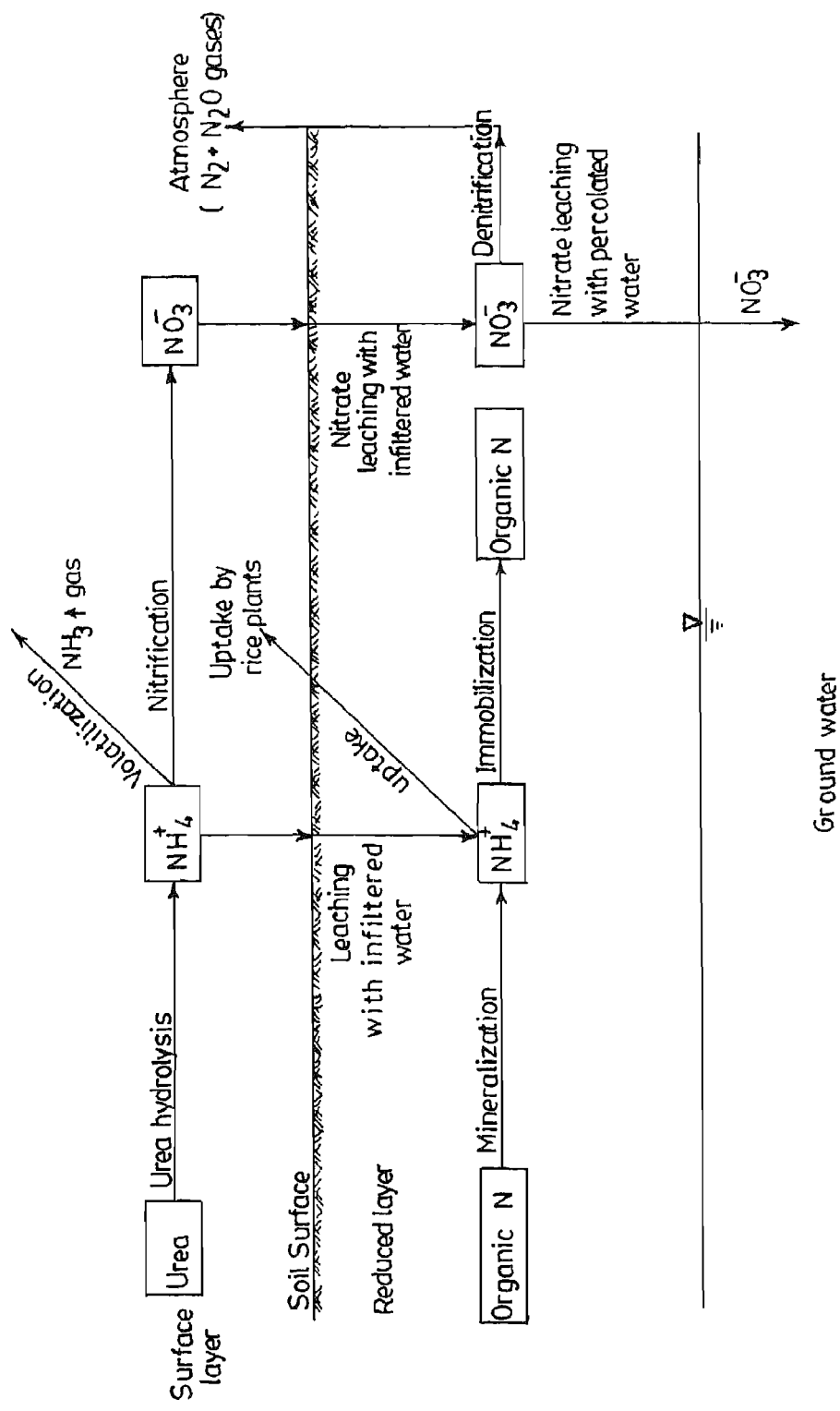
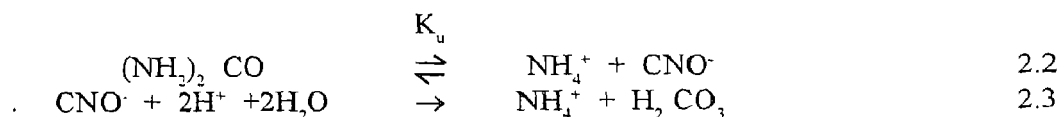


Fig2.1 Schematic representation of the N - Transformations in flooded rice field

Table 2.1 Rate constants for different N-Transformation processes

Process	Rate constant	Source
Urea hydrolysis	10^{-6} to 5×10^{-5} /sec	Rachpal Singh (1993)
	Standard 10^5 /sec	Sahrawat (1980), Savant <i>et al.</i> (1985)
	0.744/day	Jena and Mishra (1990)
Volatilization	1.27×10^{-3} - 1.54×10^{-4} /day	Chin and Kroontje (1963)
	0.25-0.30/day	Jemison <i>et al.</i> (1994)
	0.1-0.8/day	Hutson and Wagenet (1991)
	0.043-0.065/day	Singh and Prasad (1992)
Nitrification	0.2/day	Jansson and Anderson (1988)
	0.2/day	Johnsson <i>et al.</i> (1987)
	0.02-2.0/day	Rao <i>et al.</i> (1984)
	0.14-1.10/hr	Mishra and Misra (1991)
	0.04-0.06/hr	Jena and Misra (1990)
Mineralization	0.02/day	Jemison <i>et al.</i> (1994)
	0.005-0.04/day	Hutson and Wagenet (1991)
	0.0126-0.0373/day	Seyfried and Rao (1988)
	0.0077/day	Stanford and Smith (1972)
	0.019/day	Pathak and Sarkar (1995)
	2×10^{-2} /day (flood water)	Rao <i>et al.</i> (1984)
	2×10^{-2} /day (oxidized water)	
	7.5×10^{-4} /day (reduced soil layer)	
Denitrification	0.13-0.18/day	Reddy <i>et al.</i> (1978)
	0.1/hr	Misra and Mishra (1977)
	0.1/day	Johnsson <i>et al.</i> (1987); Jemison <i>et al.</i> (1994)
	0.2/day	Jansson and Anderson (1988)
	0.0027-0.0067/day	Rolston and Marino (1976)
	0.02/hr	Jena and Mishra (1990)
	0.07-0.08/hr	Mishra and Misra (1991)
	0.05-0.4/day	Hutson and Wagenet (1991)

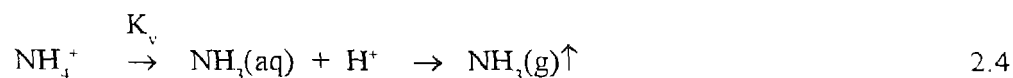


Where K_u is the urea hydrolysis rate constant, day^{-1}

A wide range of factors affect urea hydrolysis and it is important to know how they do so to provide a basis for predicting the fraction of applied N that is reaching the groundwater. The rate of urea hydrolysis depends on many factors, such as urea concentration (Sankhyan and Sukla, 1976; Caberera *et al.*, 1984), physico-chemical properties of soil *viz.*, soil pH (Beri *et al.*, 1978; Sahrawat, 1980) salt concentration of the soil (Chandra and Abrol, 1972), soil temperature (Mitsui, 1973), organic matter content (Paulson and Kurtz, 1969; Verstraeten, 1978; Connolly *et al.*, 1980; Pal and Chonkar, 1981; Tomar *et al.*, 1985), moisture content of soil (Overrein and Moe, 1967; Delaune and Patrick, 1970; Saregumba *et al.*, 1978; Bajpai *et al.*, 1984), etc. The magnitude of urea hydrolysis at a particular time will have significant influence on the subsequent major nitrogen transformation processes such as ammonia volatilization by affecting pH and NH_3 concentration of flood water.

2.3.2 Ammonia Volatilization

The inorganic NH_4^+ results from urea hydrolysis is subject to the process of ammonia volatilization. This refers to its conversion to ammonia gas and the transfer of ammonia gas to the immediate atmosphere. This reaction is generally governed by the following equations (Vlek and Stumpe, 1978):

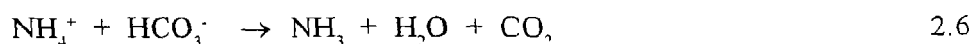


Where K_v is the volatilization rate constant, day^{-1} .

Because NH_3 volatilization is an inherently acidifying process (H^+ generating), alkalinity must be present in the flood water to sustain NH_3 fluxes. Urea hydrolysis provides a source of alkalinity (HCO_3^-) which accepts protons undergoing the reaction



Combining reactions 2.4 and 2.5



The stoichiometry of reaction is such that equivalent amounts of NH_4^+ and HCO_3^- are consumed in the reaction. Thus the amount of HCO_3^- in the surface water sets an upper limit to the amount of NH_4^+ that can possibly be volatilized. Therefore, when urea is applied to the soil, it undergoes hydrolysis and generate HCO_3^- which accounts for the higher NH_3 losses from urea than from ammonium fertilizers (Vlek and Craswell, 1979; Fillery and DeDatta 1986, De Datta, 1987, Rao, 1987).

Agronomic variables such as the source of N, its application method, time and depth of placement have significant influence on NH_3 volatilization. The potential of NH_3 emission was highest when urea was broadcast into flood water soon after transplanting. Actual losses measured ranged from 11 to 47% of N fertilizer applied (Fillery *et al.*, 1984; Simpson *et al.*, 1984; 1985; Fillery and De Datta, 1986; De Datta, 1986). When urea is broadcast and incorporated into puddled soil, especially in the absence of water, NH_3 emission is reduced to 5-13% of the applied N (Freney *et al.*, 1981, Fillery *et al.*, 1984; IRRI, 1987). Volatilization losses reported for different Indian conditions are given in Table 2.2. Deep placement of urea super granules (USG) has proved effective in reducing NH_3 concentrations in flood water and drastically reduces NH_3

Table 2.2 Reported volatilization losses from flooded soils in India

Location	Texture	pH	Organic Total		CEC	Rate of application (kg/ha)	Volatilization		Source
			C(%)	N			Kg/ha	%	
Pusa (Bihar)	Clay loam	8.3	0.45				3.6	7.3	Prasad and Singh (1992)
Pusa	Clay loam	8.3	0.45			60		12	Singh and Prasad (1991)
IARI	Clay loam	high			43.9	120		16-25	Purakayastha <i>et al.</i> (1995)
Pant Nagar	Silty Clay loam	7.6			22.3	90	16-19	18-20	Mishra <i>et al.</i> (1990)
Pant Nagar	Silty Clay loam	7.7	1.28		39.3	100		11	Reddy <i>et al.</i> (1986)
Pant Nagar	Sandy Loam	8.0	1.07			100		15-19	Reddy and Mishra (1983)
Karagpur	Sandy Loam	5.2			6.0	120	10-14.3		Mandal and kar (1995)
Mandya	Sandy Loam	6.7	0.41			116		3.5-4.2	Geethadevi <i>et al.</i> (1991)
Pant Nagar	Sandy Loam	8.0	1.07		19.8	100		15.9	Reddy <i>et al.</i> (1986)
Cuttack	Sandy clay loam	5.8-6.1			14-15.1	60	4.3	7.2	Mahapatra <i>et al.</i> (1991)
Pattambi	Sandy clay loam	5.4	2.11			90		2-6.7	Joseph <i>et al.</i> (1993)
IARI	Sandy clay loam	7.7	0.48			120		8.37	Sudhakara and Prasad (1986)
CSSRI	Coastal saline	7.5	0.86			100	15.2		Sen and Bandyopadhyay (1986)
(West Bengal)									
CAZRI (Bikaner)	Sandy soil	8.2	0.15		7.9		100	20.4	Sharma and Gupta (1989)
Hisar	Typic Comborthid	8.0			11.6			16-19	Singh <i>et al.</i> (1995)
	Typic ustrochrept	7.7			15.8			15-17	Singh <i>et al.</i> (1995)
Pant nagar	Sandy clay loam	7.4	1.15		22.9		100	12.8	Reddy <i>et al.</i> (1986)

volatilization (Vlek and Craswell, 1981; Cao *et al.*, 1984; De Datta *et al.*, 1987a,b; Rao, 1987). Savant *et al.* (1982) and Rao (1987) evaluated slow release-coated materials for NH_3 emissions in flooded soil and found that they are also effective in minimising the NH_4^+ concentration in the flood water and subsequently NH_3 loss.

Few simulation models have been developed to predict Volatilization loss of ammonia from flooded soil systems (Jayaweera and Mikkelsen, 1990). The NH_3 volatilization loss followed closely the pattern of urea hydrolysis and may follow zero order or first order kinetics (Rao *et al.*, 1984; McInnes *et al.*, 1986; Hutson and Wagenet, 1991).

2.3.3 Mineralization and Immobilization

While urea hydrolysis and volatilization occur in the flood water, mineralization and immobilization are N-transformation processes which occur simultaneously in the flooded soil. N mineralization is defined as the transformation of soil N from the organic state into the inorganic forms of NH_4^+ or NH_3 . The process is performed by heterotrophic soil organisms that utilize nitrogenous organic substances as an energy source. Whereas N immobilization is defined as the transformation of inorganic N compounds (NH_4^+ , NH_3 , NO_3^- , NO_2^-) into the organic state. Soil organisms assimilate inorganic N compounds and transform them into organic N constituents of their cells, tissues and soil mass. In low land rice soils, information regarding immobilization is more limited as compared to aerobic soils (Kai and Wada, 1979), and it is generally accepted that balance between these two opposing processes greatly influences N availability to plants. The governing equations for both the processes are given as follows;



Where K_m = Mineralization rate constant, day^{-1} , and

K_i = Immobilization rate constant, day^{-1}

Important factors that affect the mineralization - immobilization processes are temperature, moisture regime and C/N ratio. The importance of these factors on the rate of net mineralization under conditions was emphasised by many scientists (Broadbent, 1978; Die and Yamasaki, 1979; De Datta, 1981; Jansson and Persson, 1982; Sahrawat, 1980, 1983; Keeney and Sahrawat, 1986). Other parameters which also have some influence on mineralization - immobilization of applied nitrogen in rice field are rate of application of fertilizer N (Craswell *et al.*, 1985), placement of fertilized N (Voinova Raikova, 1977), nature of fertilizers (Bunyakina, 1976) and magnitude of different organic N fraction under submerged and aerobic conditions (Asami, 1971). Measurements in flooded soils showed 10 to 60 per cent of added inorganic N being immobilized within 20 days depending on the soil properties (Broadbent and Tusneem, 1971; Yoshida and Padre, 1975; Kai and Wada, 1979; Savant and De datta, 1980,1982). Thus immobilized N acts as a slowly available N source and at times may be helpful in locking up mineral N from chemical and biochemical reactions which lead to nitrogen loss. Koyama (1975) reported that about 30 per cent of the basal dressed N was initially immobilized in low land rice soils even when no crop residue was applied, and about one third of this amount was remineralized and made available to rice plants.

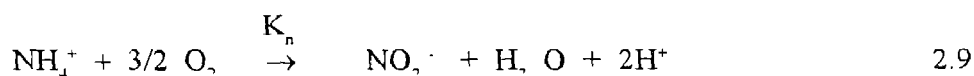
Both these processes can be combined and modelled to zero order or first order kinetics. First order kinetic model was used by Stanford and Smith,

(1972); Mehran and Tanji, (1974); Johnsson *et al.*, (1987); Stockle and Campbell, 1989; Borg *et al.*, (1990). Tabatabai and Al-Khafaji (1980) considered mineralization process as zero order kinetics. Seyfried and Rao (1988) developed a kinetic model by combining first order and zero order models for modelling mineralization process.

2.3.4 Nitrification Process

Nitrification is defined as microbially mediated reaction involving the oxidation of NH_4^+ to NO_3^- . It occurs in rice fields in the oxidized zones. The significance of nitrification leading to NO_3^- loss in flooded rice soils had been recognized as early as in 1935 by Shioiri (as cited by Mitsui, 1954).

The nitrification reaction is given by



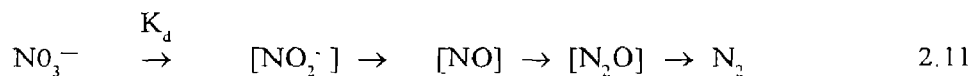
Where K_n is the nitrification rate constant, day^{-1} .

In flooded rice soils, the substrates for nitrification are provided through ammonification (organic N to NH_4^+) and chemical fertilizer application. Nitrification can potentially occur in the flood water above a soil surface (Broadbent and Tusneem, 1971; Patrick and Gotoh, 1974), the surface oxidized soil layer (Reddy and Patrick, 1986, 1986a) and the oxidized rhizosphere of rice (Armstrong, 1964). The extent of N losses through nitrification process in flooded soils is governed by the supply of NH_4^+ to oxidized zones where nitrification occurs. Several factors, including soil pH , organic matter content, temperature, O_2 diffusion and mineralization rate of soil affect nitrification rates in flooded soils. It has been generally reported that low pH inhibits nitrification (Prasad

et al., 1971; Goswami and Sahrawat, 1982). Nitrification loss varies from 0 to 60% of the applied N (Mitsui, 1954; Broadbent and Tusneem, 1971). Nitrification process was modelled as first order kinetic reaction by Mehran and Tanji, 1974; Watts and Hanks, 1978; Rao *et al.*, 1984; Stockle and Campbell, 1989; Hutson and Wagenet, 1991; Stockle and Campbell, 1994). Verma *et al.*, (1995) considered zero order for nitrification process.

2.3.5 Denitrification

Denitrification is the major biological process through which fixed N is returned from the soil to the atmosphere. This reaction is known to occur in rice fields where reduced zones exist. Under O_2 free conditions, many microbes can utilize NO_3^- as a terminal electron acceptor in a process called NO_3^- reduction to gaseous end products (N_2O , N_2) is usually known as denitrification. The denitrification process is given as :



Where K_d is the nitrification rate constant, day^{-1} .

Several factors like soil pH, temperature, organic matter content and nitrification rate of soil affect denitrification rate in flooded soils. Denitrification proceeded at a faster rate in soil with p^H of 7 or above (Goswami and Sahrawat, 1982). Similarly, higher the temperture, the greater the denitrification rate in soils (Mangaraj and Mishra, 1978).

Most of the experimental studies on denitrification losses are indirect and have been carried out either in laboratory or in green houses, because it is extremely difficult to measure oxides of nitrogen directly in fields. This is because 80% of the atmosphere constitutes N_2 , the main product of denitrification. Gaseous loss as N_2 and oxides of N ranged from 0 to 60% of the applied N

(Mitsui, 1954; Patnaik, 1965; Broadbent and Tusneem, 1971; Datta *et al.*, 1971; Daftardar, 1973; Krishnappa and Shinde, 1980, Simpson *et al.*, 1984). Extensive review on simulation models to predict the denitrification losses was given by Rolston (1990). Many investigators have reported that denitrification followed first order kinetics (Mehran and Tanji, 1974, Stockle and Campbell, 1989; Saleh, 1994, Verma *et al.*, 1995).

2.3.6 Leaching of Nitrate

Nitrate leaching is an important channel of N loss from paddy fields. The nitrate originates from mineralization of soil organic N, crop residues and the applied inorganic fertilizer N. Nitrogen loss by leaching usually takes place in NO_3^- form (Johnson, 1987; Borg, 1990; Aulakh and Singh, 1997). N in ammonium form is largely immobile with respect to leaching (i.e. largely fixed to soil colloids) and is not transported by water flow (Krantz *et al.*, 1943; Broadbent *et al.*, 1958; Wiklander, 1977).

Pande and Adak (1971) reported leaching losses of fertilizer nitrogen in paddy soils ranging from 45 to 70 per cent from basal application. These losses could be reduced from 11 to 33 percent by split application. Koshima (1975), while reviewing field lysimeter experiments in Japan reported leaching losses from 3.4 to 25.4 per cent of applied N. Leaching losses reported for different Indian conditions are given in Table 2.3

Many models of leaching have been developed over the years. These were reviewed extensively by Addiscot and Wagenet (1985). More sophisticated approaches, better suited for controlled research studies are generally based on some form of the convection - dispersion equation (Rose *et al.*, 1982; Smith, *et al.*, 1984).

Table 2.3 Reported leaching losses from flooded paddy fields in India

Location	Texture	pH	Organic C(%)	Total N	CEC	Rate of application (kg/ha)	Leaching		Source
							Kg/ha	%	
Kalyani (West Bengal)	Silty clay loam	8.4	1.23	0.11	24.5			10.7	Santra <i>et al.</i> (1994)
Kharagpur	Sandy Loam					120		27-49	Mandal and Kar (1991)
Bhubaneshwar (Orissa)	Sandy Loam	5.1	0.48			60		4% (for 2 days)	Jena and Misra (1990)
Kharagpur	Sandy loam	5.2			6	120	37-52		Mandal and Kar (1995)
Mandya	Sandy loam	6.7	0.41	0.028		116		9-14	Geethadevi <i>et al.</i> (1991)
Tabmirabani tract (TNAU)	Sandy clay loam	8.1	0.48		18-21	125	9.9		Suresh <i>et al.</i> (1994)
Pattambi	Sandy clay loam	5.4	2.11			90	7-8		Joseph <i>et al.</i> (1993)
Palampur	Alfisol					90	11-34		Bhagat <i>et al.</i> (1988)
Raichur	Typic Haplaudalf							12.4	

$$\frac{\partial C}{\partial t} = \frac{D \partial^2 C}{\partial Z^2} + \frac{V \partial C}{\partial Z} \quad 2.12$$

Where C = concentration of nitrate in the soil water,

D = dispersion coefficient,

t = time variable,

Z = soil depth, and

V = average velocity of pore water.

Simplified nitrate leaching approaches use the "piston displacement" concept, i.e. soil water above field capacity initially present in the profile is displaced ahead of the water entering the soil surface (Burns, 1975; Addiscott, 1977; Davidson *et al.* 1978; DeSmedt and Wierenga, 1978,). A useful leaching equation developed by Burns (1975) gives the fraction f , of nitrate or a similar solute that is washed below a depth h cm by the percolation of P cm of rain

$$f = \left(\frac{P}{P + (V_m/100)} \right)^h \quad 2.13$$

Where f = fraction of the surface applied nitrate (f) leached below the depth (h),

V_m = percentage of V numeric field capacity

P = percolation, and

h = thickness of soil profile

Few Stochastic models are also available for leaching process (Dagan and Bresler, 1979; Jury, 1982; Wagenet and Rao, 1983).

2.3.7 Nitrogen Uptake by Rice Plants

For submerged rice, NH_4^+ is the dominant mineral N form and NO_3^- contributed little to N-nutrition (Sahrawat and Burford, 1982; Mengel *et al.*, 1986; Brandon and Wells, 1986; Aulakh and Singh, 1997). Several factors such as climate, soil properties, amount and type of fertilizer applied, rice variety, relative

distribution of inorganic and organic N fractions in the soil profile and management practices have significant effect on total nutrient requirement and uptake (Yoshida, 1981). An ordinary rice plant absorbs 19-29 Kg N/ha¹ per tonne of brown rice or about 50 kg N/ha per tonne of rough rice (Murayama, 1979; De Datta, 1981; Yoshida, 1981). Murayama (1979) observed that rice plant absorbs 50-60 per cent of its total N absorption at panicle initiation, 70-80 per cent of heading and 20-30 per cent during ripening period. He also reported that average values for soil N supply to flooded rice vary within 50-70 kg N/ha. Uptake of N in paddy fields, for different geographical locations of India was given in Table 2.4

A potential nitrogen uptake function to determine the maximum uptake for nonlimiting soil water and nitrogen availability was developed from field data by Watts and Hanks (1978). The movement of soluble soil N to the root system is accomplished both by convective or mass flow and by diffusion (Barber, 1962; Olsen and Kemper, 1968; Nye, 1977). Mass flow has been considered by many to be the predominant mechanism (Barber and Olsen, 1968). Liao and Bartholomew (1974) gave direct evidence that diffusion can play a major role and under certain conditions can be the dominant mechanism in nitrogen transport to the root system.

Johnsson *et al.*, (1987) used a logistic uptake curve (Greenwood *et al.*, 1974) to define the cumulative potential N demand during the growing season. Verma *et al.*, (1995) assumed that nitrate is taken up by the plants in proportion to the crop water transpired. The nitrogen uptake by the plants is given by the following equation.

$$(DNTUP)_i = (ET)_i \times (NO_3-N)_i \times (F)_i \quad 2.14$$

Table 2.4 Reported uptake of Nitrogen by rice from flooded fields in India

Location	Texture	pH	Organic C(%)	Total N	CEC	Rate of application (kg/ha)	Uptake Kg/ha	Source
Rajendra Nagar (Hyderabad)	clay soil	8.5	0.66	0.098	57.8	100	89-120	Khind and Datta (1985)
Jabalpur	Clay loam	7.5	0.63			114	66-102.7	Dubey and Bisen (1989)
Cuttack	Clay loam	5.7	0.8	0.07	18.6		65-111	
Coimbatore	Clay loam					120 control	63.2 44.8	Sreedevi and Thangamuthu (1991)
Pant Nagar	Silty clay loam	6.8	0.52			120 control	71.8 26.2	Das and Singh (1994)
Pant Nagar	Silty clay loam	7.2	1.51	0.12	23.9	120 control	93.04 35.77	Singh and Singh (1989)
Bajaura	Silty clay loam	5.5-5.67	0.65-0.75			120 control	84.4-91.4 55.3	Mahajan and Tripathi (1992)
Pant Nagar	Silty clay loam	7.4	1.05	0.102		80 control	66-85 46	Mohapatra <i>et al.</i> (1983)
Pant Nagar	Silty clay loam	7.6			22.3	120 control	61.8-74.7 36.6	Mishra <i>et al.</i> (1990)
Pant Nagar	Silty Clay loam	6.8	0.52		20.2	120 control	124 50	Tahir and Singh (1994)
Karnal	Sandy loam	9.3-10.4				120	119.4	Singandhupe and Rajput (1990)
Pattambi	Sandy loam	5.32	1.08			120	86.4	Anil Kumar and John Kutty (1990)

contd.....

Location	Texture	pH	Organic C(%)	Total N	CEC	Rate of application (kg/ha)	Uptake Kg/ha	Source
Bhubaneswar	Sandy Loam	6.0-6.8				60	68	Panda (1993)
Bilaspur	Sandy loam	6.9				100 control	64-82 27-32	Shukla and Sharma (1994)
Pattambi	Sandy loam	5.6	1.38	0.123		control	50-60 28.44	Anila Kumar <i>et al.</i> (1994)
Cuttack	Sandy Loam	5.8	0.73	0.08		120 control	56-68 20.6	Mohapatra <i>et al.</i> (1983)
Kharagpur	Sandy loam	5.2				120	40-59	Mandal and Kar (1995)
Mandva	Sandy loams	6.7	0.41	0.028		116	52.2-70	Geethadevi <i>et al.</i> (1991)
Palampur	Fairly permeable					90 control	34-51.4 24	Bhagat <i>et al.</i> (1988)
Dapoli	Sandy loam		0.094			120	69.47	Thorat and Patil (1987)
IARI	Sandy clay Loam	7.5	0.45	0.068	8.7	120	96-121	Khind and Datta (1985)
Cuttack	Sandy clay loam	5.5	0.5	0.04		112	76-89	Chakravorti <i>et al.</i> (1989)
A.P.A.U. Hyderabad	Sandy clay loam	7.9				120	96.7	Ramaiah <i>et al.</i> (1986)
Thambirabam Tract	Sandy clay	8.1				125 control	76-119 33-61	Suresh <i>et al.</i> (1994)

Where $(DNTUP)_i$ = rate of nitrogen uptake from layer i ,
 $(ET)_i$ = evapotranspiration from layer i (m), and
 $(F)_i$ = Factor for approximating the amount of transpiration from layer i (0.5 for layer 1 and 2, and 1.0 for other layers).

2.4 SIMULATION OF POLLUTANT TRANSPORT IN GROUNDWATER

Once the nitrate leaches from the rice fields enter the groundwater system, its transport in groundwater can be by advection, dispersion, adsorption, decay or by chemical reaction. The incorporation of these transport mechanisms into groundwater model formulations is described in detail by Bredohoeft and Pinder (1973), Fried (1975), Anderson (1979) and Bear (1979). U.S. Geological survey method of characteristics (MOC) model was used for simulating flow and transport (Konikow and Bredehoeft, 1978). The model was two dimensional and applicable to problems involving depth-averaged, steady state, and transient flow in confined aquifers. The method of characteristics (MOC) is most useful where solute transport is dominated by convective transport, in which a particle and an associated mass of contaminant is translated a certain distance according to the flow velocity.

Guymon (1970) and Guymon *et al.* (1970) presented a variational approach to the dispersion equation in which the convective term does not appear explicitly. The approach, however, is limited to those mass transport problems in which the dispersion mechanism is much more significant than convection. Strecker and Chu (1986) used the method of characteristics (MOC) model of Konikow and Bredehoeft (1978) for simulating flow and solute transport combined with a quadratic programming formulation and estimated transmissivities, dispersivities from synthetic head and concentration data. However no statistical framework was developed for decreasing the reliability of the parameter estimates.

Wagner and Gorelick (1987) estimated flow and transport parameters simultaneously using a finite element flow and transport model combined with a quasi-Newton optimization algorithm. The procedures were formulated as a non-linear least squares multiple regression model with a quantification of the parameter uncertainty. They estimated the log conductivity, the effective porosity and dispersivities for a rather simple test sample consisting of synthetic homogeneous aquifer with steady state flow. Rashid *et al.* (1988) used a modified version of the United States Geological Survey model (Konikow and Bredehoeft, 1978) for simulating the hydrologic behaviour of the total dissolved solids (TDS) in terms of space and time. This model utilises the finite difference iterative alternating direction Implicit (AOI) scheme to solve the flow and transport partial differential equations. In SWICHA model (GeoTrans, 1990) domain, coupled flow and transport analysis is performed through picard iterations. Contrary to most of the previously reported transport studies, Keidser *et al.* (1990) extended the two stage method of Strecker and Chu (1986) to a field scale problems. Application resulted in rapid convergence and parameter estimates consistent with the geological deposits in the model area. Since no statistical analysis was carried out, quantification of the uncertainty of the parameter estimates could not be presented. Gaily *et al.* (1991) demonstrated a field application of the model presented by Wagner and Gorelick (1987). Wagner (1992) presented a inverse flow and transport model based on non-linear maximum likelihood theory. Fedler *et al.* (1989) used USGS method of characteristics model to observe movement of a conservative bromide tracer in an unconfined shallow aquifer. An application of inverse flow and transport model to a contaminated aquifer is presented by Torben *et al.* (1996).

2.5 LINKING SPATIALLY DISTRIBUTED INPUTS AND OUTPUTS TO SIMULATION MODELS

The above groundwater flow and solute transport models require inputs of spatially distributed inputs of recharge, pollutant loads and parameters. The model outputs are also spatially distributed. Geographical Information System (GIS) provide an efficient tool to deal with such spatially distributed inputs and outputs.

2.5.1 Geographical Information System (GIS)

Geographic Information Systems are computer based data input, management and display systems designed to handle large volumes of spatial information from a variety of sources. GIS provides the tools to generate store, manipulate, retrieve, analyze and display geo-referenced spatial and non-spatial data (Burrough, 1986). This facilitates distributed modelling of various processes. In GIS, successive analysis of spatial data can partition large heterogeneous areas into small hydrologically homogeneous units for which a model can be applied.

GIS applications were initially limited to data manipulation and map production. Recently, however, GIS have been used for environmental planning and natural resources management activities. GIS has been readily adopted as a planning tool as it allows spatial information from diverse sources to be displayed in an interactive manner that is readily comprehensible and visual. In natural resources management, a GIS can :

- (i) integrate spatial and non-spatial information within a single environment;
- (ii) offer a consistent framework for analyzing the spatial variability across landscapes

- (iii) allow connections to be made between entities based on geographic proximity and characteristics that are vital to understanding problems of nonpoint source pollution; and
- (iv) allow geographic entities to be manipulated and displayed in a variety of forms including reports, tabular/statistical summaries and maps ,
- (v) provide the linkage mechanisms between the models having different spatial representation;
- (vi) facilitate the conversion and standardization of data in a digital form of different scales and coordinate systems.

2.5.2 Interfacing GIS with Simulation Models

Geographical information systems have been linked to simulation models. Output from the GIS is organized as input to the model and output from the model is subsequently passed on to the GIS for display.

(a) Interfacing GIS with recharge estimation models

GIS has been coupled to a simple functional model of recharge to map a regional assessment of relative potential recharge (Boniol *et al.*, 1993, Fayer *et al.*, 1996, Rogowski, 1996). Maidment (1993) presents an excellent review of GIS applications in hydrologic modelling.

(b) Interfacing GIS with non-point source pollution models

Geographical information systems have been applied extensively in non point source pollution monitoring and control. Loague *et al.* (1990) have evaluated the linkage of soil property databases with groundwater leaching simulation models using GIS. Wilson *et al.* (1993) linked process based solute transport models with GIS for classifying soil mapping units for their susceptibility

to chemical leaching below the root zone or into shallow aquifers. Haan *et al.* (1993) linked chemical transport model (CMLS) with a weather simulation model and GIS. This system facilitated the site specific evaluation of leaching risks and evaluation of uncertainty in leaching risks because of soil spatial variability. Tim and Jolly (1994) closely coupled AGNPS model with ARC-INFO GIS.

(c) Interfacing of GIS with Groundwater flow and Transport models

GIS has been used successfully in groundwater problems and interfaced with other groundwater models and solute transport models. Schallar (1992) carried out groundwater and surface water quality studies by interfacing GIS with a two-dimensional groundwater model. Harris *et al.* (1993) and Wilson *et al.* (1996) reported on the integration of the ARC-INFO GIS with groundwater flow and contaminant transport models. Extensive reviews on coupling of GIS to simulate water flow and non point source pollutants in aquifers were covered by Corwin and Wagenet (1996) and Goodchild *et al.* (1993).

A point to note is that in nearly all the cases above, the linking between the models and GIS is loose. The models are not integrated within the GIS environment. Model development preceeds independently of the GIS and the linkages are provided only through the model inputs and outputs.

2.6 CRITIQUE

Assessment of groundwater recharge from rainfall and irrigation, estimation of pollutant loads from applied fertilizers, and assessing the response of the underlying aquifer to recharge and pollutant loadings are central to formulating and solving the problem of groundwater pollution in irrigation project areas.

Groundwater recharge in irrigation project areas occurs mainly from percolation from cropped and fallow lands from rainfall, irrigation and seepage from the water distribution system. Most of the studies in India use empirical coefficients recommended by the CGWB for estimation of recharge from rainfall, canal seepage and percolation from irrigated fields. This method of estimation gives lumped value of groundwater recharge for a region and ignores its spatial and temporal distribution over the region. In order to incorporate spatial and temporal distribution of the relevant variables responsible for spatial distribution of recharge (rainfall, irrigation, soils, crops and weather etc.) newer technologies like GIS should be used to identify spatially homogeneous units over which models can run with independent data of some important soil and crop parameters and weather variables.

Similarly, for the estimation of seepage losses in the irrigation network, many simulation studies and packages are available for solving unsteady, non uniform flows in open channels. These are computationally cumbersome and require a lot of information about the system. Instead, simple analytical models yielding better forecasts of channel transmission losses are needed for the optimal use of water resources. Moreover, the knowledge of losses that are taking place at various sections in the canal network during conveyance are required for the estimation of actual quantity of water available at field levels

The response of the groundwater basin to recharge from seepage and return flow from fields is often modelled by 2-D horizontal flow models. Several finite difference algorithms for groundwater flow modelling have been developed during the past three decades. But, few models have been actually used in practice. Generally, representation of boundaries plays an important role in groundwater flow modelling. Use of finite element method, helps in representing irregular boundaries in a better way as compared to finite difference methods.

To estimate pollutant loadings into the groundwater, N balance is to be carried out in the rootzone, considering different N-transformations like urea hydrolysis, mineralization, volatilization, nitrification, denitrification, immobilization and uptake. All of these processes can be represented adequately by first order kinetics. Many of existing models of N - balance are developed for non paddy crops under aerobic conditions. A generalized model considering different processes under anaerobic conditions needs to be developed, to quantitatively predict leaching losses from rice fields and to draw up efficient guidelines to reduce the leaching losses.

From the review it was clear that majority of research was related to quantity aspects of groundwater flow. Recently, attempts have been made to assess potential groundwater pollution over large geographical regions. Many of the water quality models developed for estimating the movement of the contaminant in the aquifer are either non-spatially distributed or single event or field scale. Some of the large scale models have been verified with smaller scale experiments.

The use of GIS facilitates linking spatial data inputs and outputs to model. Independent simple models(eg for recharge etc.) have been linked successfully to GIS.

Thus, although the different components in the problem of estimation of NPS pollution of groundwater appear to have been researched in detail, their applicability in the overall integrated framework of pollution studies in irrigation project areas is yet to be fully explored. This will require developing suitable linkages between components, models and GIS. Simplifications of some of the models may be necessary so that they can be efficiently used in a broader context of developing an integrated computational scheme which facilitates operating the models in field situations. The feasibility of achieving this, is demonstrated in the subsequent chapters.

3. THE CASE STUDY AREA

The objective of the present study is to develop a generalized analytical framework for the mathematical formulation and solution of the non-point source pollution problem in irrigation project area. The components of the framework will include models for recharge, pollution loads, groundwater flow and transport, their interlinkages and linkages with GIS. The development and testing of this framework is carried out by taking a real irrigation project area where rice is the dominant crop as a case study. The Godavari Delta Central Canal Irrigation Project is selected for this purpose. The study area lies in the East Godavari district of Andhra Pradesh and forms a part of central Godavari Delta(Fig 3.1). Its hydrological boundaries are the river Gowthami in the east, river Vasistha and its branch Vainateyam in the west and bay of Bengal in the south east. For the present work, the clear area between the nearest streams of rivers Gowthami Godavari and Vasistha Godavari has been selected for the study. Geographically, the area is located within $16^{\circ}25'$ to $16^{\circ} 55'$ N latitude and $81^{\circ} 44'$ to $85^{\circ}15'$ E longitude, and measures 825 sqkm. It covers fully or partly eleven revenue mandals namely: Amalapuram, Ambajipeta, Allavaram, Atreyapuram, Ainavilli, Katretikona, Kothapeta, Mummidivaram, Ravulapalem, Uppalaguptam and P. Gannavaram.

3.1 CLIMATE

The normal annual rainfall of Central Godavari delta is 1142 mm. More than half of it occurs during the south-west monsoon season (i.e. June to September) A large portion of the rest occurs in October and November. A good network of rain gauge stations exists in the study area. Daily rainfall data from 1987 to 1995 of 7 stations, located within the study area, were used in

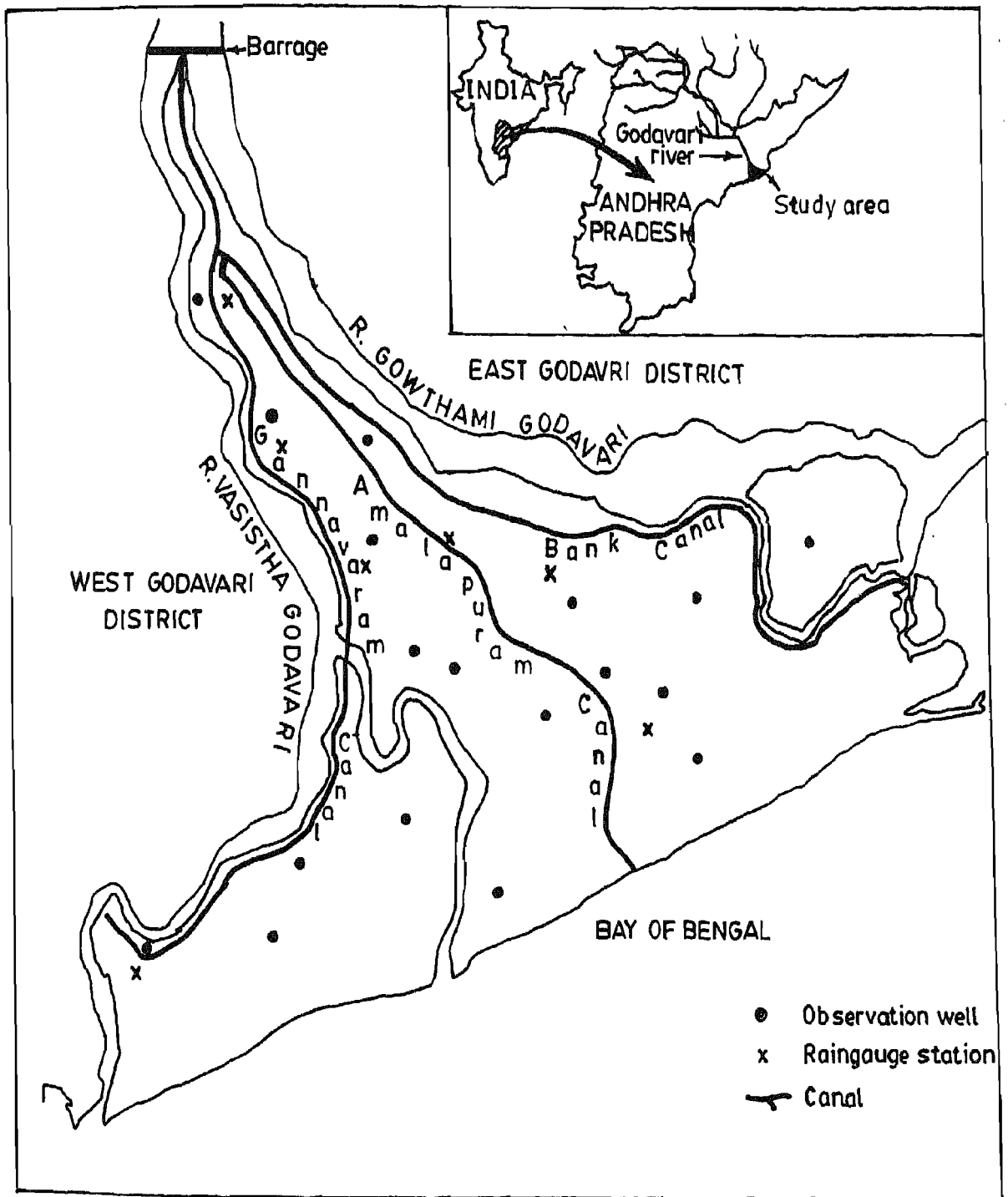


Fig. 3.1 LOCATION MAP OF GODAVARI DELTA CENTRAL CANAL IRRIGATION PROJECT, ANDHRA PRADESH

this study. Thiessen polygons were drawn around these stations (Fig 3.2) to delineate the area influenced by each rainguage station. The climate of the study area is comparatively equitable. The mean maximum temperature varies between 35° C to 37° C during summer and mean minimum temperature varies between 19° C to 21° C during winter.

3.2 TOPOGRAPHY AND SOILS

The study area is an alluvial plain formed by the river Godavari. It has a very gentle land slope of about 1 m per km. The coastal line along the study area measures about 40 km and the general elevation varies from about 2 m near the sea to about 13 m at the upper reaches. The topographical map of the area is given in Fig 3.3. Texturally, a major part of the study area consists of clay loams and sandy clay loam. The soil map of the study area is prepared by NRSA Hyderabad is given in Fig. 3.4. The hydrophysical properties of the soils in the study area are given in Table 3.1

Table 3.1. Hydro-physical properties of soils in the case study area

Soil texture	PWP mm/cm	FC mm/cm	saturated moisture content mm/cm	Saturated hydraulic conductivity mm/day
Clay loam	2.2	3.4	4.1	50.5
Sandy clay loam	1.5	3.2	3.9	70.5

3.3 CROPPING PATTERN

There are mainly two cropping seasons namely *kharif* and *rabi*. The study area is predominantly a rice growing area in both *kharif* and *rabi* seasons. The *kharif* season commences from 1st June when irrigation water is released through the canal system and extends up to November. The *rabi* season is from November

GODAVARI DELTA CENTRAL
CANAL IRRIGATION PROJECT

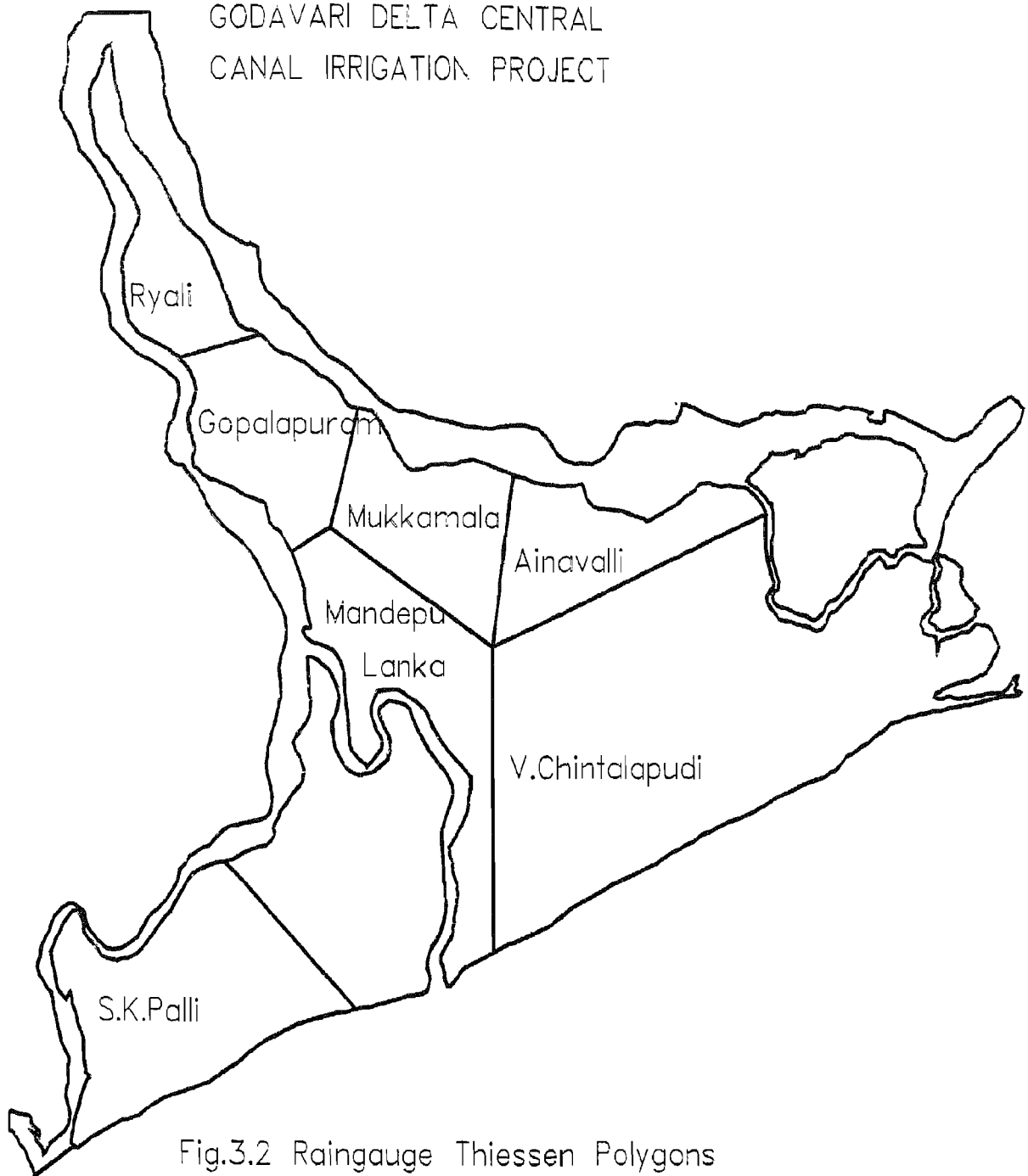


Fig.3.2 Raingauge Thiessen Polygons

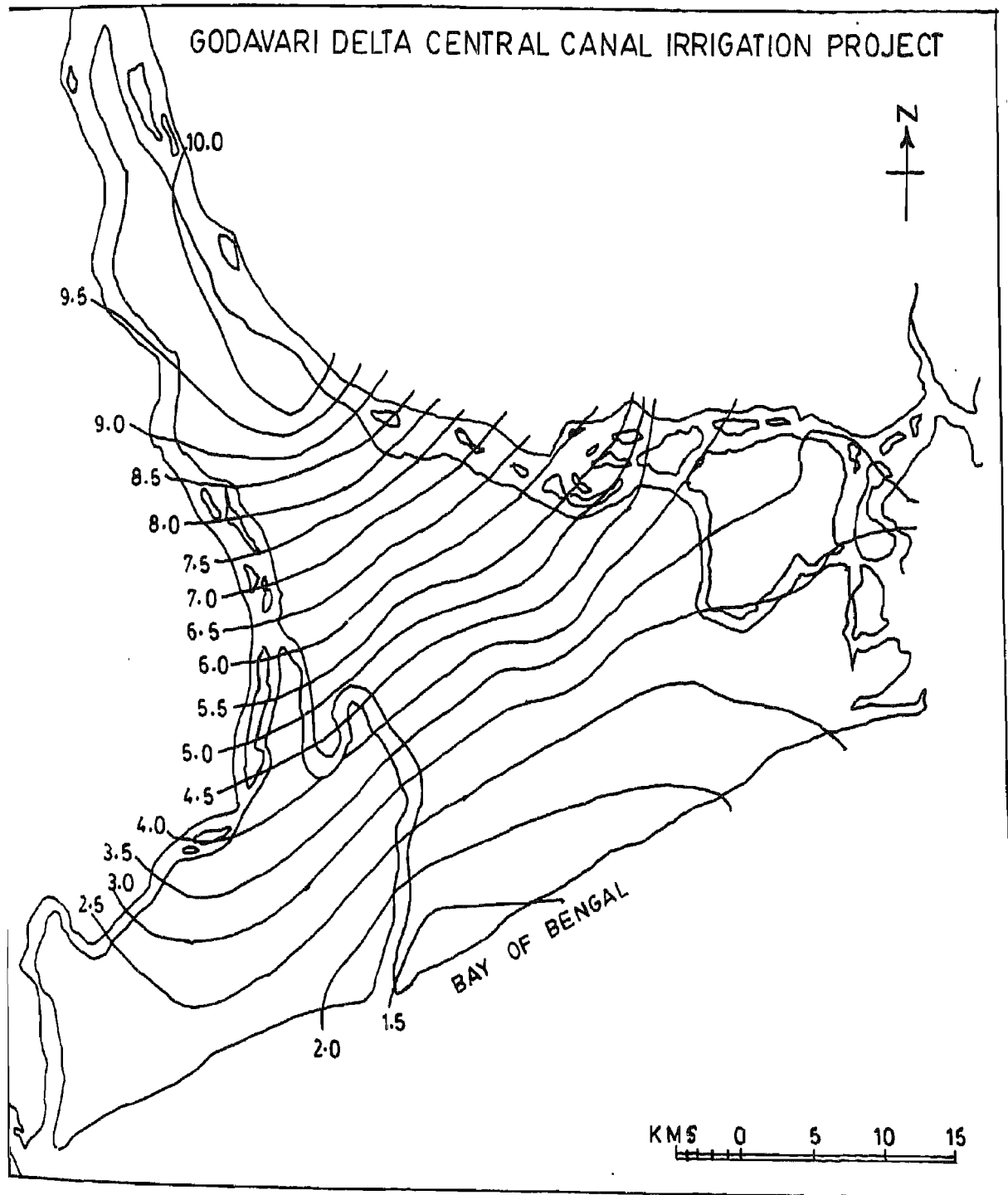


Fig.3.3 Topographical Map

GODAVARI DELTA CENTRAL
CANAL IRRIGATION PROJECT

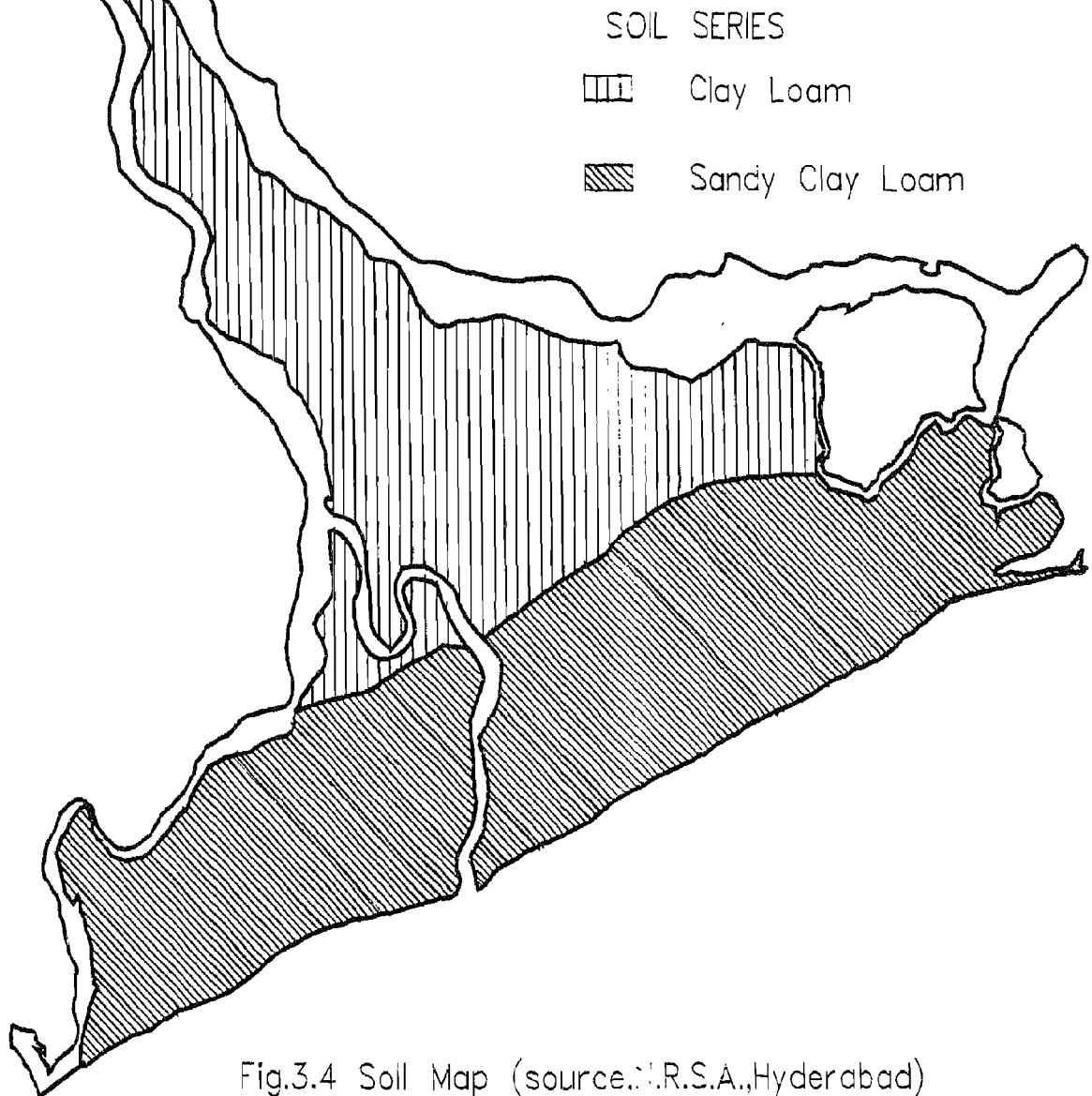


Fig.3.4 Soil Map (source: N.R.S.A., Hyderabad)

to April of the succeeding year. The most common cropping pattern in the study area is paddy-paddy and pulses or fodder crop. The net area sown forms about 68% of total geographical area under study. The gross cropped area is about 95,000 ha of which about 75% is occupied by paddy alone. About 15% of total area is under coconut plantations. There is no forest in the study area. Perennial crops like sugarcane and seasonal crops like maize, jowar, bajra etc. are found in patches. The land use and cropping pattern data for Central Godavari Delta is presented in Table 3.2.

Table 3.2 Cropping pattern in Godavari delta central canal irrigation project

Administrative blocks	Geographical area (acres)	Area (%)				
		Paddy		Sugarcane	Pulses	Coconut
		(Kharif)	(Rabi)			
Sakhinipalli	24886	39.58	38.23	-	10	18.8
Malkipuram	22128	26.39	25.19	-	8	28.46
Razole	19111	54	54	-	6	24.03
Mamidikuduru	19756	30.68	30.15	-	7	44.45
P Gannavaram	20710	35.72	34.22	4.8	14.1	33.48
Ravula Palem	17925	32.54	30.04	1.67	20.04	7.99
Aytreyapuram	21279	24.97	26.5	6.78	8.68	4.34
Kothapeta	19660	44.64	42.27	4.57	22.27	18.8
Ambajipeta	13721	28.0	28.0	-	6.29	57.4
Amalapuram	19917	46.0	41.58	-	13.03	34.6
Allavaram	25927	50.14	48.79	-	13.71	19.16
Uppalaguptam	29046	54.61	54.94	-	18.96	6.07
Ainavilli	23100	41.81	29.05	3.46	8.71	24.78
Mammidivaram	23559	40.89	4.86	-	17.55	27.74
Katritikona	33590	44.94	25.63	-	27.63	7.08

3.4 IRRIGATION

3.4.1 Canal Irrigation

The entire study area is under the command of Godavari Central Canal system. The irrigation system comprises one main canal taking off from the Sir. Arthur Cotton Anicut at Dhowleswaram and 3 branch canals namely Gannavaram canal, Amalapuram canal and Bank canal all taking off from Ryalli lock off the main canal. A number of channels take off from these branch canals at different chainages. The command areas of the main and branch canals are shown in Fig. 3.5. The canal system remains operational for 11 months with a closure period of one month during April-May. The design details of the canal, namely length, full supply depth, and full supply discharge are given in Table 3.3. Daily discharge data at the head of the main canal and branch canals were obtained from the State Irrigation Department and the data for the year 1995 are given in Appendix A. The area of rice crop under each canal during *khari*f and *rabi* seasons is given in Table 3.4.

3.4.2 Groundwater

Alluvial deposits occupy a major part of the study area. Groundwater in alluvium occurs generally under water table conditions. Water table levels in the study area vary from 0 to 7 m below ground level. The Water table gradient in the aquifer is towards the sea.

The yield of the tube wells tapping fresh water zones in the area varies from 2.22 m³/hr (at Alamuru) to 47.7 m³/hr (Devarapalli) for drawdowns ranging from 0.07 to 7.0 m. Water table levels vary from 2.44 m bgl (Vanampalli) to 5.90 m bgl (at Jonnada). The depth of the filter points which are being used for irrigation purposes varies from 10.0 m to 68.0 m below ground level but

GODAVARI DELTA CENTRAL
CANAL IRRIGATION PROJECT

 Amalapuram canal

 Bank canal

 Gannavaram canal

 Main canal

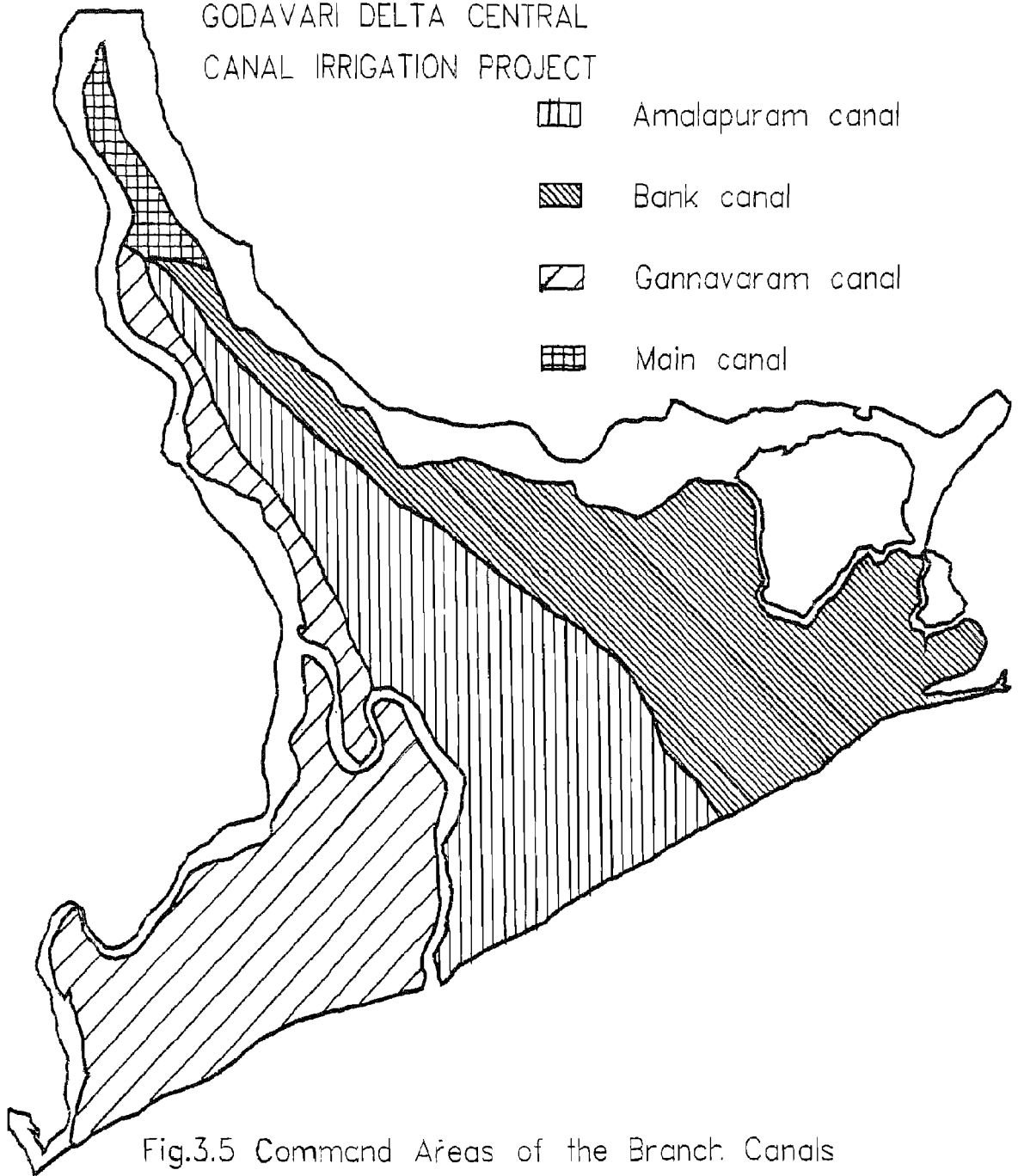


Fig.3.5 Command Areas of the Branch Canals

Table 3.3 Cross sectional details of canals in Central Godavari Delta Irrigation Project

Canal	parameters	Section 1	Section 2	Section 3	Section 4	Section 5
Main canal	Average bed width, m	32.03				
	Bed slope	5.2×10^{-5}				
	Section length, m	13280.0				
	Full supply level, m	2.49				
	Design discharge, cumec	104.89				
Amalapuram canal	Average bed width, m	15.555	15.555	12.650	10.590	5.5
	Bed slope	5.0×10^{-5}	2.05×10^{-5}	6.25×10^{-5}	5.59×10^{-5}	7.94×10^{-5}
	Section length, m	5400.0	12,200.0	17160.0	7330.0	8900.0
	Full supply level, m	2.26	2.675	2.01	1.975	1.86
	Design discharge, cumec	42.67	36.3	31.96	24.0	14.3
Gannavaram canal	Average bed width, m	15.25	12.81	13.5	5.7	5.1
	Bed slope	5.33×10^{-5}	5.0×10^{-5}	4.0×10^{-5}	7.7×10^{-5}	1.94×10^{-5}
	Section length, m	14120.0	12260.0	14400.0	7900.0	10000.0
	Full supply level, m	2.275	2.325	2.14	2.16	2.07
	Design discharge cumec	43.7	37.0	30.3	14.89	8.0
Bank canal	Average bed width, m	18.15	15.175	13.2		
	Bed slope	2.5×10^{-5}	3.33×10^{-5}	5.0×10^{-5}		
	Section length , m	9050.0	20950.0	19300.0		
	Full supply level, m	47.38	36.16	29.47		
	Design discharge, cumec	2.7	2.45	1.996		

Table 3.4 Rice cropped areas under each canal during *kharif* and *rabi* seasons in the study area, ha

Canal	Rice cropped area, ha	
	<i>kharif</i> season	<i>rabi</i> Season
Gannavaram canal	15936.7	15474.25
Amalapuram canal	19562.13	19318.00
Bank Canal	18081.58	11870.51
Main canal	54353.91	47436.26

generally within 20.0 m bgl. The total number of abstraction structures in the study area is about 5052 (Central Ground Water Board, CGWB, 1993).

3.5 GROUNDWATER QUALITY

Representative well water samples were collected from various locations covering the entire study area (Fig. 3.1) during the months of May and November 1995. Prewashed one litre polythylene bottles were used for sample collection and preservation. The water samples were analysed in the laboratory for nitrate levels. The location of observation wells along with the nitrate concentrations in the groundwater are given in the Table 3.5.

3.6 AQUIFER PARAMETERS

Only one pumping test has been conducted in the study area, in Uppalaguptam *mandal* by the A.P. state Groundwater Dept. and data of the coefficient of transmissivity and specific yield are available. The well log data for one well in Mandapeta *mandal* which is about 8 Kms from the study area is available with State Groundwater Dept. The available information for these two stations have been collected and are given in Appendix A. Transmissibility values of 3580 m²/day and 3826 m²/day have been obtained from the pumping

Table 3.5 Nitrate concentration of groundwater at different observation wells in the study area, ppm

S.No	Observation well	Administrative Block (Mandal)	Location of observation well	Nitrate concentration in the groundwater, ppm	
				may,1995	Nov.,1995
1	Sakhinetipalli	Sakhinetipalli	16°24'50"-81°45'15"	22.67	27.49
2	Malkipuram	Malkipuram	16°24'35"-81°48'37"	26.74	30.32
3	Razole	Razole	16°28'33"-81°50'38"	24.57	28.60
4	Mamidikuduru	Mamidikuduru	16°30'18"-81°55'18"	21.21	26.10
5	Mungonda	P. Gannavaram	16°36'-81°55'10"	41.30	45.69
6	Machavaram	Ambajipeta	16°35'50"-81°56'	42.85	50.03
7	Kundalapalli	P. Gannavaram	16°39'30"-81°54"	40.77	43.78
8	Ethakota	Ravulapalem	16°45'-81°49'30"	33.87	36.83
9	Kattunga	Atreyapuram	16°49'-81°46'	28.86	31.92
10	Mandapalli	Kothapeta	16°44'-81°53'	37.81	42.89
11	Ainavilli	Ainavilli	16°38'20"-82°1'	40.86	47.01
12	Mummidivaram	Mummidivaram	16°38'-82°5'35"	37.36	41.39
13	Cheyuru	Katritikona	16°35'40"-82°5'20"	16.47	20.01
14	Amalapuram	Amalapuram	16°34"-82°1'20"	18.64	22.67
15	Bendamurilanka	Allavaram	16°26'27"-81°58'27"	17.22	20.05
16	Uppalaguptam	Uppalaguptam	16°33'5"-82°5'48"	40.24	45.20
17	Ananthavaram	Mummidivaram	16°36'15"-82°3'30"	21.16	24.13

tests conducted at Surasani Yanam, Uppalaguptam mandal and Mandapeta respectively (NIH, 1992). Moreover the exploratory drilling in delta region has revealed that the shallow fresh water aquifers with high transmissivity values varying from 3798 to 6215 m²/day are confined to the area lying between Vasista and Gowthami starting from Devarapalli and Ambajipeta. The storativity values at Devarapalli and Ambajipeta area are 5.5×10^{-4} and 3.14×10^{-3} (CGWB, 1993) respectively.

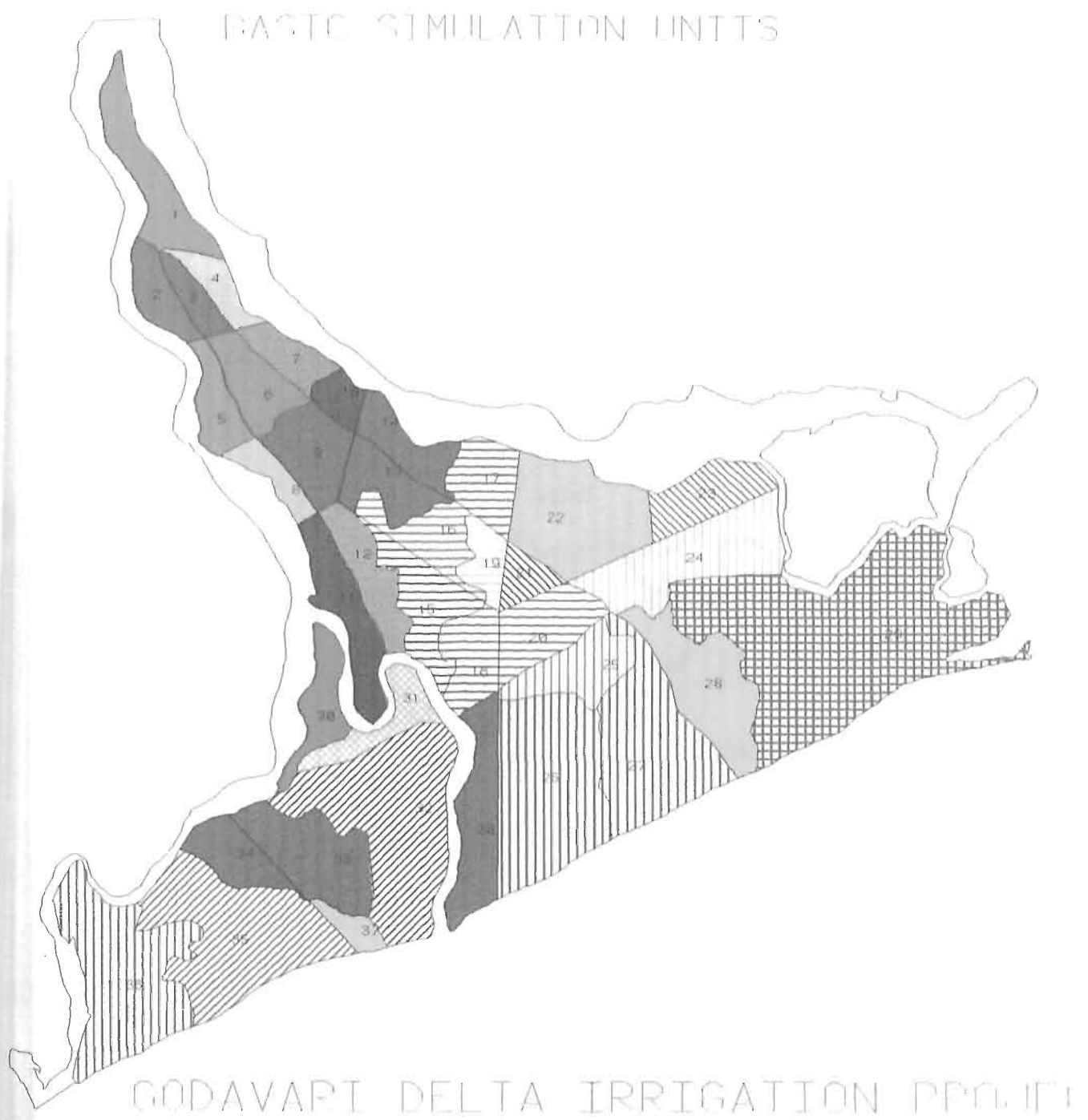
3.7 GENERATION OF BASIC SIMULATION UNITS (BSU) USING GIS

The spatial variability in topography, soil, climate, water resources and land management influence the response of natural systems and limits the applicability of most of the simulation models that are developed for homogenous units. Recent advances in GIS, a technology designed to store, analyze, manipulate, retrieve and display spatial and attribute data, provide the tools for organizing spatially variable model input data. The Geographical Information System (GIS) is used to create digitized maps of different input data. The Rainuage Thiessen polygens (Fig. 3.2), soil map (Fig. 3.4), canal command area map (Fig. 3.5) and *mandal* boundaries map (Fig. 3.6) were digitized using ARC-INFO GIS version 3.4.2. Using the analytical capabilities of ARC-INFO GIS, all these map layers were overlaid. The resulting thematic map comprised of 44 polygons. This map was edited to eliminate very small polygons and the final map consisted of 38 polygons (Fig. 3.7). Each polygon is homogeneous in respect to the input data of rainfall, soils, crop areas and water supplies. The simulation models of soil water balance and nitrogen balance can be run for each unit with the same input data of rainfall, soil parameters and canal supplies. Hence these polygons are termed as **Basic Simulation Units(BSU)**. The Polygon Attribute Table (PAT) file of the resulting BSU map generated by the GIS is given in Table 3.6. Thus by dividing the study area into a number of basic simulation units, the spatial non homogeneity is taken care of by using piece wise smaller homogeneous unit areas.

The daily soil water model (Chapter 4, Section 4.2) is applied over these Basic Simulation Units derived by GIS overlay helps in development of a recharge map, which serves as input to the ground water flow model. Further, nitrogen balance model (Chapter 5) is also applied over these units to provide a map of nitrate pollutant load which provide the input to the ground water transport model (Chapter 6).

T- 6303

Fig. 3.7



GODAVARI DELTA CENTRAL CANAL IRRIGATION PROJECT

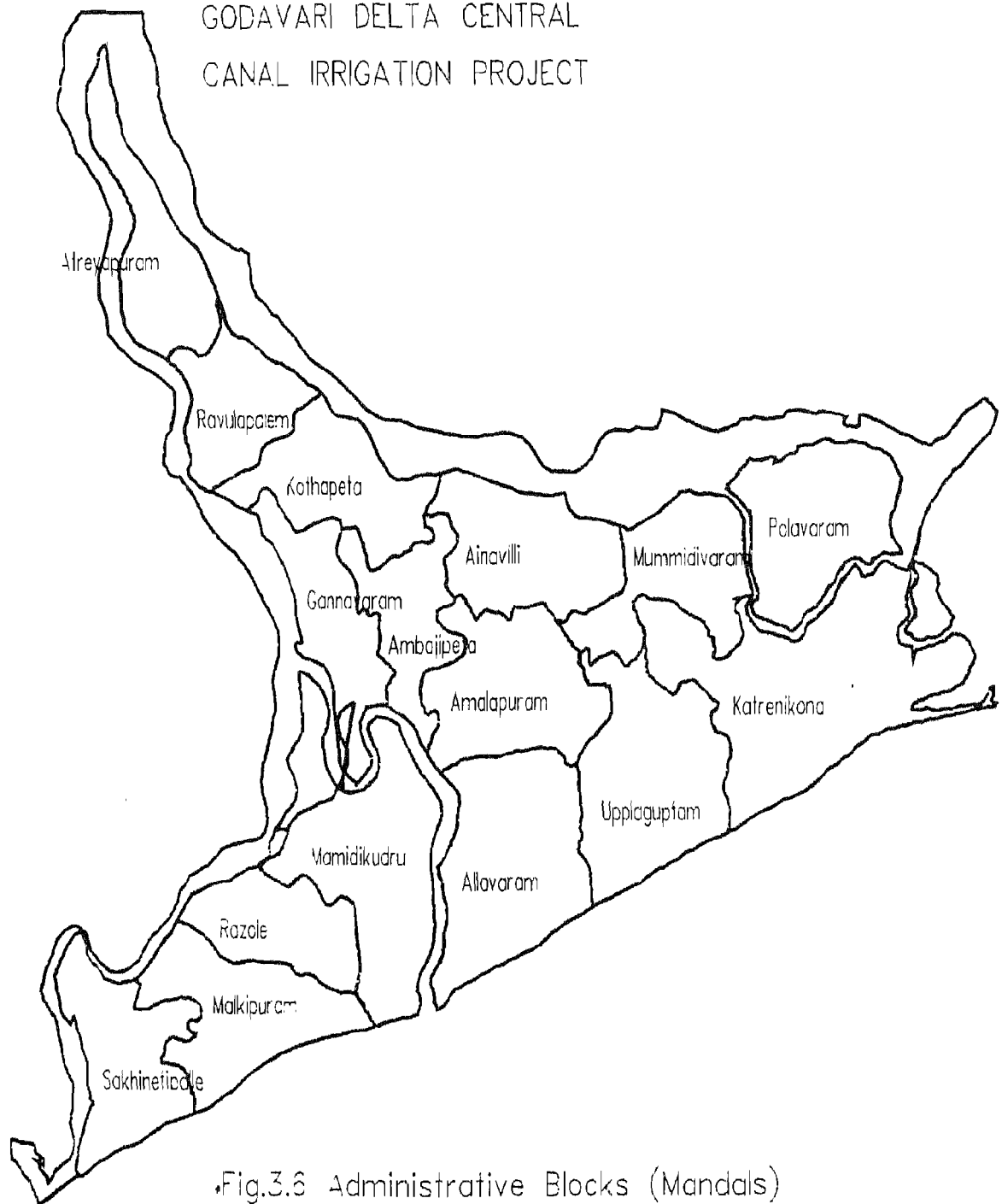


Fig.3.6 Administrative Blocks (Mandals)

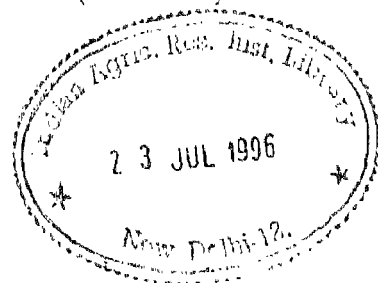


Table 3.6 Polygon Attribute Table (PAT) for the resulted Basic Simulation Units (BSU)

NPOLY	IDPOLY (BSU)	IDSOIL	IDRAING	IDMANDAL	IDCANAL
1	0	0	0	0	0
2	1	1	7	1	4
3	2	1	7	1	1
4	4	1	7	1	3
5	3	1	7	1	2
6	7	1	6	2	3
7	6	1	6	2	2
8	5	1	6	2	1
9	10	1	6	3	3
10	14	1	5	3	3
11	09	1	6	3	2
12	0	0	0	0	0
13	13	1	5	3	2
14	17	1	5	6	3
15	08	1	6	3	1
16	22	1	4	6	3
17	23	1	4	7	3
18	24	1	3	5	3
19	16	1	5	7	2
20	12	1	2	5	2
21	11	1	2	4	1
22	19	1	5	4	2
23	15	1	2	6	2
24	29	1	3	5	3
25	00	0	0	0	0
26	21	1	4	6	2
27	20	1	3	11	2
28	28	1	3	10	3
29	18	1	2	11	2
30	27	2	3	10	1
31	25	2	3	11	2
32	30	2	2	04	1
33	31	1	2	13	1
34	38	2	3	12	2
35	26	2	3	12	2
36	32	2	2	13	1
37	33	2	2	14	1
38	34	2	1	14	1
39	35	2	1	15	1
40	36	2	1	16	1
41	37	2	3	15	1
42	0	0	0	0	0

Index :

- Idraing : 1. Sakhineti palli, 2. Mandepu Ianka, 3. Chintalapudi, 4. Amavilli, 5. Mukkanala, 6. Gopalapuram, 7. Ryali
- ID canal : 1. Gannavaram canal, 2. Amalapuram canal, 3. Bank canal, 4. Main canal
- ID soil : 1. Clay loam, 2. Sandy clay loam

4. ESTIMATION OF GROUNDWATER RECHARGE

Seepage from the water distribution system (canals, branch canals and distributaries) and percolation losses from fields are the main source of groundwater recharge in irrigation project areas. Seepage losses depend on the canal geometry, discharge and the seepage rate coefficient which is a function of the material of the canal section. Percolation losses depend on rainfall, soils, crops, frequency and depth of irrigation. All of these vary spatially and temporally. But often, simple empirical methods are used in most practical situations to estimate recharge. For example, recharge from rainfall is estimated as 20-30 per cent of rainfall. Such lumped estimates are not acceptable when rainfall, soils, irrigation and crops are spatially varying.

In this chapter, physically based models are developed for the estimation of seepage and percolation losses in irrigation project command area. The spatial distribution of the soils, rainfall, crops and canal supplies is accounted for by dividing the project area into homogeneous land units using the capabilities of GIS and running the model for each BSU (Fig 3.7).

4.1 CANAL FLOW MODEL TO ESTIMATE SEEPAGE LOSSES

Generally a large amount of water supplies are lost as seepage during conveyance through the canal network. Elaborate procedures are required to determine the seepage losses in the canal sections. Normally, this approach is both expensive and not always feasible. In the absence of a systematic measurement of daily seepage losses in the canals, it is necessary to make logical estimates of these values. A simple model for estimating conveyance losses in canal based on the principles of hydraulics is developed. The simple model

proposed by Vyas and Sarma (1992) provided the basis for development of the present model

4.1.1 Model Development

Seepage losses vary with canal flow conditions. They depend primarily on the wetted perimeter and the seepage rate. The wetted perimeter is a function of depth of flow in the canal and depends on canal geometry and discharge through the section. As the flow in the section varies along the length of the canal, the depths of flow at the upstream and downstream ends as well as along the section would be different. An iterative procedure, together with the uniform flow equation was used to account for the variation of flows between the upstream and downstream ends of the section (Fig 4.1).

Let Q_1 and Q_2 respectively be the discharges (m^3/sec) in the canal at the upstream and downstream ends of a section of the canal. The computations for seepage losses between sections 1 - 1 and 2 - 2 (Fig 4.1) and discharge available at section 2 - 2 are carried out in the following sequential steps.

(i) Determination of depth of flow, D_1 , at head of the section

The depth of flow is estimated using Manning's equation for uniform flow,

$$Q_1 = A \cdot 1/n \cdot R^{2/3} S^{1/2} \quad (4.1)$$

where

- Q_1 = discharge at the head of the section, m^3/sec (Known value)
- A = area of cross section of flow ($A = BD_1 + ZD_1^2$), m^2
- B = bed width of canal section, m
- n = Manning's roughness coefficient
- R = hydraulic radius [$R = A/P$; $P = B + 2 D_1 \sqrt{1 + Z^2}$]
- P = Length of wetted perimeter, m
- S = Slope of the channel bed
- Z = side slope of the channel

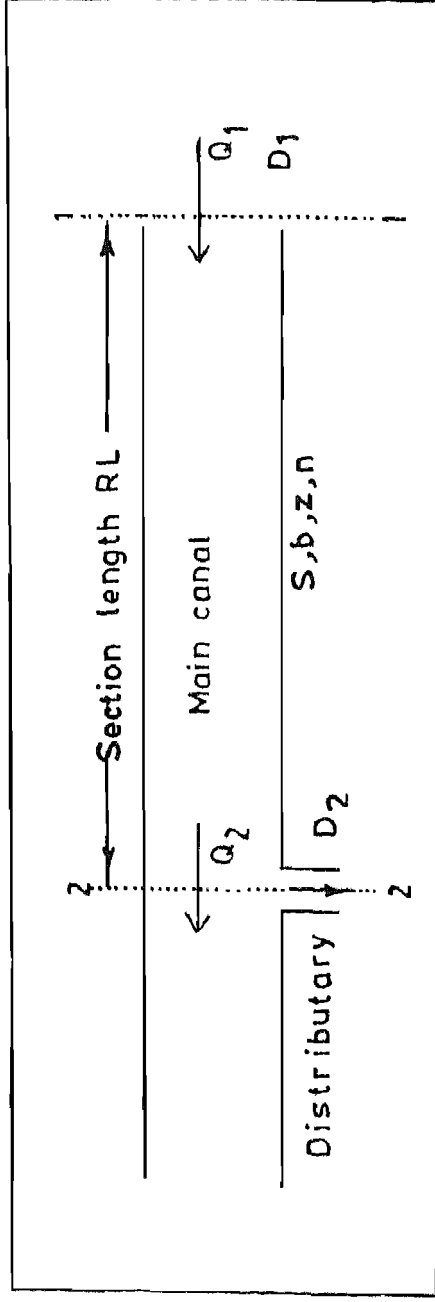


Fig.4.1 Schematic representation of canal section for seepage estimation

Substituting the values of A and R, Eqn. (4.1) becomes

$$Q_1 = (BD_1 + ZD_1^2) \frac{1}{n} \left[\frac{BD_1 + ZD_1^2}{B + 2D_1\sqrt{1 + Z^2}} \right]^{2/3} S^{1/2} \quad (4.2)$$

For a particular reach B, Z, n, and S are constant.

The depth of flow D_1 can be estimated by solving the Eqn (4.2) using Newton-Raphson iteration procedure for known Q_1 . In order to find out discharge at the downstream end of the reach, seepage losses in the section are to be estimated

(ii) Estimation of seepage losses

The seepage losses in a canal are given by the relationship

$$SL = SR * P * RL \quad (4.3)$$

Where

SL = Rate of seepage loss in the canal section m^3/sec .

P = Wetted perimeter of the section, m.

RL = Section length, m

SR = Seepage losses per unit wetted surface area per unit time, $m^3/m^2/sec$.

The actual seepage losses (SL) in the canal section of length RL will depend on the average depth of flow in the section and not only on the depth of flow at the upstream end (D_1). Hence to calculate SL, the average depth of flow D in the section must be known,

$$\text{i.e. } D = \frac{D_1 + D_2}{2} \quad (4.4)$$

Since D_2 is not known, the seepage losses are determined in two stages. The first estimate of the seepage losses $SL(1)$ is obtained using eq 4.3 by assuming

that the depth of flow in the section is D_1 . Then corresponding estimate of the discharge at the downstream end of the section (Q_2) is set to

$$Q_2 = Q_1 - SL(1) \quad (4.5)$$

The depth of flow at the down stream end (D_2) is calculated for this value of discharge Q_2 using equation 4.2 after replacing the different terms in the equation with the corresponding values for the downstream end. Repetitive iterations were carried out till we get a near constant value of depth (D_2).

The average depth of flow in the canal is calculated as

$$D = \frac{D_1 + D_2}{2}$$

The seepage losses (SL) are finally calculated for this average depth of flow (D) using equation 4.3. So the discharge at the downstream end of the reach, Q_2 , after accounting for seepage losses (SL) is given by

$$Q_2 = Q_1 - SL \quad (4.6)$$

(iii) Advancement of calculations to the next section:

The value of discharge Q_2 obtained will be the discharge at the head of next section 2-2. The steps (i) and (ii) are repeated to get the seepage losses and the discharge at the end of section. The same procedure is repeated till the end of canal is reached.

(iv) Estimation of total seepage loss from a canal:

The total seepage loss corresponding to a discharge at the head of the canal is estimated by summing the estimated seepage losses in different reaches of the canal. Losses due to evaporation were not considered during the course

of study. Similar procedure was adopted for estimating seepage from branch canals also.

(v) Estimation of seepage losses in distributaries

Since the details of the channel geometry are not available for all distributaries, the CGWB norms were adopted. By these norms 7 per cent of releases at the head of the distributary is taken to represent seepage losses in the distributary for the present study (Sarma *et al.*, 1986: Regional soil and water management pilot project report, Andhra Pradesh, PPR, 1980).

4.1.2 Estimation of Irrigation Depth

The discharge available for irrigation at field level is calculated from the daily data of discharge at canal head after accounting for seepage losses from main canal, branches and distributaries. The assumptions made while deriving the irrigation depths are based on general practices adopted in the area. These are :

- (a) Rice is the only crop irrigated by canal water.
- (b) The irrigation interval for rice is 3 days
- (c) Rice field is drained once at peak tillering stage (45 days after transplanting)
- (d) Irrigation is stopped two weeks before harvesting the rice crop.

Suitable adjustment is made to account for the harvesting of the rice crop in a particular month.

The amount of irrigation supplied per unit area at three day intervals was obtained as cumulative successive three day discharge minus cumulative three

day seepage loss divided by the total rice area to be irrigated in that period and is given by the following equation:

$$ID = \frac{\sum_{i=1}^3 Q_i - \sum_{i=1}^3 SL_i - \sum_{i=1}^3 SLD_i}{A \times 10} \quad (4.7)$$

where

ID = Irrigation depth at field level, mm

A = Area under paddy crop, ha

Q_i = daily discharge at the head of the canal, m³/day

SL_i = seepage loss in the canal corresponding to a discharge Q_i , m³/day

SLD_i = Seepage loss from distributaries, m³/day.

Assumed at 7% of the flows ($SLD_i = (Q_i - SL_i) \times 0.07$)

4.1.3 Computer Programme

A computer programme was written in Fortran 77 for computations involved in the canal flow model discussed above, and is listed in Appendix B. The programme first calculates depth of flow and seepage losses. These seepage losses are accounted while calculating irrigation depths.

4.1.4 Data Input for the Model

(a) Canal system details

1. Daily discharge rate at the head of the major canal
2. Length of the section.
3. Width of the section.
4. Side slope and channel gradient in the section
5. Seepage loss factor.
6. Manning's roughness coefficient

(b) Cropping system details

1. Transplanting date and month for rice
2. Rice area under canal command area during *kharif* season
3. Rice area under canal command area during *Rabi* season.
4. Irrigation scheduling duration, days.
5. Irrigation cutoff date (days before harvesting), days.
6. Crop duration for *kharif* season (rice crop)
7. Crop duration for *Rabi* season (rice crop).

4.2 ESTIMATION OF DEEP PERCOLATION BY SOIL WATER BALANCE

Soil moisture content is the critical state variable that determines the response of a soil plant system to any water input. Continual monitoring of soil moisture content is, therefore, of significance both in irrigation management and aquifer recharge studies. At the field level, this is most conveniently done by soil water balance studies. For the present study, soil water balance studies are carried out separately for paddy and non paddy crops as there is marked difference in irrigation management practices of these crops.

4.2.1 Water Balance in Rice Field

Traditionally, rice is grown under continuously flooded condition with about 5 to 10 cm depth of standing water throughout the season. This practice has been considered desirable not only for adequately meeting the water needs of rice, but also for an efficient supply of nutrients to the crop and effective weed control in the field. Hence the practices like allowing standing water in the rice fields continuously throughout the growing season, puddling of soils for reducing percolation rates, construction of bunds along the boundary of field to allow standing water in the field make the above soil water balance approach

complex for water balance computations for rice field. Therefore, an appropriate water balance procedure approach is developed to suit water management practices in rice fields to estimate percolation losses.

The water balance components of a puddled rice field (Fig 4.2) are irrigation supply, rainfall, evapotranspiration, percolation and runoff. The inflow components in the water balance are irrigation supply and effective rainfall, which together constitute total water supply. Evapotranspiration, percolation and surface runoff are the outflow components. The change in field storage is represented by the changes in ponded surface water in the paddy field after accounting for all the component water inflows and outflows

The generalized water balance equation for a paddy field can be expressed as follows;

$$FR = R + IRR - ET - DP - Q \quad (4.8)$$

In eqn. 4.8, FR is water depth in the field, R is rainfall reaching the surface, ET is crop evapotranspiration together with evaporation from the free water surface of the standing pool of water, DP is percolation, IRR is the amount of irrigation, Q is surface runoff. These components are expressed in depth units (mm) and the time period considered is one day. Capillary rise from ground water is ignored on the basis that the plough layer remains under saturated conditions for a considerable length of the crop growth period and is at a higher moisture potential than the capillary fringe at deeper depths (Odhiambo and Murthy, 1996).

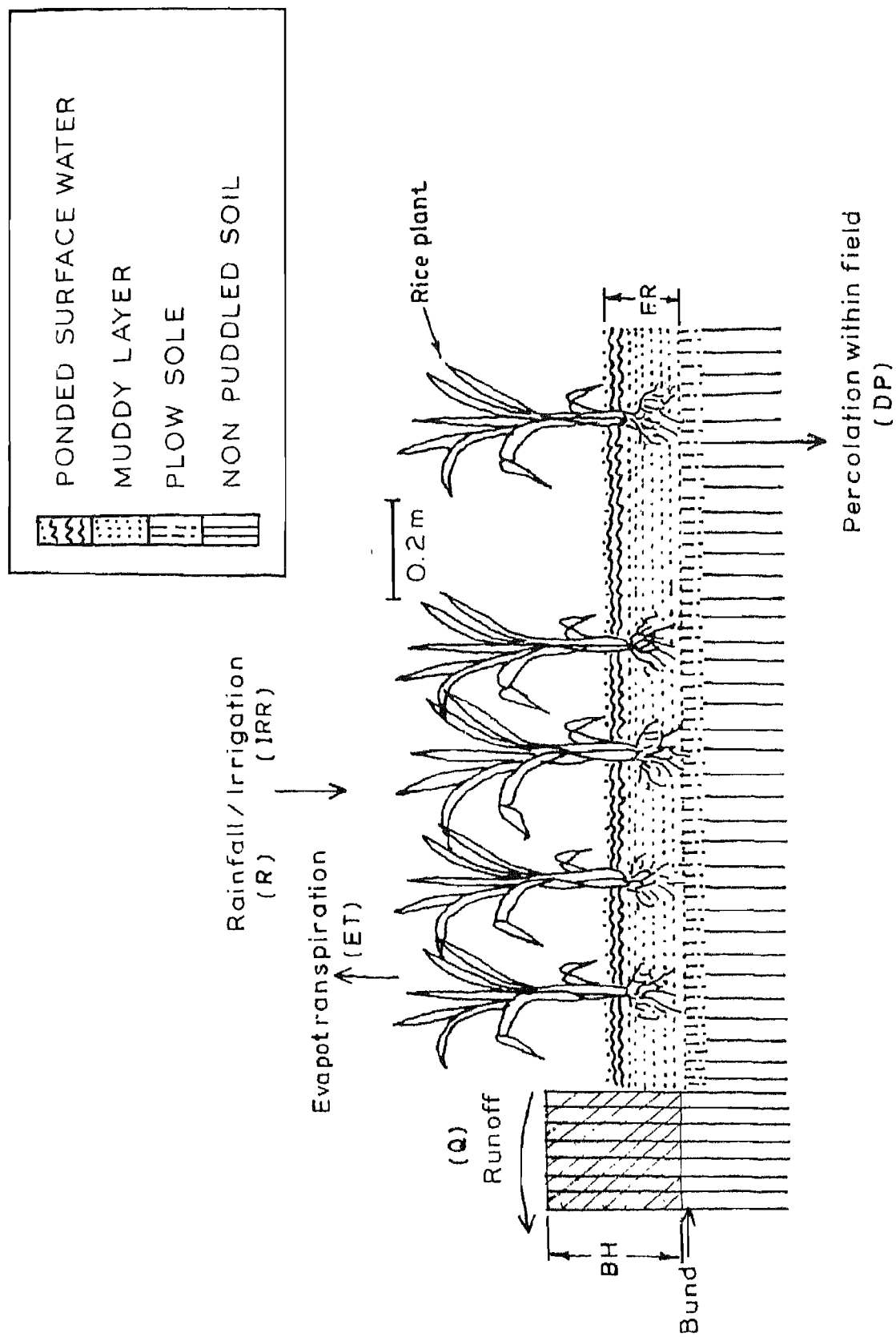


Fig. 4.2 Water balance components of Rice Field

Surface runoff (Q)

Rainfall in excess of bund height leaves the system as surface run off. Thus,

$$Q = R - BH \quad (4.9)$$

where BH is bund height, mm.

This surface runoff can be an input for a neighbouring field, but in a sequence of fields, neighbouring fields will pass on the surface runoff until it is lost in a drain. In the present study, bund height of 20 cm is considered. Further the entire rice field is drained once during the entire season at the peak tillering stage and this drainage condition is maintained for three days, so as to prepare the field for application of fertilizers. The specific days of drainage period being 45 to 47 days after transplanting. Standing water depth at the beginning of three days and any amount of rainfall which occurs during these days is treated as runoff.

Deep percolation (DP)

It is the vertical downward movement of water below the crop root zone. Percolated water is not available for use by the crop. Percolation is governed by the hydraulic conductivity of the soil profile and the depth of standing water on the field.

The percolation rate of puddled rice fields is affected by a variety of factors (Wickham and Singh, 1978) structure, texture, bulk density, mineralogy, organic matter content and concentration of salts in soil solution etc. The percolation rate is further influenced by the water regimes in and around the field. Increased depths of ponded water increase percolation due to the larger hydraulic gradient (Ferguson, 1970, Sanchez, 1973). Because of puddling, the soil layer at the

bottom of the root zone i.e. approximately 30 cm from surface gets compacted thereby reducing saturated hydraulic conductivity compared to that of unpuddled fields. The reduction in saturated hydraulic conductivity caused by puddling varies with the texture of the soil. The reduction is by four to five times for clay loam soils and eight to ten times for sandy loam soils (Varade and Ghildyal, 1967b; Naphade and Ghildyal, 1971; Sharma and De datta, 1985) and ten to fourteen times for sandy clay loam soils (Ghildyal and Satyanarayana, 1965; Pande, 1975). Accordingly, in the present study, the saturated hydraulic conductivity values are assumed to reduce because of puddling by four times for clay loam soils and twelve times for sandy clay loam soils.

The daily percolation rate out of the root zone (30 cm) layer is computed by Darcy's law as.

$$DP = -k_s \frac{dh}{dz} \quad (4.10)$$

Where DP = percolation out of the root zone, mm/day

k_s = saturated hydraulic conductivity, mm/day

dh/dz = head gradient

Evapotranspiration

Evaporation from the soil and water surface and transpiration from the plant leaves are combined and treated together as evapotranspiration (ET). ET for rice depends mostly on climatic conditions (Wickham and Singh, 1978). Maintaining ET at the potential rate i.e. the rate which is not hindered by water shortage, is essential for high yields of rice (IRRI 1987), because yields will decline with decreasing rate of ET. In the present study, actual evapotranspiration is assumed to equal potential evapotranspiration if soil moisture content is above or equal to field capacity. During drainage periods, when the moisture falls below

field capacity, actual evapotranspiration is assumed to decrease linearly with soil moisture content between field capacity and permanent wilting point (Fig 4.3). Crop coefficients used in the estimation of actual evapotranspiration are adopted from FAO (Doorenbos and Pruitt, 1977).

The following relationship was used to estimate daily mean evapotranspiration (Doorenbos and Pruitt, 1977).

$$PET = K_c \quad ETO \quad (4.11)$$

Where ETO = Crop reference evapotranspiration, mm

K_c = Crop coefficient

PET = Potential evapotranspiration from crop, mm.

Crop reference evapotranspiration values used in the estimation of potential evapotranspiration are adopted from Khumbate and Biswas (1992).

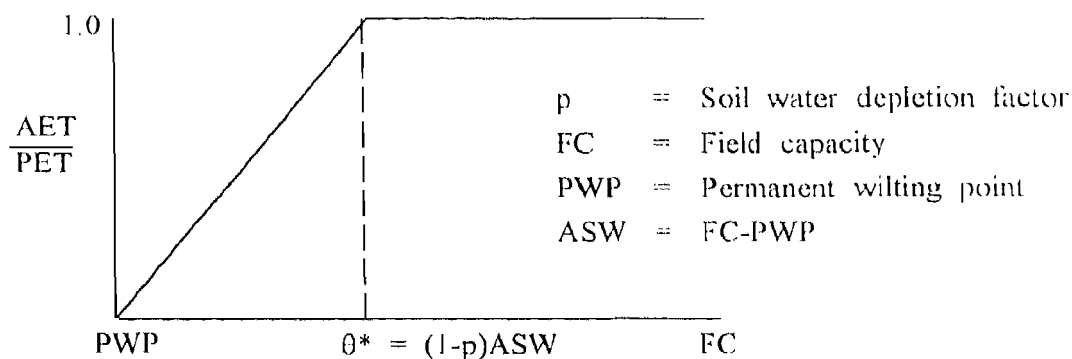


Fig 4.3 Relationship between soil moisture availability and AET

4.3 SOIL WATER BALANCE FOR NON-PADDY CROPS

For the present study, the maximum depth up to which the roots will grow was considered as the total soil reservoir (Fig 4.4). Since root growth

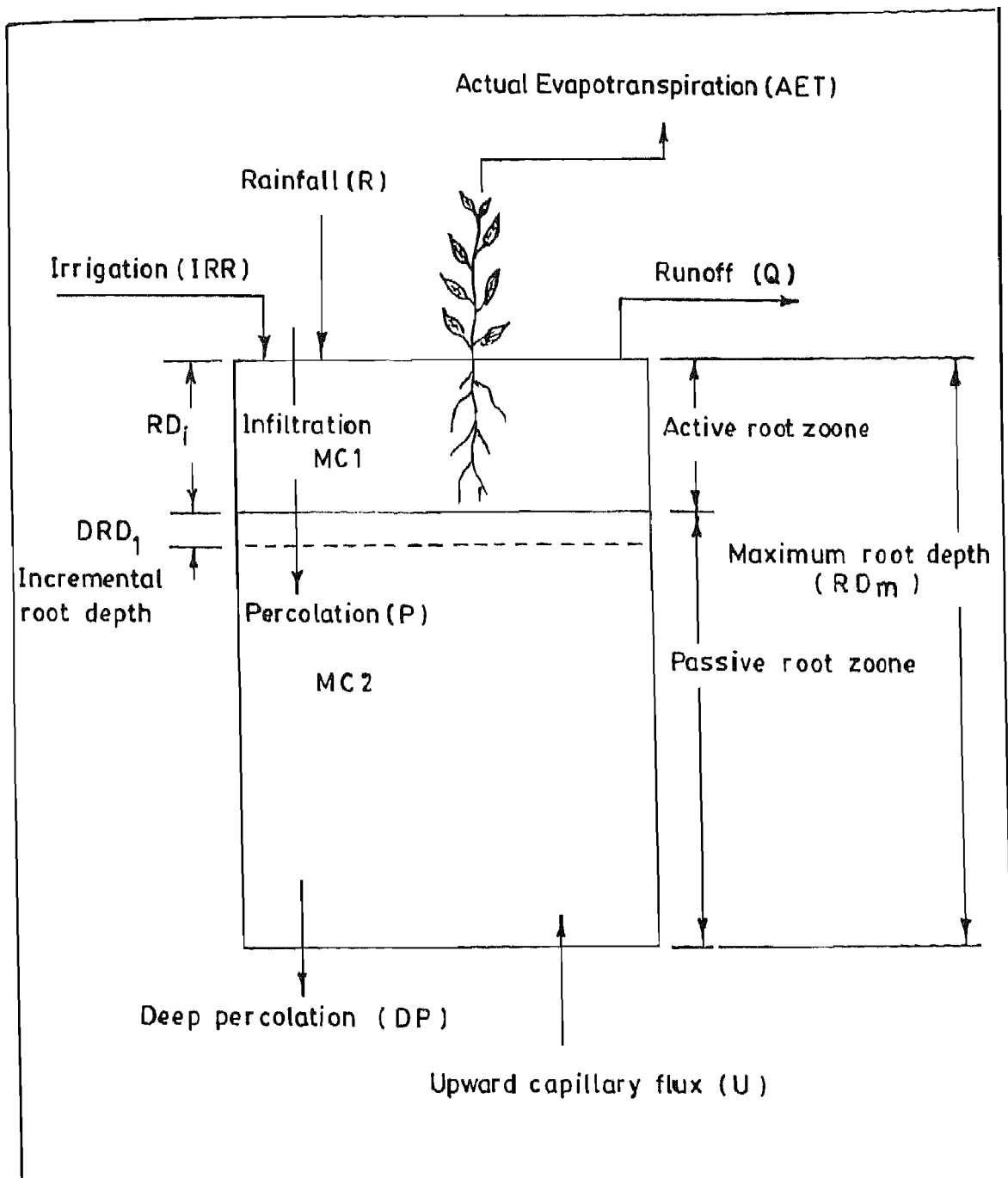


Fig44Components of Soil Water Balance Model

varies with time, the soil reservoir is divided into two layers (Fig. 4.4), (i) an active layer of depth RD in which roots are present at any given time and from which both moisture extraction and drainage would occur, and (ii) a passive layer of depth (RDM-RD) from which only drainage would occur. The two layers are distinct in the initial phase of crop growth and their relative depths are governed by the rate of root growth. But once the maximum root depth is attained, the entire rootzone becomes only one layer. Thus the soil water balance in the upper layer is governed by daily values of rainfall (R), runoff (Q), irrigation (IRR), actual evapotranspiration (AET) and drainage to the second layer (P). The soil water balance in the lower layer is governed by drainage into it from the upper layer and drainage out of the layer (DP) as deep percolation.

It is assumed that the effective rainfall (R-Q) and the applied irrigation (IRR) on any day are redistributed instantaneously and uniformly over the root zone. The applied rainfall and irrigation in excess of field capacity percolates to the lower passive zone and is instantaneously redistributed in that zone. The remaining water in excess of field capacity of the passive zone moves out of it as deep percolation.

For layer 1, or the active root zone, the average soil moisture content (MC1, mm/cm) at the end of any day (i) can be estimated by the daily soil water balance equation for this layer given by,

$$MC1_i = (MC1_{i-1} \cdot RD_{i-1} + R_i - Q_i + IRR_i + DRD_i \cdot MC2_{i-1} - P_i - AET_i) / RD_i$$

$$i = 1, 2, \dots, N; N = \text{No. of days crop season} \quad (4.12)$$

where

$MC1_{i-1}$ = Average soil moisture content at the end of previous day (i-1) (that is, start of day i), mm/cm

RD = root depth in cm

$$DRD = RD_i - RD_{i-1} \quad (4.13)$$

MC2_{i-1} = Average soil moisture content in the lower layer at the end of previous day, mm/cm.

The percolation (P_i) out of the top layer is given by

$$P_i = [R_i - Q_i + IRR_i] - (FC - MC1_{i-1})RD_{i-1} - (FC - MC2_{i-1})DRD$$

(IF P_i < 0, P_i = 0) (4.14)

For the passive rootzone,

$$MC2_i = MC2_{i-1} ; \text{ if } P_i < 0 \quad (4.15)$$

otherwise

$$MC2_i = MC2_{i-1} + P_i / (RDM - RD_i) - DP_i + u \quad (4.16)$$

where u is capillary rise

in which

$$DP_i = P_i - (FC - MC2_{i-1}) (RDM - RD_i) \quad (4.17)$$

if DP_i < 0 ; DP_i = 0

4.3.1 Estimation of Components of Soil Water Balance

Rainfall (R)

The data of daily rainfall for the growing season of each crop are used directly as input

Runoff (Q)

Daily runoff values are estimated from daily rainfall data using the SCS curve number method (USDA, 1972) adapted for Indian conditions (Ministry of Agriculture, 1972) and combined with the soil moisture accounting procedure suggested by Sharpley and Williams (1990). The runoff equation for soil conditions in India is

$$Q = \frac{(R-0.3S)^2}{(R+0.7S)} ; \text{ if } R > 0.3S \text{ For non-black soil regions} \quad (4.18)$$

$$= 0 , \text{ if } R < 0.3S$$

$$Q = \frac{(R-0.1S)^2}{(R+0.9S)} ; \text{ if } R > 0.1S \text{ For black soil regions} \quad (4.19)$$

$$= 0 , \text{ if } R < 0.1S$$

The retention parameter, S varies with time because of changes in soil moisture content. The parameter S is related to curve number (CN) by the relationship

$$S = 254 \left(\frac{100}{CN} - 1 \right) \quad (4.20)$$

The values of the curve number CN vary with antecedent moisture conditions (AMC), the soil hydrologic group and land use. In the original procedure of USDA and its Indian adaptation three AMC conditions are defined, AMCI, AMCII and AMCIII corresponding to dry, average and wet catchment conditions. The conditions are identified empirically based on the cumulative rainfall in the five days preceding the current rainfall event (Table C-1, Appendix C). For the growing season, two limiting values of the previous 5-day cumulative rainfall are defined for identifying the AMC conditions. If this rainfall is less than 36.6 mm then AMCI applies. If it is more than 53.3 mm

AMCIII applies. The values of the curve number for average antecedent moisture conditions (CN for AMCII or $CN = CN_2$) are tabulated for various soil, land use and management conditions by the Ministry of Agriculture (1972) (Table C-2, Appendix C). The corresponding values of CN for dry (CN1) and wet (CN3) catchment conditions are given by

$$CN1 = CN2 - [20 (100 - CN2) / \{100 - CN2 + \exp(2.533 - 0.0636(100 - CN2))\}] \quad (4.21)$$

and

$$CN3 = CN2 \exp [0.00673 (100 - CN2)] \quad (4.22)$$

However, in real situations, the AMC value is not restricted to the three discrete conditions identified empirically for the cumulative rainfall, but can vary over a continuous range and can be quantified by the soil moisture. Using CN1 and CN3, the retention parameter can be directly related to the soil moisture content in the active layer by the equations of Sharpley and Williams (1990).

$$S = S1 [1 - FFC / \{ FFC + \exp (W1 - W2 \cdot FFC) \}] \quad (4.23)$$

Where S1 is the value of S associated with CN1, FFC is the fraction of field capacity and W1 and W2 are called shape parameters. FFC is given by

$$FFC = (MC1 - PWP) / (FC - PWP) \quad (4.24)$$

Where MC1 is the soil water content in the root zone and FC and PWP are the field capacity and permanent wilting point respectively. Values of W1 and W2 are obtained from the simultaneous solution of the two equations obtained from eq. (4.21) according to the conditions that $S = S2$ (value of S in eq. 4.18 when $CN = CN2$) when $FFC = 0.5$ and $S = S3$ (value of S in eq. 4.18 when $CN = CN3$) when $FFC = 1.0$.

$$W1 = \ln [(1.0 / (1-S3/S1)) - 1.0] + W2 \quad (4.25)$$

$$W2 = 2[\ln \{0.5 / (1-S2/S1) - 0.5\} - \ln \{1.0 / (1-S3/S1) - 1.0\}] \quad (4.26)$$

Once the parameters W1, W2 and FFC are estimated, the value of S can be obtained from equation 4.23 and runoff from eqn 4.19

Percolation (P and DP)

The quantities P and DP can be estimated using eq 4.14 and 4.17. To start the model the initial soil moisture content at the beginning of the season (MC_0) must be known. This moisture is assumed to be uniformly distributed over both the soil zones. Since measured values of soil moisture, MC_0 at the beginning of the balance period is considerably difficult to determine for a model applied on a large scale, assumptions are made according to the situation. In the present study, for crops with sowing dates after prolonged dry spells of rain (before onset of monsoon) MC_0 is set to PWP (mm/cm) of the soil and a presowing irrigation of 75 mm is given. For crops with sowing dates at the beginning of the monsoon season, MC_0 was set to 0.5 FC (mm/cm) with no presowing irrigation. For crops sown at the end of the monsoon season MC_0 was set to FC mm/cm.

Root depth (RD)

The depth of the effective soil reservoir for any stage varies with the depth of roots at that stage. The crop root depth increases with time and attains a maximum value by the end of flowering period for most crops. The root growth is usually assumed to follow sigmoidal relationship. The sigmoidal relationship given by the Borg and Grimes (1986) is used to determine the root depth

$$RD = RD_m [0.5 + 0.5 * \sin (3.14 * DAP/DTM - 1.47)] \quad (4.27)$$

Where

RD = Root depth on any day given by DAP, mm

RD_m = maximum rooting depth, mm

DAP = Days after planting

DTM = Number of days to maturity

The minimum value of RD is set equal to 15 cm, as soil evaporation can take place from the top 15 cm of the profile. Representative values of RD_m for different crops are obtained from the literature.

Actual Evapotranspiration (AET)

Actual evapotranspiration (AET) occurs only from the active upper soil layer in the root zone. It depends on the available soil moisture content (MC1) in this layer and potential evapotranspiration, PET (Fig. 4.3). PET is obtained from reference evapotranspiration (ETO) and crop factors (K_c). For the present study, generally applicable K_c values developed by Doorenbos and Pruitt, 1977) were used.

$$PET = K_c \cdot ETO \quad (4.28)$$

and

$$AET = PET \quad ; \text{ if } MC \cdot RD \geq MCT \cdot RD \quad (4.29)$$

$$AET = (MC - PWP) / (MCT - PWP) \cdot PET \quad ; \text{ if } MC \cdot RD < MCT \cdot RD \quad (4.30)$$

in which MCT is the critical threshold soil moisture (Fig. 4.3) given by

$$MCT = (1-p) \cdot (FC - PWP) \quad (4.31)$$

p = soil water depletion factor which depends on the type of crop and PET

The value of p for a crop in a given environment is to be determined from controlled field experiments or after consultations with agronomists and plant physiologists. A representative set of p values given by FAO (Doorenbos and Kassam, 1979) after summarizing data of a large number of experiments were used for the present study.

Irrigation (IRR)

The irrigation requirement was considered as the unknown quantity to be determined through the soil water balance for all crops except paddy. To determine the timing of irrigation, the soil water balance model was run for each crop, starting from the first day of the season to the end of the season for the soil and weather data of the study area. Whenever the soil moisture in the active layer falls below MCT (eqn 4.30), an irrigation is timed for the next day. For the present study a fixed irrigation of 75 mm was assumed to be applied for all the crops except for paddy, where the depth of irrigation was estimated from canal flow model (chapter 4, Section 4.1.2)

Upward capillary flux

Contribution of moisture through upward capillary flux is usually insignificant except under shallow water table conditions. This component is ignored in the present study.

4.4 SOIL WATER BALANCE FOR UNCULTIVATED LANDS

For estimation of recharge from uncultivated lands, soil water balance approach adopted for non paddy crops (Section 4.3) was considered, with the modification for the component of evaporation.

4.4.1 Estimation of Evaporation from Uncultivated Lands

In the absence of vegetation, and when the soil surface is subjected to radiation and wind effects, evaporation occurs directly from the soil surface. Generally evaporation from bare soil (E) takes place in two stages, the constant and the falling rate stages (Philip, 1957). In constant rate stage, the soil is sufficiently wet for the water to be transported to the surface at a rate equal to the potential evaporation and is given by the following equation

$$PE = ETO \quad (4.32)$$

where

PE = Potential evaporation, mm and

ETO = Reference evaporation, mm (Khumbate and Biswas, 1992).

In the falling rate stage, the soil water content is below a threshold value and E depends on the flux of water through the upper layer of soil to the evaporating site near the surface.

Ritchie's (1972) cumulative law is used for estimation of second stage of bare soil evaporation given by

$$\Sigma E = at^{1/2} \quad (4.33)$$

Where E = bare soil evaporation, mm

t = time since the start of 2nd stage, days

a = a constant dependent on the hydraulic conductivity of the soil (mm/day^{1/2}). Representative values of 'a' for different soils are given in Table 4.1

The E for each day is obtained as

$$E = at^{1/2} - a(t-1)^{1/2} \quad (4.34)$$

Table 4.1 **Representative value of 'a' for estimation of evaporation from uncultivated soils, mm/day^{1/2}**

Soil Type	a
Clay loam	5.08
Loam	4.04
Sand	3.34

(Source : Ritchie, 1972)

4.5 SOIL WATER BALANCE FROM RICE FALLOW LANDS

For estimation of recharge from rice fallow lands, soil water balance approach adopted for rice crop (Section 4.2.1) was considered with the modification for the component of evaporation. The model which was used to compute the bare soil evaporation from uncultivated lands (Section 4.4.1) was adopted for rice fallow lands between two *kharif* and *rabi* rice crops

4.6 COMPUTER PROGRAMME

A computer programme in Fortran 77 was written for computations involved in the soil water balance model discussed above, and is listed in Appendix C.

4.7 INTERFACE BETWEEN SOIL WATER BALANCE MODEL AND GIS

The general flow of information between the GIS and the soil water balance models is shown in Fig. 4.5. The GIS PAT file of the BSU coverage is used to select the input files required to run the soil water balance model

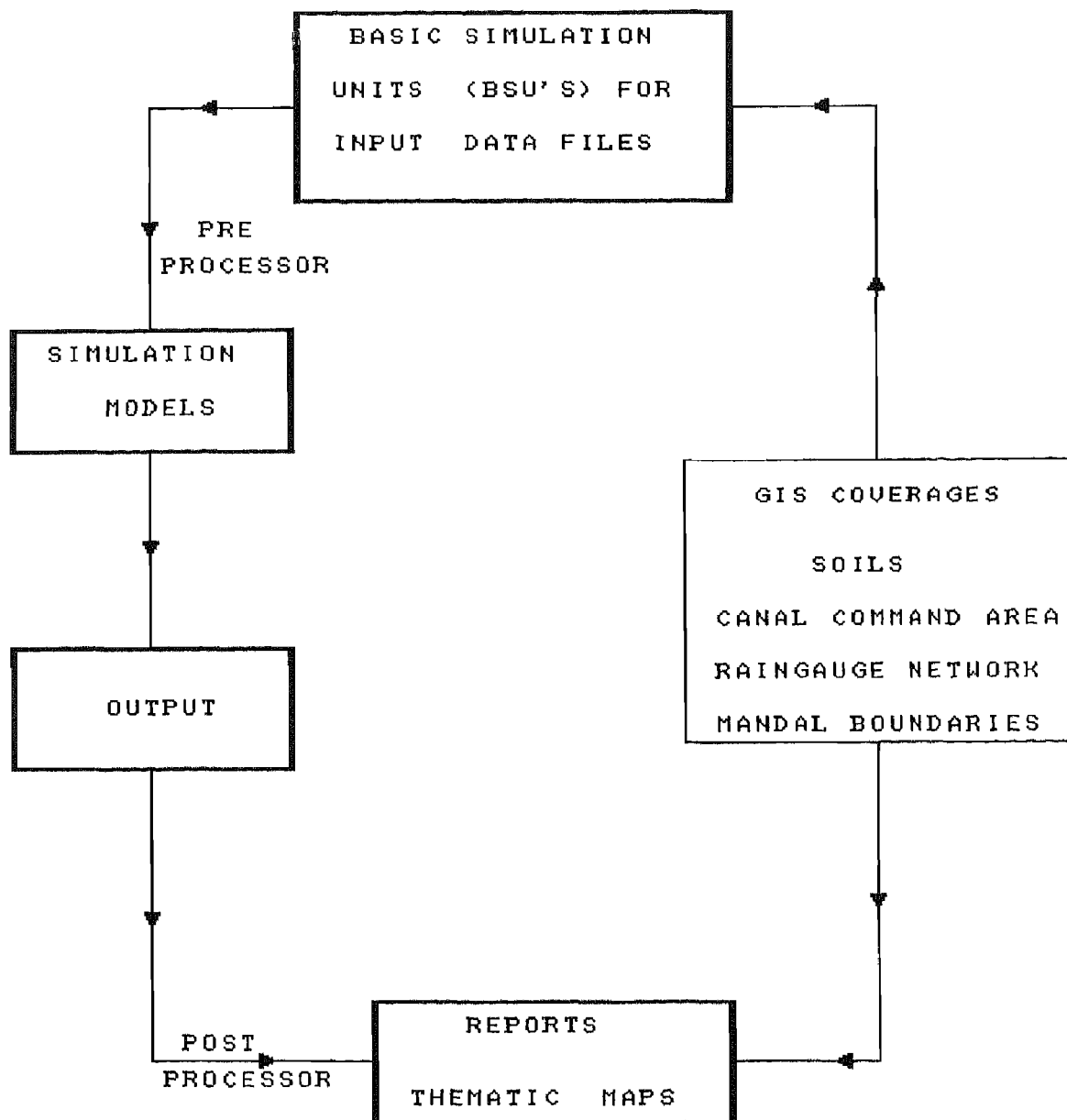


FIG 4.5 GIS - MODEL LINKAGES FOR GENERATING THEMATIC MAPS

The GIS PAT file lists the BSU ID number, raingauge number, soil type, *mandal* and canal system for each unit (Table 3.6). A pre processor is written to the model programmes in Fortran 77 language that reads the GIS PAT file, selects the relevant data file for each BSU and runs the model for each year. This is repeated for all the 38 basic simulation units. A post processor is written at the end of the model programmes to read the model output file for each BSU and summarise the output file into attributes to facilitate creation of thematic maps of recharge potential for all the 38 BSUs.

The percolation losses in each BSU were obtained by running the soil water balance model (SWB. FOR) with relevant rainfall, soil and water supply data

4.8 APPLICATION TO STUDY AREA

Recharge to the groundwater in the study area is estimated separately from two sources.

- (i) Seepage from main canals, branches and distributaries.
- (ii) Percolation from fields.

4.8.1 Estimation of Seepage Losses in the Study Area

The irrigation system comprises one main canal and three branches canals namely Gannavaram canal, Amalapuram canal and Bank canal all taking off from Ryalli Lock off the main canal. The following data of relevance to estimation of recharge by seepage losses was used

- 1) Daily canal discharges (Q) (10 years from 1987 to 1995 at headworks of main canal and 3 branch canals).
- 2) Map of area commanded by each canal (Fig 3.5).

- 3) Design characteristics of canals (eg. reach length (RL), bed width (B), slopes (S) and full supply discharge etc.) (Table 3.3)

The seepage losses were calculated by the canal flow model described in (Section 4.1, eqns. 4.1 to 4.6) and the source code for the computer programme IRRIG.FOR is given in (Appendix B).

The values of Manning constant (n), side slope (Z) and seepage rate (SR) adopted were 0.01, 1.0 and 15 ha-m/day/10⁶ sq m of wetted area of canal (Central Groundwater Board, CGWB, 1984).

Daily seepage losses corresponding to different discharges at the head of the canal were estimated by summing up the seepage losses in different sections of the canal.

For the distributaries, data of daily discharges at headworks and design characteristics were not available. So, 7% of the supplies left after accounting for seepage losses in the canals were taken as seepage in distributaries (CGWB, 1984, Sarma *et al.*, 1986). Thus the total seepage losses for each canal were obtained by summing up seepage losses for both major canals and distributaries. Monthly seepage rates were also obtained for all the four canals from 1987 to 1995 by summing corresponding daily values (Table 4.2).

A rating curve of discharge at canal headworks vs seepage losses was developed using the results obtained from the canal flow model. A power function form $y = ax^b$ and an exponential function form $y = ab^x$ were tried to fit the relationship between discharge and seepage losses for all the four canals. The procedure given by Gupta and Kapoor (1983) was followed for fitting the relationship between the discharge and seepage losses. Suitable statements were incorporated in the computer programme of the canal flow model to find the

Table 4.2 Monthly seepage rates from the canal distribution system, cumec

YEAR	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
MAIN CANAL												
1987	4.753	6.489	6.389	6.274	2.730	1.674	4.733	4.395	3.986	4.012	1.056	2.655
1988	3.612	3.704	3.809	4.286	4.155	4.623	5.419	5.295	5.116	4.070	0.000	3.036
1989	4.659	4.502	3.210	3.592	4.404	4.697	5.700	4.987	4.577	2.507	0.000	0.101
1990	3.141	4.846	4.820	4.815	3.495	3.643	4.504	2.871	3.856	1.348	0.000	1.654
1991	3.328	5.169	5.555	5.477	4.251	1.543	5.059	5.021	5.912	4.167	0.095	0.038
1992	2.081	6.824	6.056	7.051	5.142	3.387	6.043	5.549	5.933	4.827	0.341	0.418
1993	2.066	6.631	7.102	6.275	4.654	4.964	6.334	4.743	4.775	3.873	0.000	0.495
1994	4.132	5.359	5.273	5.225	3.313	2.372	6.101	5.480	6.121	5.302	0.000	0.043
1995	5.629	5.087	5.809	5.465	2.746	4.612	5.705	5.166	5.673	4.422	0.464	0.480
NAME OF THE BRANCH CANAL - GANNAVARAM CANAL												
1987	2.579	3.165	3.170	3.171	1.730	1.114	2.570	2.490	2.315	2.327	0.554	1.499
1988	2.152	2.324	2.273	2.603	2.339	2.377	2.781	2.716	2.703	2.312	0.000	1.659
1989	2.508	2.543	1.888	2.205	2.304	2.366	2.961	2.669	2.535	1.478	0.000	0.065
1990	1.720	2.582	2.525	2.578	2.122	2.088	2.343	1.475	1.929	0.786	0.000	1.209
1991	1.621	2.577	2.885	2.877	2.326	0.812	2.679	2.511	2.809	2.235	0.000	0.053
1992	1.234	3.186	2.946	3.293	2.805	1.987	2.959	3.041	3.132	2.906	0.272	0.000
1993	0.776	2.954	3.282	3.003	2.629	2.647	2.891	2.556	2.591	2.361	0.000	0.424
1994	2.265	2.899	2.835	2.832	2.003	1.470	3.055	2.721	3.023	2.643	0.000	0.000
1995	2.764	2.736	2.970	2.886	1.644	2.942	2.674	2.596	2.859	2.636	0.407	0.053
NAME OF THE BRANCH CANAL - AMALAPURAM CANAL												
1987	2.546	2.841	2.881	2.830	1.554	1.056	2.494	2.322	2.307	2.311	0.706	1.453
1988	2.132	2.090	2.211	2.305	2.275	2.630	2.738	2.792	2.719	2.313	0.000	1.665
1989	2.508	2.161	1.559	2.024	2.497	2.591	2.788	2.579	2.444	1.489	0.000	0.064
1990	1.665	2.525	2.591	2.613	2.117	2.162	2.442	1.432	1.915	0.723	0.000	0.964
1991	1.261	2.678	2.708	2.731	2.508	0.919	2.534	2.526	2.823	2.047	0.057	0.000
1992	1.132	3.179	2.941	3.323	2.643	2.013	3.224	3.053	3.172	2.648	0.200	0.193
1993	1.313	3.412	3.313	3.139	2.583	2.729	2.988	2.583	2.627	2.286	0.000	0.409
1994	2.357	2.899	2.833	2.729	2.031	1.352	3.105	2.993	3.082	2.768	0.000	0.045
1995	2.929	2.640	3.021	2.892	1.632	2.623	3.137	3.053	3.171	2.547	0.200	0.193
NAME OF THE BRANCH CANAL - BANK CANAL												
1987	2.922	3.962	3.808	3.733	1.616	1.097	2.961	2.837	2.567	2.581	0.705	1.747
1988	2.471	2.497	2.528	2.576	2.753	2.893	3.270	3.145	3.034	2.571	0.000	2.000
1989	2.923	2.871	2.406	2.495	2.842	2.976	3.353	3.062	2.863	1.552	0.000	0.071
1990	2.008	3.044	2.962	2.920	2.387	2.545	2.973	2.628	3.173	0.836	0.000	1.460
1991	2.903	3.210	3.343	3.186	2.641	1.017	3.084	3.264	3.696	2.502	0.114	0.000
1992	1.573	3.931	3.553	3.974	3.032	2.230	3.295	2.844	3.060	2.487	0.000	0.495
1993	1.358	3.752	4.049	3.551	2.556	2.907	3.915	2.899	2.856	2.327	0.000	0.000
1994	2.719	2.922	2.961	2.974	2.336	1.526	3.385	3.142	3.419	3.016	0.000	0.051
1995	3.325	3.032	3.232	3.064	1.868	3.021	3.251	2.857	3.042	2.418	0.000	0.495

constants a and b . These constants were obtained for all four canals and for both the curve forms (Table 4.3). So as to select the best fit equation, mean square error (MSE), mean per cent error (MPE) and mean average per cent error (MAPE) were also calculated for all fitted curves (Table 4.3). The MSE, MPE and MAPE values were smaller for power curve and was selected as the best fit equation for all four canals. Hence, for a given discharge at the head of the canal, the seepage losses can be obtained following fitted equation

$$y = ax^b \quad (4.35)$$

Curves fitted for power form of the equation $y = ax^b$ for three canals, Gannavaram canal, Amalapuram canal and Bank canal are given as Fig 4.6 to Fig 4.8. The daily seepage losses vary between 5 to 25% of the discharge at the headworks. It was assumed that these losses were equally distributed over the respective command areas of each canal.

The remaining supplies, after accounting for seepage losses in canals and distributaries are available to the crops in the fields and these represent the daily values of irrigation requirement in the soil water balance computations. Irrigation depths are calculated for all four canals from 1987 to 1995 for both *kharij* and *rabi* seasons and the results for the year 1995 are given in Appendix B.

4.8.2 Estimation of Percolation Losses from Fields in the Study Area

The soil water balance model for rice and other crops, uncultivated areas and rice fallow lands are used to estimate the percolation losses in the study area. The model is run for data of each BSU identified for the command area using GIS (Chapter 3, Section 3.7, Fig. 3.7). The following data are used for each BSU:

Fig.4.6 Rating curve for estimation of seepage losses
(Gannavaram Canal)

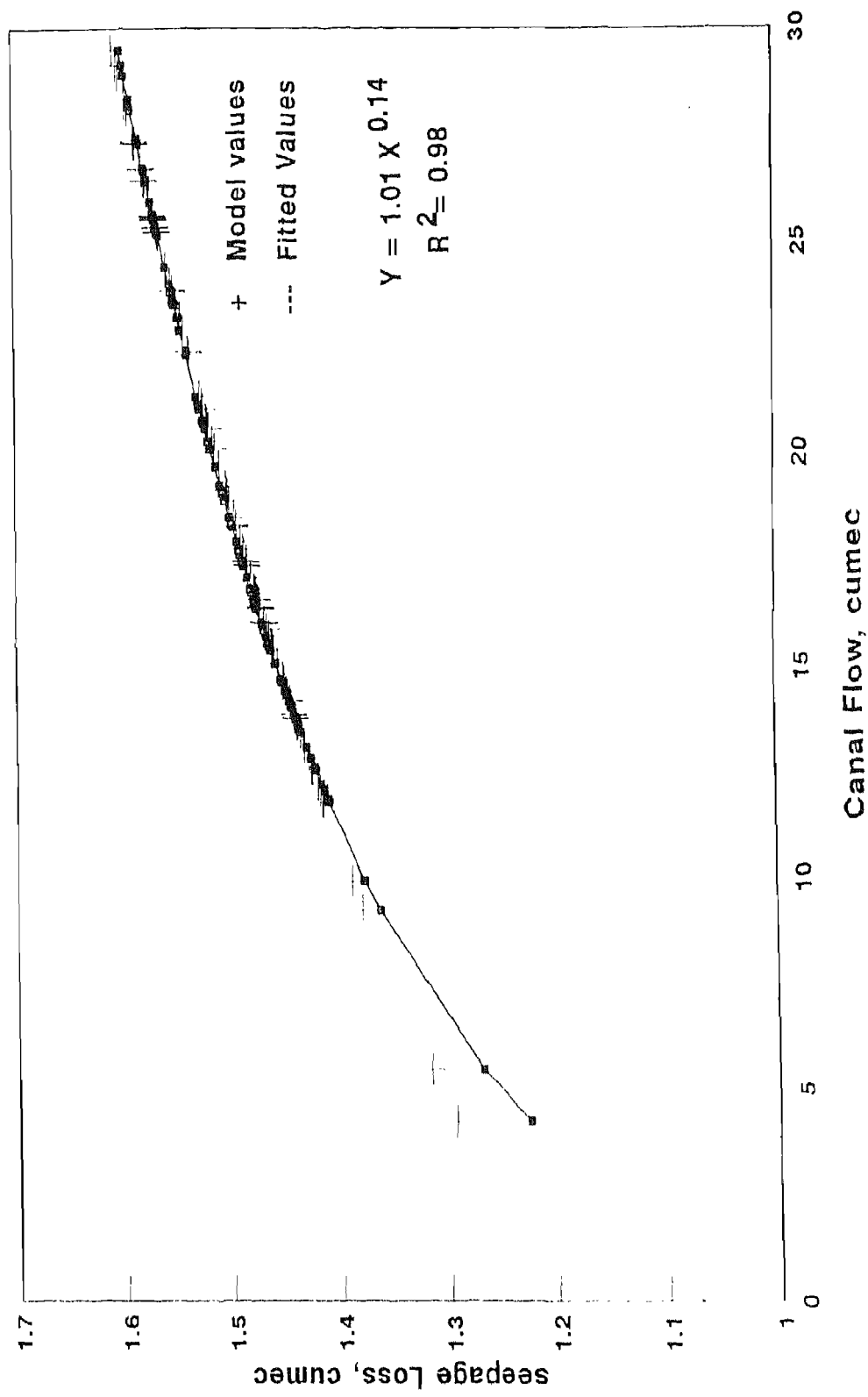


Fig.4.7 Rating curve for estimation of seepage losses
(Amalapuram Canal)

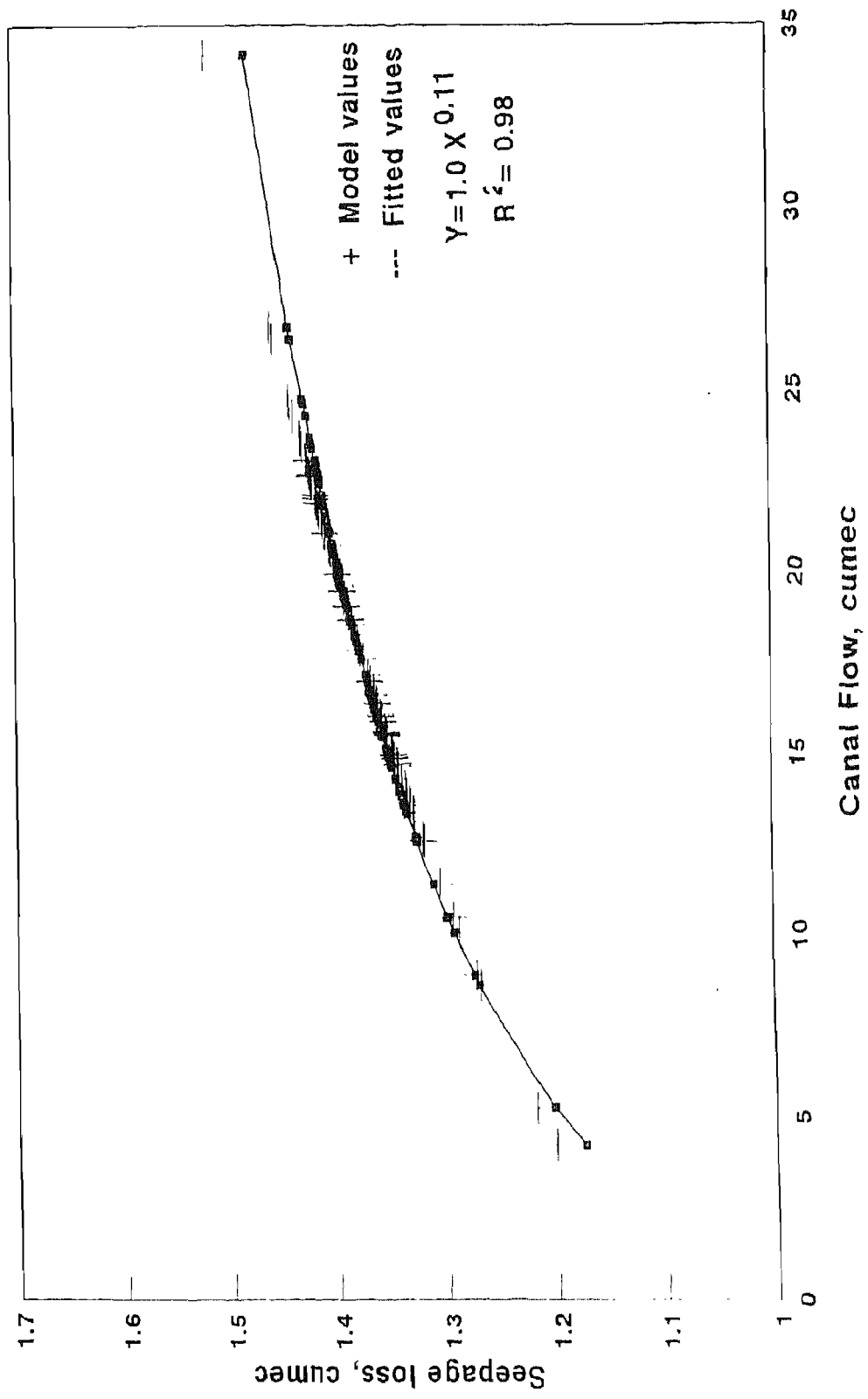


Fig.4.8 Rating curve for estimation of seepage losses
(Bank Canal)

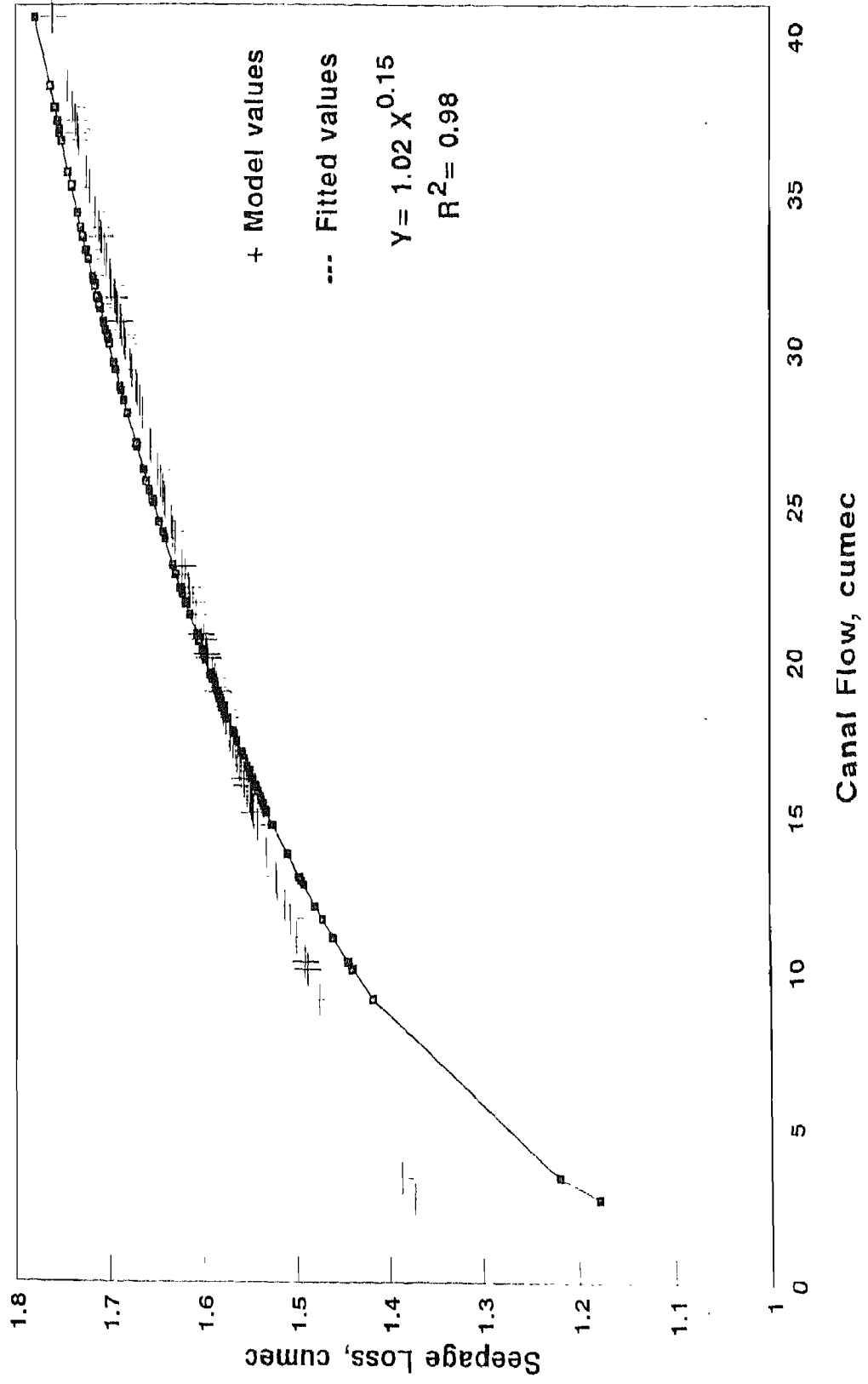


Table 4.3 Statistical parameters for rating curves obtained for estimation of seepage losses.

Coefficients	Gannavaram canal		Amalapuram canal		Bank canal		Main canal	
	$Y=AX^B$	$Y=AB^X$	$Y=AX^B$	$Y=AB^X$	$Y=AX^B$	$Y=AB^X$	$Y=AX^B$	$Y=AB^X$
A	1.01	1.09	1.00	1.07	1.02	1.14	0.97	0.91
B	0.14	1.02	0.11	1.01	0.149	1.02	-3.59×10^{-2}	0.99
MSE	1.43×10^{-4}	2.89×10^{-4}	6.56×10^{-6}	1.19×10^{-4}	9.03×10^{-4}	6.78×10^{-4}	8.29×10^{-4}	1.17×10^{-4}
MPE	-8.93×10^{-4}	-8.68×10^{-4}	-3.37×10^{-4}	-7.03×10^{-4}	-2.52×10^{-4}	-1.35×10^{-2}	3.57×10^{-2}	1.11×10^{-2}
MAPE	4.14×10^{-3}	2.89×10^{-2}	3.59×10^{-3}	2.04×10^{-2}	1.09×10^{-2}	3.91×10^{-2}	2.42×10^{-2}	2.89×10^{-2}
R ²	0.98	0.98	0.98	0.98	0.98	0.96	0.98	0.98

1. Daily rainfall (for 8 years from 1987-88 to 1994-95, at 7 raingauge stations in the study area).
2. Evaporation (weekly average values for the area, Table 4.4)
3. Soil map of command area (Fig. 3.4).
4. Cropping pattern (for each *mandal*/administrative block, Table 3.2).
5. Crop characteristics (Table 4.5).
6. Crop coefficients (Table 4.6)

A representative set of p values given by FAO (Table 4.7) after summarizing data of large number of experiments were used for the present study.

The model was run on daily basis for each BSU for the four land use conditions (rice, crops other than rice, rice fallow lands, and uncultivated) for all the seasons from 1987-88 to 1994-95. The irrigation supplies in case of paddy were obtained from canal flow model as discussed earlier (Chapter 4, Section 4.1.2). A sample result of the daily soil water balance in one BSU for paddy (*kharif* season) during the season 1995-96 is reproduced in Table 4.8. The daily percolation losses and standing water depths in the paddy fields, estimated by soil water balance model for one BSU during the *kharif* season of year 1995, are also given (Table 4.8). This may be noted that the daily percolation losses and standing water depths also serve as inputs to the nitrogen

balance model (Chapter 5). The daily percolation losses were summed to obtain monthly percolation losses for all the crops and seasons from 1987 to 1995 for each BSU. A sample result of the total monthly percolation losses for all the BSU's from rice crop for *kharif* season of 1995 is given in (Table 4.9). Then monthly percolation losses for each of the four land use areas are multiplied by their respective areas and added to get the monthly percolation rates for each BSU. The cropping pattern for each BSU is given in Table 4.10.

Table 4.4 Weekly average reference evaporation values

Standard Week No.	Rajahmundry	Standard Week No.	Rajahmundry
1	3.3	27	4.7
2	3.4	28	5.0
3	3.5	29	4.7
4	3.6	30	4.7
5	3.8	31	4.6
6	4.0	32	4.6
7	4.2	33	4.6
8	4.5	34	4.4
9	4.9	35	4.5
10	5.0	36	4.6
11	5.3	37	4.6
12	5.5	38	4.2
13	5.8	39	4.1
14	6.3	40	4.1
15	6.2	41	3.9
16	6.2	42	4.1
17	8.5	43	4.1
18	6.7	44	4.1
19	7.0	45	4.1
20	7.0	46	4.0
21	6.8	47	3.8
22	7.0	48	3.6
23	7.0	49	3.6
24	6.5	50	3.4
25	5.6	51	3.3
26	4.9	52	3.3

(Source : Khumbate and Biswas, 1992)

Table 4.5 Details of crop characteristics adopted for the soil water balance model

Crop	Crop period (days)	Establishment phase (days)	Vegetative phase (days)	RD _m (cm)	Crop group for p
Sugarcane	365	1-30	31-75	150	4
Gram	108	1-20	21-45	130	2
Coconut	365	—	—	120	—

Source : Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; and Thangaraj and Muthuswami, 1990

Table 4.6 K_c values adopted for various crops of study area

Month		Crop			
		Sugarcane	Paddy	Gram	Coconut
June	I	1.05			0.54
	II	1.05			0.54
July	I	1.06	1.05		0.54
	II	1.06	1.05		0.54
Aug	I	1.10	1.10		0.54
	II	1.15	1.10		0.54
Sept	I	1.20	1.0		0.54
	II	1.13	1.0		0.54
Oct	I	1.03	0.95	0.29	0.54
	II	0.95	0.95	0.39	0.54
Nov	I	0.92	1.05	0.85	0.57
	II	0.88	1.05	1.10	0.57
Dec	I	0.87	1.10	1.10	0.57
	II	0.86	1.10	1.10	0.57
Jan	I	0.82	1.10	0.43	0.55
	II	0.87	1.10		0.55
Feb	I	0.92	1.10		0.55
	II	0.94	1.10		0.55
Mar	I	0.96	1.0		0.48
	II	0.94	1.0		0.48
Apr	I	1.03	0.95		0.48
	II	1.06	0.95		0.48
May	I	1.05			0.48
	II	1.05			0.48

(Source : Joshi *et al.*, 1986; Jayakumar *et al.*, 1988)

Table 4.7 Soil water depletion factor (p) for crop groups at different potential evapotranspiration (PET) values

Crop group	PET (mm/day)								
	2	3	4	5	6	7	8	9	10
Onion, Pepper Potato (1)	0.5	0.43	0.35	0.30	0.25	0.23	0.20	0.20	0.18
Banana, Cabbage Grape, Pea, Tomato (2)	0.68	0.58	0.48	0.40	0.35	0.33	0.28	0.25	0.23
Alfalfa, Bean, Citrus, Groundnut, Pineapple, Sunflower, Watermelon, Wheat (3)	0.8	0.7	0.6	0.5	0.45	0.43	0.38	0.35	0.30
Cotton, Maize, Olive, Safflower, Sorghum, Sugarcane, Soybean, Sugarbeet, Tobacco (4)	0.88	0.80	0.70	0.60	0.55	0.50	0.45	0.43	0.40

(Source : Doorenbos and Kassam, 1979)

4.9 ASSESSMENT OF SPATIAL DISTRIBUTION OF RECHARGE IN THE STUDY AREA

The total recharge from each BSU consists of both percolation losses and seepage losses from the water distribution system. Percolation losses for all the land use conditions are determined as described above (Chapter 4). To obtain seepage losses from basic simulation units, the units covered by each canal command area are identified and monthly seepage rates of that particular canal (Table 4.2) are allocated to the BSU in proportion to its area. The monthly seepage and percolation rates are added for each BSU, to obtain the total monthly recharge rates for each simulation unit.

The monthly, seasonal and annual recharge for each BSU are calculated for all the years from 1987-88 to 1994-95. The results for the years 1992-

Table 4.8 Daily water balance in the rice fields for one BSU of the study area, (Kharif season, 1995)

Day NO	RAIN	RUNOFF	IRRI	STANDING WATER	DEEP PERCOL	TSW	AET	CROP COEFFI.
Units for all are in mm								
1	0.00	0.00	31.75	110.28	14.54	123.00	6.30	1.10
2	2.50	0.00	0.00	91.96	13.90	123.00	6.30	1.10
3	0.00	0.00	0.00	71.83	13.20	123.00	6.30	1.10
4	0.00	0.00	31.45	82.61	13.58	123.00	6.45	1.10
5	0.00	0.00	0.00	62.63	12.88	123.00	6.45	1.10
6	11.25	0.00	0.00	54.20	12.59	123.00	6.45	1.10
7	10.00	0.00	34.60	78.28	13.43	123.00	6.45	1.10
8	0.00	0.00	0.00	58.45	12.74	123.00	6.45	1.10
9	0.00	0.00	0.00	39.29	12.07	123.00	6.45	1.10
10	0.00	0.00	32.00	51.69	12.50	123.00	6.45	1.10
11	0.00	0.00	0.00	33.80	11.84	123.00	5.50	1.10
12	21.25	0.00	0.00	37.05	11.95	123.00	5.50	1.10
13	21.25	0.00	33.81	72.86	13.20	123.00	5.50	1.10
14	0.00	0.00	0.00	54.25	12.55	123.00	5.50	1.10
15	7.50	0.00	0.00	43.52	12.18	123.00	5.50	1.10
16	0.00	0.00	27.98	52.95	12.51	123.00	5.50	1.10
17	0.00	0.00	0.00	35.01	11.88	123.00	5.50	1.10
18	0.00	0.00	0.00	17.91	11.28	123.00	5.30	1.10
19	0.00	0.00	35.47	35.65	11.90	123.00	5.30	1.10
20	0.00	0.00	0.00	18.52	11.30	123.00	5.30	1.10
21	0.00	0.00	0.00	1.97	10.72	123.00	5.30	1.10
22	0.00	0.00	37.95	22.64	11.44	123.00	5.30	1.10
23	0.00	0.00	0.00	5.95	10.86	123.00	5.30	1.10
24	0.00	0.00	0.00	0.00	10.30	106.87	5.30	1.10
25	0.00	0.00	37.39	5.11	10.82	123.00	4.85	1.10
26	12.75	0.00	0.00	1.82	10.70	123.00	4.85	1.10
27	0.00	0.00	0.00	0.00	10.16	107.50	4.85	1.10
28	11.25	0.00	30.61	10.04	10.99	123.00	4.85	1.10
29	0.00	0.00	0.00	0.00	10.44	107.23	4.85	1.10
30	15.50	0.00	0.00	0.00	10.09	107.30	4.85	1.10
31	17.00	0.00	20.25	5.39	10.83	123.00	4.85	1.10
32	82.50	0.00	0.00	69.94	13.06	123.00	4.45	1.10
33	46.25	0.00	0.00	97.28	14.01	123.00	4.45	1.10
34	16.00	0.00	13.69	107.70	14.37	123.00	4.45	1.10
35	3.50	0.00	0.00	92.46	13.84	123.00	4.45	1.10
36	0.00	0.00	0.00	74.35	13.21	123.00	4.45	1.10
37	7.00	0.00	10.74	74.00	13.20	123.00	4.45	1.10
38	9.00	0.00	0.00	65.21	12.89	123.00	4.45	1.10
39	0.00	0.00	0.00	47.96	12.30	123.00	4.50	1.10
40	15.00	0.00	23.07	68.09	13.00	123.00	4.50	1.10
41	8.25	0.00	0.00	58.94	12.67	123.00	4.50	1.05
42	0.00	0.00	0.00	42.13	12.08	123.00	4.50	1.05
43	0.00	0.00	28.59	53.52	12.48	123.00	4.50	1.05
44	0.00	0.00	0.00	36.89	11.90	123.00	4.50	1.05
45	0.00	36.89	0.00	0.00	10.10	108.18	4.50	1.05
46	0.00	30.12	30.12	0.00	10.10	123.00	4.60	1.05
47	10.50	10.50	0.00	0.00	10.10	118.57	4.60	1.05
48	0.00	0.00	0.00	0.00	9.95	103.79	4.60	1.05
49	1.25	0.00	28.68	0.00	10.46	118.43	4.60	1.05
50	11.25	0.00	0.00	0.00	10.32	114.52	4.60	1.05
51	3.75	0.00	0.00	0.00	9.94	103.50	4.60	1.05

contd.

52	0.00	0.00	33.01	0.00	10.55	121.13	4.60	1.05
53	21.25	0.00	0.00	4.37	10.75	123.00	4.05	1.05
54	45.50	0.00	0.00	33.84	11.78	123.00	4.05	1.05
55	0.00	0.00	30.14	47.47	12.25	123.00	4.05	1.05
56	0.00	0.00	0.00	31.52	11.70	123.00	4.05	1.05
57	0.00	0.00	0.00	16.11	11.16	123.00	4.05	1.05
58	4.50	0.00	28.35	32.96	11.75	123.00	4.05	1.05
59	6.00	0.00	0.00	23.30	11.41	123.00	4.05	1.05
60	0.00	0.00	0.00	8.00	10.88	123.00	4.20	1.05
61	0.00	0.00	32.45	24.58	11.46	123.00	4.20	1.05
62	0.00	0.00	0.00	9.24	10.93	123.00	4.20	1.05
63	0.00	0.00	0.00	0.00	10.41	108.18	4.20	1.05
64	6.75	0.00	34.19	10.73	10.98	123.00	4.20	1.05
65	0.00	0.00	0.00	0.00	10.46	108.13	4.20	1.05
66	0.00	0.00	0.00	0.00	9.60	94.12	4.20	1.05
67	22.75	0.00	33.72	11.89	11.03	123.00	4.45	1.05
68	0.00	0.00	0.00	0.00	10.50	107.83	4.45	1.05
69	0.00	0.00	0.00	0.00	9.59	93.57	4.45	1.05
70	0.00	0.00	34.16	0.00	10.26	112.79	4.45	1.05
71	3.50	0.00	0.00	0.00	9.87	101.75	4.45	1.05
72	0.00	0.00	0.00	0.00	0.00	97.11	4.45	1.05
73	18.75	0.00	30.40	7.70	10.88	123.00	4.45	1.05
74	2.50	0.00	0.00	0.00	10.44	110.59	4.25	1.05
75	2.50	0.00	0.00	0.00	9.77	98.87	4.25	1.05
76	24.50	0.00	28.33	13.17	11.07	123.00	4.25	1.05
77	2.50	0.00	0.00	0.58	10.63	123.00	4.25	1.05
78	0.00	0.00	0.00	0.00	10.12	108.42	4.25	1.05
79	0.00	0.00	31.03	1.33	10.65	123.00	4.25	1.05
80	0.00	0.00	0.00	0.00	10.14	108.39	4.25	1.05
81	0.00	0.00	0.00	0.00	9.61	94.27	4.30	1.05
82	0.00	0.00	31.51	0.00	10.19	111.07	4.30	1.05
83	0.00	0.00	0.00	0.00	9.70	96.86	4.30	1.05
84	0.00	0.00	0.00	0.00	0.00	92.99	4.30	1.05
85	0.00	0.00	29.56	0.00	0.00	119.16	4.30	1.05
86	0.00	0.00	0.00	0.00	9.97	105.11	4.30	0.95
87	8.00	0.00	0.00	0.00	9.77	99.26	4.30	0.95
88	10.00	0.00	33.20	4.38	10.75	123.00	4.55	0.95
89	2.50	0.00	0.00	0.00	10.33	110.85	4.55	0.95
90	0.00	0.00	0.00	0.00	9.69	96.83	4.55	0.95
91	15.00	0.00	27.78	1.63	10.66	123.00	4.55	0.95
92	0.00	0.00	0.00	0.00	10.15	108.52	4.55	0.95
93	0.00	0.00	0.00	0.00	9.61	94.59	4.55	0.95
94	0.00	0.00	23.85	0.00	0.00	115.01	4.55	0.95
95	12.50	0.00	0.00	0.00	10.25	112.98	4.50	0.95
96	0.00	0.00	0.00	0.00	9.76	98.94	4.50	0.95
97	0.00	0.00	0.00	0.00	0.00	95.03	4.50	0.95
98	6.75	0.00	0.00	0.00	0.00	98.33	4.50	0.95
99	75.00	0.00	0.00	34.26	11.79	123.00	4.50	0.95
100	0.00	0.00	0.00	18.73	11.25	123.00	4.50	0.95
101	0.00	0.00	0.00	3.73	10.73	123.00	4.50	0.95
102	0.00	0.00	0.00	0.00	10.23	108.31	4.70	0.95
103	0.00	0.00	0.00	0.00	9.61	94.24	4.70	0.95
104	0.00	0.00	0.00	0.00	0.00	90.74	4.70	0.95
105	0.00	0.00	0.00	0.00	0.00	87.67	4.70	0.95
106	8.00	0.00	0.00	0.00	0.00	92.98	4.70	0.95
107	0.00	0.00	0.00	0.00	0.00	89.63	4.70	0.95
108	0.00	0.00	0.00	0.00	0.00	86.70	4.70	0.95

Table 4.9 Monthly percolation rates during Kharif season(1995), mm

BSU	JUN	JUL	AUG	SEP	OCT	SEASUM
1	217.5	361.1	321.6	194.2	0.0	1094.4
2	173.8	370.4	331.1	217.2	0.0	1092.5
4	179.5	400.0	327.1	205.0	0.0	1111.6
3	172.7	355.0	304.9	195.9	0.0	1028.5
7	176.4	397.9	373.2	301.8	9.8	1259.1
6	169.7	361.2	350.5	284.9	9.8	1176.1
5	170.7	371.9	376.7	313.8	9.8	1242.9
10	176.4	397.9	373.2	301.8	9.8	1259.1
14	177.7	343.4	357.2	171.3	19.7	1069.3
9	169.7	361.2	350.5	284.9	9.8	1176.1
13	170.9	271.1	346.3	144.2	19.8	952.3
17	177.7	343.4	357.2	171.3	19.7	1069.3
8	170.7	371.9	376.7	313.8	9.8	1242.9
22	181.1	419.9	346.1	267.9	19.5	1234.5
23	181.1	419.9	346.1	267.9	19.5	1234.5
24	180.4	407.8	307.8	145.2	0.0	1041.2
16	170.9	271.1	346.3	144.2	19.8	952.3
12	168.1	359.1	332.1	144.7	0.0	1004.0
11	169.2	369.1	357.1	184.5	0.0	1079.9
19	170.9	271.1	346.3	144.2	19.8	952.3
15	168.1	359.1	332.1	144.7	0.0	1004.0
29	180.4	407.8	307.8	145.2	0.0	1041.2
21	174.3	383.9	328.2	226.5	19.4	1132.3
20	173.7	365.5	287.1	122.5	0.0	948.8
28	180.4	407.8	307.8	145.2	0.0	1041.2
18	168.1	359.1	332.1	144.7	0.0	1004.0
27	102.2	260.5	204.2	211.1	5.1	783.1
25	101.6	256.8	197.3	180.2	0.0	735.9
30	99.0	258.0	226.9	231.6	16.9	832.4
31	169.2	369.1	357.1	184.5	0.0	1079.9
38	101.6	256.8	197.3	180.2	0.0	735.9
26	101.6	256.8	197.3	180.2	0.0	735.9
32	99.0	258.0	226.9	231.6	16.9	832.4
33	99.0	258.0	226.9	231.6	16.9	832.4
34	101.9	266.3	201.1	231.3	19.7	820.3
35	101.9	266.3	201.1	231.3	19.7	820.3
36	101.9	266.3	201.1	231.3	19.7	820.3
37	102.2	260.5	204.2	211.1	5.1	783.1

Table 4.10 Cropping pattern in all BSU's of Godavari Delta Central Canal Irrigation Project

BSU	AREA, ha					
	AREA OF EACH BSU	PADDY		SUGAR- CANE	PULSES	COCO- NUT
		(KILARI)	(RABI)			
01	4018.89	1003.02	1064.47	272.35	348.67	174.33
02	1944.57	485.56	515.31	131.84	168.79	84.39
04	1199.38	299.49	317.84	81.32	104.11	52.05
03	1310.52	372.24	347.29	88.85	113.75	56.88
07	2199.07	715.58	660.60	36.72	400.69	175.71
08	3026.69	984.88	909.22	50.55	606.55	241.83
05	2002.03	651.48	601.41	33.43	401.21	159.96
10	835.59	373.00	353.20	38.19	186.08	157.09
14	1826.49	815.35	772.06	83.47	406.76	343.38
09	2405.00	1073.59	1016.59	109.91	535.59	452.14
13	1880.11	839.28	794.72	85.92	418.70	353.46
17	2089.69	873.69	607.05	72.30	182.00	517.82
08	980.20	437.56	414.33	44.79	218.29	184.28
22	5324.11	2226.01	1546.65	184.21	483.73	1319.31
23	3041.88	1243.82	147.84	0.00	533.85	843.82
24	6457.12	2640.32	313.82	0.00	1133.22	1791.21
16	2351.70	858.48	658.48	0.00	147.92	1349.88
12	2588.39	924.57	885.75	124.24	364.96	866.59
11	3311.04	1182.70	1133.04	158.93	466.86	1108.54
19	944.95	395.08	274.51	32.69	82.31	234.16
15	3180.96	890.67	890.67	0.00	200.08	1825.87
29	6538.65	2938.47	1675.85	0.00	1806.60	462.94
21	955.75	399.59	277.65	33.07	83.25	236.83
20	2995.66	1378.00	1245.59	0.00	390.33	1036.49
28	3748.95	1700.30	1500.67	0.00	710.80	227.56
18	2216.30	1019.49	921.54	0.00	288.78	766.84
27	4129.65	2255.20	1805.82	0.00	782.98	250.67
25	2819.09	1296.78	1172.18	0.00	367.33	975.41
30	2233.64	797.88	764.35	107.22	314.94	747.80
31	1272.62	390.44	383.69	0.00	89.08	565.68
38	1998.65	1002.12	975.14	0.00	274.00	382.94
26	5596.11	2805.88	2730.30	0.00	767.23	1072.03
32	6693.51	2053.57	2018.09	0.00	468.55	2975.27
33	5164.15	2788.64	2788.64	0.00	309.85	1240.95
34	2541.9	1372.63	1372.63	0.00	150.89	604.33
35	8186.94	2160.53	2062.29	0.00	654.96	2330.00
36	10034.68	3971.73	3836.20	0.00	1003.47	1886.52
37	735.64	194.13	185.31	0.00	58.85	209.36
Total	120777.97	47811.45	39940.79	1770.00	16026.01	28264.32

95 are given in Table 4.11 to Table 4.14. Thematic maps of the spatial distribution of the recharge for each year are generated by transferring the above results for annual recharge on to GIS. The distribution of the recharge potential of the irrigation project area, given by the average annual recharge for 3 years (1992-93 to 1994-95) is displayed on GIS (Fig. 4.9). The recharge rates in these 3 years varied from 0.1 to 3 m³/sec over the area. These variations reflect variations in weather, soils, water supplies and land use over the command area of the irrigation project.

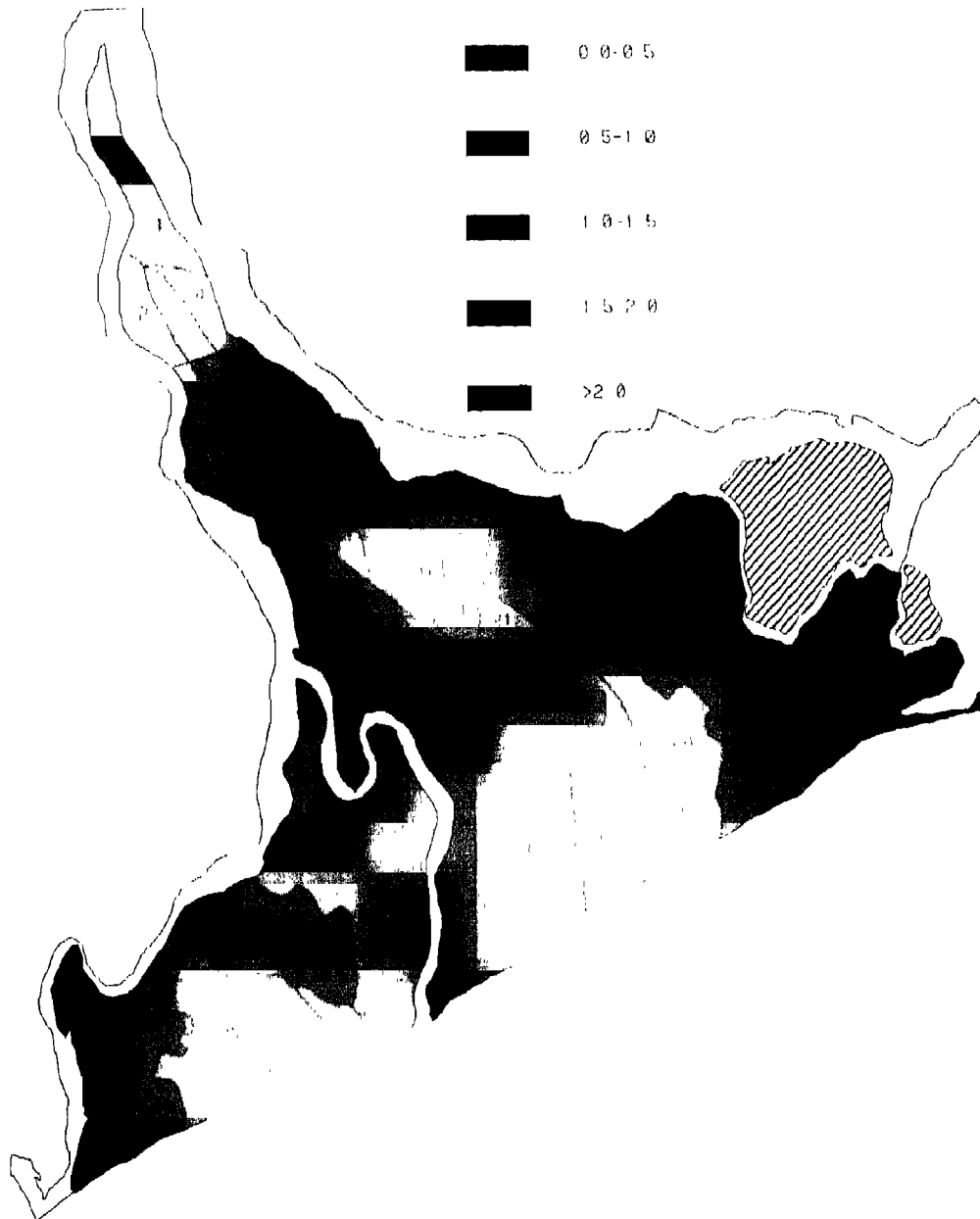
4.10 DISCUSSION

Assessment of recharge and its spatial variation is critical for irrigation management, drainage design, developing conjunctive water use plans and non point source pollution studies. At present, recharge from these sources is estimated by empirical norms developed by the Central Ground Water Board. These norms are based on the annual / seasonal precipitation and/or the irrigation supplies for the region. The estimate of recharge, runoff etc. are lumped and do not taken into account the spatial variations. They also ignore the temporal variations of recharge. Any realistic estimate of groundwater recharge should take into account these variations in the field conditions over the command area. In this chapter it was shown that this can be done by combining models of canal flow and soil water balance with GIS. Successive overlays of multiple data layers such as soil, land use, canal supplies and weather partitioned the study area into hydrologically homogeneous sub areas (BSU) by GIS over which the models could be run.

The simple model of canal flow used in this study is based on uniform flow in a canal reach and the discharges at either ends of the section (Fig 4.1). The seepage losses estimated using the simple model of canal flow compared

Fig. 4.9

AVERAGE ANNUAL RECHARGE, cum/sec (1992-95)



GODAVARI DELTA CENTRAL CANAL IRRIGATION PROJECT

Table 4.11 Recharge rates (m³/sec) for basic simulation units, 1992-93

BSU	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	MON	NMON	ANN
1	0.7	2.6	2.2	2.2	1.3	1.4	1.9	2.1	1.1	0.8	0.3	0.2	1.7	1.1	1.4
2	0.1	0.9	0.7	0.7	0.2	0.3	0.5	0.7	0.2	0.1	0.0	0.0	0.5	0.3	0.4
4	0.1	0.6	0.5	0.5	0.2	0.3	0.4	0.4	0.2	0.1	0.0	0.0	0.4	0.2	0.3
3	0.1	0.6	0.4	0.5	0.1	0.2	0.3	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.2
7	0.2	1.4	1.1	1.1	0.4	0.5	0.9	0.9	0.4	0.1	0.0	0.0	0.8	0.4	0.6
6	0.3	1.5	1.1	1.2	0.3	0.6	0.7	1.1	0.3	0.1	0.0	0.0	0.8	0.2	0.5
5	0.1	1.2	0.9	0.9	0.3	0.4	0.5	0.8	0.2	0.1	0.0	0.0	0.6	0.3	0.5
10	0.1	0.7	0.5	0.6	0.2	0.3	0.4	0.5	0.2	0.0	0.0	0.0	0.4	0.2	0.3
14	0.3	1.6	1.2	1.2	0.5	0.6	1.0	1.0	0.4	0.1	0.0	0.2	0.9	0.5	0.7
9	0.4	1.6	1.2	1.3	0.3	0.6	0.8	0.1	0.3	0.0	0.0	0.0	0.9	0.2	0.6
13	0.3	1.2	0.9	1.0	0.2	0.5	0.6	0.0	0.2	0.0	0.0	0.2	0.7	0.2	0.4
17	0.3	1.7	1.3	1.3	0.5	0.5	0.8	0.8	0.4	0.1	0.0	0.2	0.9	0.4	0.7
8	0.1	0.8	0.6	0.6	0.2	0.2	0.4	0.5	0.1	0.0	0.0	0.0	0.4	0.2	0.3
22	0.7	4.3	3.3	3.4	1.3	1.3	2.0	2.1	1.1	0.3	0.0	0.1	2.4	0.9	1.7
23	0.4	2.4	1.8	1.9	0.7	0.4	0.3	0.3	0.6	0.1	0.0	0.0	1.3	0.2	0.7
24	0.8	5.1	3.9	4.1	1.5	0.7	0.7	0.7	1.3	0.3	0.0	0.7	2.7	0.6	1.7
16	0.2	1.0	0.7	0.8	0.2	0.4	0.5	0.0	0.2	0.0	0.0	0.1	0.6	0.1	0.3
12	0.3	1.4	1.0	1.2	0.3	0.6	0.7	0.1	0.3	0.1	0.3	0.0	0.8	0.3	0.5
11	0.2	2.2	1.7	1.7	0.5	0.6	1.0	1.4	0.4	0.1	0.4	0.0	1.2	0.6	0.8
19	0.1	0.6	0.4	0.5	0.1	0.2	0.2	0.0	0.1	0.0	0.0	0.1	0.3	0.1	0.2
15	0.3	1.3	1.0	1.1	0.3	0.6	0.7	0.1	0.3	0.1	0.3	0.0	0.8	0.3	0.5
29	0.8	5.6	4.3	4.5	1.7	1.5	2.2	2.3	1.4	0.3	0.0	0.8	3.1	1.2	2.1
21	0.1	0.6	0.4	0.5	0.1	0.2	0.2	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.2
20	0.4	2.0	1.5	1.7	0.4	0.7	1.0	0.1	0.4	0.1	0.0	0.3	1.1	0.3	0.7
28	0.5	3.3	2.5	2.6	1.0	1.1	1.9	1.9	0.8	0.2	0.0	0.4	1.8	0.9	1.4
18	0.4	1.6	1.2	1.3	0.4	0.7	0.8	0.1	0.4	0.1	0.3	0.1	0.9	0.3	0.6
27	0.2	2.5	2.0	2.4	2.1	1.0	1.3	1.3	0.7	0.2	0.0	0.5	1.7	0.7	1.2
25	0.2	1.3	1.0	1.2	1.0	0.5	0.9	0.9	0.4	0.1	0.0	0.3	0.9	0.4	0.7
30	0.1	0.9	0.7	0.9	0.8	0.4	0.6	0.6	0.3	0.1	0.3	0.1	0.6	0.3	0.5
31	0.1	0.7	0.6	0.6	0.2	0.2	0.3	0.5	0.1	0.0	0.1	0.0	0.4	0.2	0.3
38	0.2	1.0	0.8	0.9	0.7	0.4	0.8	0.8	0.3	0.0	0.0	0.2	0.7	0.4	0.5
26	0.5	2.8	2.2	2.6	2.1	1.1	2.1	2.1	0.8	0.1	0.0	0.6	1.9	1.0	1.4
32	0.3	2.3	2.0	2.3	2.0	1.1	1.5	1.6	0.8	0.3	0.7	0.2	1.7	0.8	1.3
33	0.3	3.0	2.5	2.9	2.6	1.4	2.0	2.0	0.9	0.2	0.9	0.2	2.1	1.0	1.6
34	0.1	1.4	1.2	1.4	0.8	0.5	1.0	1.0	0.4	0.1	0.0	0.0	0.9	0.4	0.7
35	0.3	2.4	2.2	2.4	1.4	0.9	1.6	1.6	0.9	0.3	0.1	0.0	1.6	0.8	1.2
36	0.5	4.2	3.7	4.1	2.4	1.5	2.8	2.8	1.4	0.4	0.1	0.0	2.7	1.2	2.0
37	0.0	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.2	0.1	0.1

Total Gross Recharge
 Total Gross Recharge from the area considered for Groundwater Model
 (BSU'S not included are 30,31,32,33,34,35,36,37)

29.8
22.0

Table 4.12 Recharge rates (m³/sec) for basic simulation units, 1993-94

BSU	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	MON	NMON	ANN
1	0.8	2.6	2.2	2.2	2.1	1.5	2.1	2.1	1.1	0.8	0.0	0.2	1.9	1.0	1.5
2	0.1	0.9	0.8	0.7	0.8	0.3	0.5	0.1	0.2	0.1	0.0	0.0	0.6	0.2	0.4
4	0.1	0.6	0.5	0.5	0.4	0.3	0.6	0.6	0.1	0.1	0.0	0.0	0.4	0.2	0.3
3	0.2	0.7	0.5	0.5	0.5	0.2	0.3	0.0	0.1	0.0	0.0	0.0	0.4	0.1	0.3
7	0.3	1.3	1.1	1.1	0.8	0.5	1.3	1.3	0.4	0.1	0.0	0.0	0.9	0.5	0.7
6	0.4	1.6	1.2	1.1	1.0	0.5	0.8	0.1	0.3	0.1	0.0	0.0	1.0	0.2	0.6
5	0.1	1.1	1.0	0.8	0.8	0.4	0.7	0.1	0.3	0.1	0.0	0.0	0.7	0.2	0.4
10	0.1	0.7	0.6	0.5	0.4	0.3	0.7	0.7	0.2	0.0	0.0	0.0	0.4	0.3	0.4
14	0.3	1.5	1.2	1.5	1.5	0.7	1.5	1.4	0.3	0.1	0.0	0.0	1.1	0.6	0.8
9	0.4	1.7	1.3	1.2	1.0	0.6	0.9	0.0	0.3	0.0	0.0	0.0	1.0	0.2	0.6
13	0.3	1.4	1.1	1.3	1.3	0.5	0.8	0.0	0.2	0.0	0.0	0.0	1.0	0.2	0.6
17	0.3	1.6	1.3	1.6	1.5	0.6	1.2	1.2	0.4	0.1	0.0	0.0	1.1	0.5	0.8
8	0.0	0.7	0.6	0.5	0.5	0.3	0.5	0.0	0.2	0.0	0.0	0.0	0.4	0.1	0.3
22	0.8	4.0	3.4	4.0	1.8	1.5	3.1	3.0	0.9	0.2	0.0	0.0	2.6	1.2	1.9
23	0.4	2.2	1.9	2.2	1.0	0.4	0.4	0.4	0.5	0.1	0.0	0.0	1.4	0.2	0.8
24	0.9	4.7	3.8	3.9	3.3	0.5	0.9	0.9	1.1	0.3	0.0	0.0	2.9	0.5	1.7
16	0.2	1.2	0.8	1.0	1.0	0.4	0.7	0.0	0.2	0.0	0.0	0.0	0.8	0.1	0.5
12	0.4	1.5	1.1	0.9	0.9	0.5	0.8	0.1	0.2	0.1	0.0	0.0	0.9	0.2	0.5
11	0.1	1.9	1.7	1.4	1.3	0.7	1.3	0.1	0.4	0.1	0.0	0.0	1.2	0.3	0.8
19	0.1	0.7	0.5	0.6	0.6	0.2	0.3	0.0	0.1	0.0	0.0	0.0	0.5	0.1	0.3
15	0.3	1.5	1.1	0.9	0.9	0.5	0.9	0.1	0.2	0.1	0.0	0.0	0.9	0.2	0.5
29	1.0	5.2	4.2	4.3	3.7	1.4	3.3	3.3	1.2	0.3	0.0	0.0	3.3	1.4	2.3
21	0.2	0.7	0.5	0.6	0.3	0.2	0.3	0.0	0.1	0.0	0.0	0.0	0.4	0.1	0.2
20	0.5	2.2	1.5	1.7	1.5	0.7	1.0	0.1	0.3	0.1	0.0	0.0	1.4	0.3	0.8
28	0.6	3.0	2.4	2.5	2.1	1.1	0.9	0.1	0.3	0.1	0.0	0.0	2.0	1.1	1.5
18	0.4	1.7	1.3	1.0	1.1	0.6	0.9	0.1	0.5	0.1	0.0	0.0	1.0	0.2	0.6
27	0.1	2.4	2.0	2.4	2.4	1.7	1.6	1.6	0.5	0.1	0.0	0.0	1.8	0.6	1.2
25	0.3	1.4	1.0	1.2	1.3	1.0	1.0	0.9	0.2	0.1	0.0	0.0	1.0	0.4	0.7
30	0.1	0.9	0.8	0.8	0.9	0.6	0.7	0.7	0.2	0.1	0.0	0.0	0.7	0.3	0.5
31	0.0	0.6	0.6	0.5	0.4	0.3	0.4	0.0	0.1	0.0	0.0	0.0	0.4	0.1	0.2
38	0.2	1.0	0.8	1.0	1.0	0.8	0.8	0.8	0.2	0.0	0.0	0.0	0.8	0.3	0.6
26	0.6	2.9	2.2	2.6	2.9	2.1	2.2	2.1	0.5	0.1	0.0	0.0	2.2	0.8	1.5
32	0.1	2.2	2.1	2.1	2.1	1.6	2.0	1.9	0.6	0.2	0.0	0.0	1.8	0.8	1.3
33	0.2	2.9	2.6	2.7	2.9	2.1	2.6	2.5	0.7	0.2	0.0	0.0	2.2	1.0	1.6
34	0.1	1.5	1.2	1.4	1.4	1.0	1.3	1.3	0.4	0.1	0.0	0.0	1.1	0.5	0.8
35	0.2	2.7	2.2	2.6	2.5	1.7	2.2	2.1	0.8	0.3	0.0	0.1	2.0	0.9	1.4
36	0.3	4.6	3.7	4.4	4.3	2.9	3.9	3.8	1.3	0.4	0.0	0.1	3.4	1.6	2.5
37	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.2	0.1	0.1

Total Gross Recharge

32.5

Total Gross Recharge from the area considered for Groundwater Model

24.1

(BSU'S not included are 30,31,32,33,34,35,36,37)

Table 4.13 Recharge rates (m³/sec) for basic simulation units, 1994-95

BSU	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	MON	NMON	ANN
1	1.2	2.7	2.2	1.7	1.7	1.7	2.0	2.1	1.2	0.9	0.0	1.0	1.9	1.2	1.5
2	0.2	1.0	0.7	0.5	0.5	0.6	0.5	0.7	0.2	0.1	0.0	0.5	0.6	0.3	0.5
4	0.2	0.6	0.4	0.3	0.3	0.4	0.5	0.5	0.2	0.1	0.0	0.3	0.4	0.3	0.3
3	0.1	0.7	0.5	0.3	0.3	0.4	0.3	0.4	0.1	0.0	0.0	0.4	0.4	0.2	0.3
7	0.3	1.3	1.0	1.0	0.9	1.1	1.1	1.0	0.4	0.1	0.0	0.7	0.9	0.6	0.7
6	0.3	1.7	1.3	1.3	1.2	1.4	0.7	1.1	0.3	0.1	0.0	1.2	1.2	0.5	0.9
5	0.2	1.2	0.9	1.0	0.8	0.9	0.6	0.8	0.2	0.1	0.0	0.6	0.8	0.4	0.6
10	0.1	0.7	0.5	0.5	0.5	0.6	0.6	0.5	0.2	0.0	0.0	0.4	0.5	0.3	0.4
14	0.3	1.6	1.2	1.3	1.5	1.3	1.2	1.2	0.6	0.1	0.0	0.8	1.2	0.7	0.9
9	0.3	1.8	1.4	1.4	1.3	1.5	0.8	1.2	0.3	0.0	0.0	1.0	1.3	0.6	0.9
13	0.2	1.6	1.2	1.3	1.5	1.3	0.6	1.0	0.2	0.0	0.0	0.8	1.2	0.4	0.8
17	0.4	1.7	1.3	1.4	1.6	1.3	1.0	0.9	0.6	0.1	0.0	0.8	1.3	0.6	0.9
8	0.1	0.8	0.6	0.6	0.5	0.6	0.4	0.5	0.1	0.0	0.0	0.4	0.5	0.2	0.4
22	0.9	3.8	3.0	2.5	3.0	3.3	2.5	2.4	1.2	0.3	0.0	2.4	2.8	1.5	2.1
23	0.5	2.1	1.7	1.4	1.7	1.4	0.4	0.4	0.7	0.2	0.0	1.3	1.5	0.5	1.0
24	1.0	4.7	3.5	3.1	2.3	1.9	0.8	0.8	1.5	0.3	0.0	1.8	2.8	0.9	1.8
16	0.2	1.2	0.9	1.0	1.2	1.1	0.5	0.8	0.2	0.0	0.0	0.6	0.9	0.4	0.6
12	0.3	1.5	1.1	0.9	1.1	1.4	0.7	1.1	0.3	0.1	0.0	1.3	1.5	0.7	1.1
11	0.4	2.1	1.6	1.3	1.5	1.9	1.1	1.5	0.4	0.1	0.0	0.4	0.6	0.2	0.4
19	0.1	0.7	0.6	0.6	0.7	0.6	0.2	0.3	0.1	0.0	0.0	1.0	1.0	0.5	0.8
15	0.3	1.5	1.1	0.8	1.1	1.4	0.7	1.1	0.3	0.1	0.0	1.0	1.0	0.5	0.8
29	1.1	5.2	3.9	3.4	2.6	2.9	2.8	2.7	1.6	0.3	0.0	2.0	3.2	1.6	2.4
21	0.1	0.6	0.5	0.4	0.5	0.6	0.2	0.3	0.1	0.0	0.0	0.4	0.5	0.2	0.3
20	0.4	2.3	1.7	1.5	1.1	0.9	0.9	1.5	0.4	0.1	0.0	0.9	1.3	0.6	1.0
28	0.6	3.0	2.2	2.0	1.5	2.0	2.4	2.3	0.9	0.2	0.0	1.1	1.9	1.1	1.5
18	0.3	1.7	1.3	1.0	1.3	1.6	0.8	1.2	0.4	0.1	0.0	1.1	1.2	0.6	0.9
27	0.4	2.6	2.1	2.4	2.3	2.0	1.5	1.6	0.7	0.1	0.0	1.6	2.0	0.9	1.4
25	0.2	1.4	1.1	1.2	1.2	1.1	0.9	0.9	0.4	0.1	0.0	0.9	1.0	0.5	0.8
30	0.2	0.9	0.7	0.8	0.8	0.8	0.7	0.7	0.3	0.1	0.0	0.6	0.7	0.4	0.6
31	0.1	0.7	0.5	0.4	0.5	0.6	0.4	0.5	0.1	0.0	0.0	0.4	0.5	0.2	0.4
38	0.2	1.1	0.9	1.0	1.0	0.9	0.8	0.8	0.3	0.0	0.0	0.7	0.9	0.4	0.6
26	0.4	3.1	2.4	2.7	2.7	2.5	2.2	2.1	0.8	0.1	0.0	2.0	2.3	1.2	1.7
32	0.5	2.4	1.9	2.1	2.2	2.1	1.8	1.9	0.8	0.2	0.0	1.7	1.9	1.1	1.5
33	0.5	3.1	2.4	2.6	2.8	2.8	2.3	2.5	0.9	0.2	0.0	2.2	2.4	1.4	1.9
34	0.3	1.5	1.3	1.5	1.5	1.4	1.1	1.2	0.4	0.1	0.0	1.3	1.3	0.7	1.0
35	0.6	2.7	2.4	2.7	2.8	2.6	1.9	2.0	0.8	0.3	0.0	2.5	2.3	1.3	1.8
36	0.8	4.6	4.0	4.6	4.7	4.3	3.3	3.5	1.3	0.3	0.0	4.1	3.8	2.1	3.0
37	0.0	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.2	0.2	0.1	0.2

Total Gross Recharge

Total Gross Recharge from the area considered for Groundwater Model

(BSU'S not included are 30,31,32,33,34,35,36,37)

32.5

24.1

**Table 4.14 Recharge rates (m³/sec) for basic simulation units, 1995
(Monsoon season)**

BSU	JUN	JUL	AUG	SEP	OCT	NOV	MON
1	1.8	2.2	2.1	1.6	2.1	1.6	1.9
2	0.4	0.7	0.7	0.5	0.7	0.4	0.6
4	0.3	0.5	0.4	0.3	0.4	0.3	0.4
3	0.3	0.5	0.5	0.3	0.5	0.2	0.4
7	0.6	1.2	1.1	0.9	1.0	0.5	0.9
6	0.7	1.4	1.4	1.1	1.3	0.5	1.1
5	0.5	1.0	1.0	0.9	0.9	0.4	0.8
10	0.3	0.6	0.6	0.5	0.5	0.3	0.5
14	0.7	1.1	1.2	0.6	1.1	0.7	0.9
9	0.8	1.5	1.5	1.2	1.4	0.6	1.2
13	0.6	0.9	1.1	0.5	1.1	0.6	0.8
17	0.7	1.2	1.3	0.7	1.2	0.6	1.0
8	0.3	0.6	0.7	0.6	0.6	0.3	0.5
22	1.9	3.8	3.2	2.6	3.4	1.6	2.8
23	1.0	2.1	1.8	1.4	1.9	0.5	1.4
24	2.2	4.3	3.4	1.8	3.3	1.4	2.7
16	0.5	0.7	0.9	0.4	0.9	0.5	0.7
12	0.7	1.3	1.2	0.6	1.3	0.6	1.0
11	0.9	1.8	1.7	1.0	1.7	0.9	1.3
19	0.3	0.4	0.5	0.2	0.5	0.2	0.4
15	0.6	1.3	1.2	0.6	1.2	0.6	0.9
29	2.4	4.8	3.7	2.0	3.6	2.2	3.1
21	0.3	0.6	0.5	0.4	0.6	0.2	0.4
20	1.0	1.9	1.5	0.7	1.6	0.8	1.2
28	1.4	2.8	2.1	1.1	2.1	1.6	1.8
18	0.8	1.5	1.4	0.7	1.4	0.7	1.1
27	1.0	2.4	2.0	2.0	1.8	1.9	1.8
25	0.6	1.3	1.0	1.0	1.0	1.1	1.0
30	0.4	0.9	0.8	0.8	0.8	0.7	0.7
31	0.3	0.6	0.6	0.3	0.6	0.3	0.5
38	0.4	1.1	0.8	0.7	0.8	0.9	0.8
26	1.2	2.9	2.3	2.1	2.2	2.4	2.2
32	1.0	2.3	2.2	2.1	2.2	1.8	1.9
33	1.3	3.0	2.7	2.7	2.8	2.3	2.5
34	0.6	1.5	1.2	1.3	1.4	1.2	1.2
35	1.2	2.9	2.3	2.2	2.8	1.9	2.2
36	2.0	4.8	3.8	3.9	4.6	3.4	3.7
37	0.1	0.2	0.2	0.2	0.2	0.2	0.2

well with the values obtained by Hydraulics Research Station, (1975) and Bos and Nugteren, (1978). A rating curve derived from these results facilitated the direct estimation of seepage losses for any given discharge at the canal headworks. Though it was possible to develop separate regression relationship for each of the section considered, only a general relationship based on the flow rate at the headworks and other associated seepage losses is attempted. It can be seen from the rating curves (Fig 4.6 to Fig 4.8), that as the flow increases the seepage losses also increases. But this rate of increase in seepage loss is not in proportion to rate of increase in canal flow rate, i.e. even at smaller flow rate, substantial amount of seepage losses occurred.

The soil water balance model was run for each BSU to estimate percolation losses. The soil water balance model used in this study incorporated several features to facilitate estimation of percolation losses from multiple cropped areas. Specifically daily percolation losses from

- (i) rice fields which require flooded conditions (*Kharif* and *Rabi* season)
- (ii) other cropped areas (pulses, sugarcane and coconut plantations)
- (iii) Rice fallow lands, and
- (iv) uncultivated lands

could be estimated for several years in one model run for each set of soil, weather and water supply conditions (BSUs).

In the case of water balance studies for paddy, runoff was estimated as rainfall in excess of that stored within the bunds of the field, and deep percolation was calculated using Darcy's law. Similar procedures were adopted by Pereira,

1989, Rao and Rees, 1992; Rao, 1995, Odhiambo and Murthy, 1996. The amount of irrigation applied to paddy crop was obtained from canal discharge values after accounting for seepage losses from main canal, branches and distributaries

For other crops, the two layer daily soil water balance model incorporates the runoff estimation which uses the soil moisture accounting procedure by Sharpley and Williams (1990). In this, the curve number is directly related to the actual soil moisture status while the earlier approaches used previous five days rainfall amounts.

Further in some earlier studies, for example, Rao (1987); Porwal and Rao (1988) and Doraiswamy (1992), the soil moisture in the soil below the active rootzone was considered to have the same initial soil moisture content for the entire crop period. This is not necessarily true in field conditions, as good rain or irrigation can vary the soil moisture in this region too. In the present study, the quantity of water percolating into this zone was assumed to be uniformly distributed in this region. So, the moisture content in the passive layer keeps changing, if the quantity of rainfall or irrigation is more than that required for saturating the active layer. The soil water balance model used in this study has been tested previously at several locations in India and applied in field scale irrigation scheduling models (Hajilal *et al.*, 1998 ; Purohit and Gosain, 1990; Rao 1987; Rao and Sarma, 1988; Rao *et al.*, 1988, 1990; Doraiswamy, 1992).

The deep percolation out of root zone depth (RDM) is considered to contribute to recharge. The underlying assumption is that the surface conditions responsible for the measured deep percolation rates will remain same such that the recharge rate will eventually equal the deep percolation rate. Similar assumption was made in several other studies (Allison, 1994, Fayer *et al.*, 1996 , Hajilal *et al.*, 1998). This approach is applicable to basin wide recharge

estimations. Some of the earlier studies in which recharge was computed by equating it to infiltration at the soil surface, and stream beds, in response to rainfall, irrigation and stream flow (Rantz and Eakin, 1971; Howard and Lloyd, 1979; Keith, 1981; Rao and Sarma, 1982, 1984). The recharge rates obtained here are also subsequently validated by giving them as input to the groundwater flow model to simulate groundwater levels (Chapter 6).

For uncultivated areas evapotranspiration is replaced by soil evaporation, which is estimated by a two stage evaporation model (Ritchie, 1972). In case of rice fallow lands, soil water balance model for paddy crops was combined with two stage evaporation model (Ritchie, 1972). Suitable adjustment was made to account for the harvesting of a crop in a particular month.

Recharge maps were developed for a case study irrigation project area using GIS, soil water balance model and canal model. The development of the interface between the GIS and models facilitated efficient use of both GIS and models. The GIS was used to generate files that can be read by the Fortran programme. Once the models were run, the output was brought into GIS to generate thematic maps. Thus instead of building a new single environment for GIS and models, each was developed independently. Such loose integration between models and GIS is considered both time and cost effective as no testing of established model is necessary and model development can be carried out independently (Harris *et al.*, 1993).

In some of the earlier studies, GIS was used to delineate the primary recharge contributing areas on large watershed (Rogowaski, 1996, Fayer *et al.*, 1996). These studies did not take the spatial distribution of rainfall into account, while delineating the watershed area. In the present study, the basic simulation units derived by GIS overlays represent a unique combination of soil, canal

to the earlier studies by Rogowski (1996), Fayer *et al.* (1996) etc. In the present study, the capabilities of GIS are explored not only for derivation of BSU's but also for selecting the input files required to run the soil water balance model. More over, recharge estimates in these studies were made mainly from grass lands and non paddy crops. In the present study, percolation amounts from paddy fields are also included in the recharge in addition to uncultivated areas and non-paddy cropped areas. It was thus shown that it is possible to take advantage of the capabilities of soil water balance model and GIS to assess the spatial distribution of recharge in irrigation projects by taking account the spatial variations in agrohydrologic processes. Though several techniques like lysimetry, water content measurements and tracers are available for estimation of recharge, conflicting results were obtained by these methods (Fayer *et al.*, (1996)) because of upscaling from point measurements to large areas. Hence, these potential errors associated with upscaling were eliminated by linking GIS with soil water balance model.

The results obtained in this chapter are used to provide the data input to models developed to

- (i) estimate nitrate pollutant loads from rice fields (Chapter 5)
- (ii) simulate the groundwater levels in the aquifer underlying command area (Chapter 6), and
- (iii) simulate nitrate transport in the aquifer underlying the command area.

5. ESTIMATING NITRATE POLLUTANT LOADS TO GROUNDWATER

Introduction

Rice is the dominant crop in the study area and consume bulk of the applied fertilizer. Leaching of nitrate from applied fertilizers is the main source of pollution of groundwater underlying flooded rice fields. In general nitrogen fertilizers usually contain nitrogen in one of three forms: ammonium, nitrate or urea. Of these, the commonest is urea which is the organic compound, $\text{CO}(\text{NH}_2)_2$. When urea is applied in flooded water, it is converted to ammonium (NH_4^+) and nitrate (NO_3^-). Nitrate is soluble and moves with the water percolating through the soil and is not adsorbed to soil particles. On the other hand, ammonium gets adsorbed to the soil particles and is taken up by the plants. In order to predict the concentration of nitrate in the water percolating out of the root zone it is necessary to maintain a budget of nitrate and water in the root zone. Many complex models have been developed to quantify the nitrogen transformation processes in the soil. These complex models require numerous parameters which are not usually available. Moreover, most of these models were developed for aerobic conditions. As anaerobic conditions exist in flooded soils, which greatly affect N transformations and fertilizer use by rice, a simple model which requires minimum number of parameters that will provide an acceptable means for quantifying nitrogen transformation processes is necessary. The development of such a model is presented in this chapter

The proposed model considers all the important nitrogen transformation processes in the soil root zone namely, urea hydrolysis, volatilization, nitrification,

mineralization, immobilization, denitrification, uptake and leaching. Since nitrate moves with water, the model development is such that it can be linked to the output of the soil water balance model for rice developed in the previous chapter. The parameter identification and data input are such that simulations can be carried out for a wide range of weather regimes, soil types and irrigation applications. The model is expected to serve two purposes namely,

- (i) to assess spatially variable potential pollutant loadings from rice fields over the study area, and
- (ii) to provide the input to a groundwater transport model (Chapter 6) for simulating the movement of pollutant within the aquifer

5.1 DEVELOPMENT OF A MODEL FOR QUANTIFYING NITROGEN TRANSFORMATION PROCESSES

A flooded soil is a unique soil water system that has three distinct zones (Fig 5.1) established by the prevailing oxidation - reduction or redox potential of the system (Keeney and Sahrawat, 1986). These zones are (i) a layer of flood water of about 5 to 7 cm thickness, (ii) an oxidized top soil layer of thickness of about few mm to 1 cm below the soil surface, and (iii) a reduced layer in the rest of the root zone. The thickness of the rootzone is normally about 30 cm.

Transformation reactions that occur in the different redox zones of an idealized flooded soil - water system can be represented as follows:

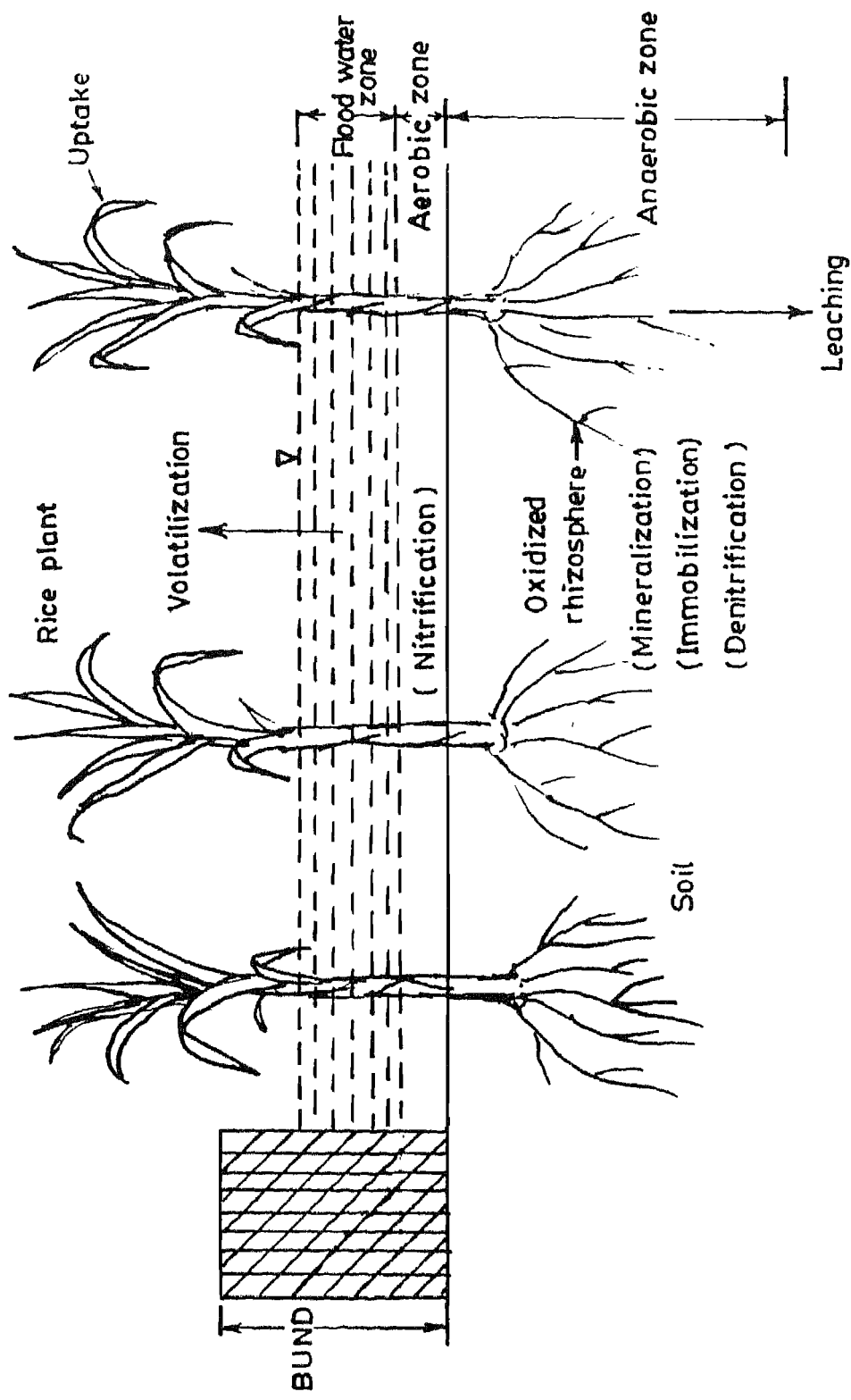


Fig.5.1 Zoning of ideal paddy field for N - balance studies

Zone	Redox State	Dominant N transformation Processes
Flood water	Oxidized	Nitrification, NH_4^+ Volatilization
Oxidized surface layer	Partially oxidized	Nitrification
Reduced soil layer	Reduced	Mineralization, Immobilization, Denitrification, Uptake
Rhizosphere	Partially oxidized	Mineralization, Nitrification, Denitrification

Source : Keeney and Sahrawat (1986)

The presence of oxidized and reduced soil layers (Fig 5.1) makes the flooded soils a unique system where both aerobic and anaerobic N metabolism can occur in close proximity. The schematic diagram of the various N-transformation processes considered in the model is illustrated in Fig. 5.2.

The nitrogen balance equation considering all N-Transformation processes is given as

$$\begin{aligned} \text{Fertilizer N (hydrolyzed inorganic N from Urea) + Mineralized N (from organic N in soil)} &= \text{Volatilized N + Nitrified N (Denitrified N} \\ &+ \text{Leached N + } \text{NO}_3^- \text{ left in the soil) +} \\ &\text{Immobilized N + N uptake by plants +} \\ &\text{NH}_4^+ \text{ left in the soil} \end{aligned} \quad (5.1)$$

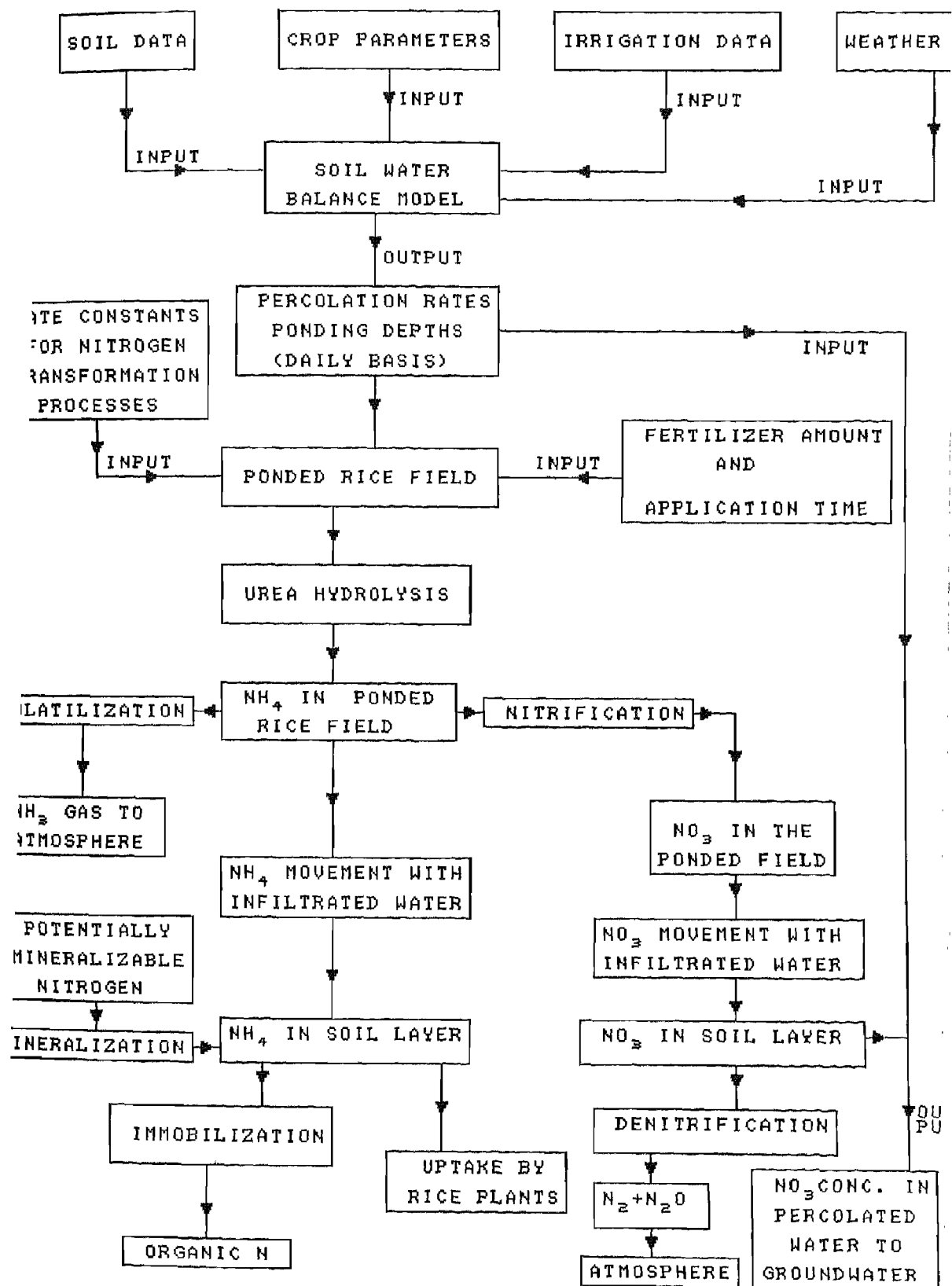
5.1.1 Modelling Individual Components of N Balance Equation

In general all the processes except plant uptake and leaching can be considered to follow first order kinetics and can be represented by first order differential equations with one parameter.

a. Urea hydrolysis

Urea is an inexpensive and widely used N fertilizer. When urea is broadcast on flooded soil, it is hydrolyzed to NH_4^+ and HCO_3^- ions. The process of urea hydrolysis can be represented by a first order reaction as follows.

FIG. 5.2 Schematic Representation of Nitrogen Balance Model



$$UNH_4 = U (1 - \exp(-k_u \cdot t)) \quad (5.2)$$

U = amount of fertilizer (urea) applied, kg/ha

UNH_4 = amount of ammonium produced during urea hydrolysis, kg/ha

K_u = rate constant for urea hydrolysis, day⁻¹, and

t = time, day

b. Volatilization

During volatilization part of the ammonium produced during urea hydrolysis is converted to gaseous ammonia. Part of the ammonia produced dissolves in the aqueous phase in flood water and is in equilibrium with ammonium ions in solution and ammonia gas in the adjacent gas phase. The process of transfer of ammonia gas from the soil surface to the immediate atmosphere is also assumed to follow first order kinetics (Rao *et al.*, 1984; Mc Innes *et al.*, 1986, Hutson and Wagenet, 1991) and given as follows:

$$UNH_3 = UNH_4 (1 - \exp(-k_v \cdot t)) \quad (5.3)$$

UNH_3 = Ammonia produced during volatilization process, kg/ha

K_v = Volatilization rate constant, day⁻¹, and

UNH_4 = Ammonium produced during hydrolysis process, kg/ha (obtained from equation 5.2).

c. Nitrification

The conversion of NH_4^+ to nitrate is called nitrification. In flooded rice soils, the substrates for nitrification are provided in the form of ammonium ions (NH_4^+) produced during urea hydrolysis. Nitrification is an oxidation process and can potentially occur in the flood water above soil surface, the oxidized top soil layer of few mm thickness just below the soil surface, and the oxidized part of the rhizosphere. For the present model nitrification in the oxidized

rhizosphere and the reduced layer is not considered because of the small size of this layer. Nitrification in the flooded zone follows the first order rate equation (Mehran and Tanji, 1974; Watts and Hanks, 1978; Rao *et al.*, 1984; Stockle and Campbell, 1989, 1994; Hutson and Wagenet, 1991; Verma *et al.*, 1995) given by :

$$\text{UNO}_3 = \text{UNH}_4 (1 - \exp (-k_n \cdot t)) \quad (5.4)$$

UNO_3 = Nitrate produced during nitrification, kg/ha

K_n = nitrification rate constant, day⁻¹, and

UNH_4 = Ammonium produced during urea hydrolysis process, kg/ha
(from equation 5.2)

Part of the nitrate produced during this process is transported from the surface layer by the infiltrating water into the root zone. The daily soil water balance in paddy fields provides the estimate of the daily percolation rates. Since the soil is saturated and ponded conditions are maintained at the soil surface, this is also the infiltration rate. The nitrate left on the surface after accounting for transported amount is added to the nitrate available on the succeeding day and this process is carried out throughout the season.

d Mineralization

Mineralization of organic N to inorganic NH_4^+ in the root zone is a key process in the N nutrition of lowland rice. The NH_4^+ produced in the root zone cannot be oxidized to nitrate in the absence of oxygen. Moreover ammonium is strongly attached to negatively charged clay particles and is rarely leached out of a rootzone in any quantity, unless the soil is a very sandy one with little clay (Aulakh and Singh, 1997). The mineralization process is represented by the first order kinetics equation as (Stanford and Smith, 1972; Mehran and Tanji, 1974; Johnsson *et al.*, 1987; Stockle and Campbell, 1989; Borg *et al.*, 1990)

$$MNH_4 = PMN [1 - \exp (- k_m \cdot t)] \quad (5.5)$$

where

PMN = Potentially, mineralizable N, kg/ha

MNH_4 = NH_4 produced during mineralization, kg/ha, and

K_m = mineralization rate constant, day^{-1} .

Part of ammonium produced during urea hydrolysis process is also leached from the surface layer to the root zone along with infiltrated water and is added to the ammonium produced during mineralization process in the root zone. Thus total NH_4^+ is available for uptake by plants and for the immobilization process.

e Immobilization

Mineralization and immobilization are N - transformation processes which occur simultaneously in flooded soils. During immobilization process soil organisms assimilate inorganic N compounds and transform them into organic N constituents of their cells, tissues and soil mass. For the present model immobilization process is also considered to follow first order kinetics (Stanford and Smith, 1972, Mehran and Tanji, 1974) and is represented by the equation:

$$\text{Immobilized N} = NH_4^+ [1 - \exp (- k_i \cdot t)] \quad (5.6)$$

where

NH_4^+ = Amount of ammonium in the root zone, kg/ha (Mineralized ammonium + ammonium from applied urea infiltrated from the surface along with infiltrated water)

K_i = Immobilization rate constant, day^{-1} .

f. Denitrification

During denitrification the fixed N is returned from the soil to the atmosphere. This occurs in the reduced zones of the flooded rice fields. Part of the nitrates produced during the nitrification process on the surface layer are transported to the reduced zone along with the infiltrated water and readily reduced to nitrogenous gases. This reduction of nitrates into gaseous products can be represented by a first order rate equation (Bownaam and Focht, 1974; Stanford *et al.*, 1975a, 1975b, Stockle and Campbell, 1989; Saleh, 1994; Verma *et al.*, 1995) as

$$\text{DNI} = \text{NO}_3 [1 - \exp \{-k_d \cdot t\}] \quad (5.7)$$

where,

DNI = amount of nitrates denitrified, kg/ha

k_d = denitrification rate constant, day⁻¹, and

NO_3 = amount of nitrates in the reduced zone, kg/ha.

Nitrate left in the soil after accounting for denitrification losses is available for leaching.

g. Uptake

For submerged rice, ammonium is the dominant mineral N form available for uptake and plant nutrition (Sahrawat and Burford, 1982; Mengal *et al.*, 1986; Brandon and Wells, 1986; Aulakh and Singh, 1997). Nitrates contribute little to rice plant nutrition (Aulakh and Singh, 1997). In the present model, ammonium is considered to be taken up by the plants along with the transpired water. It is also assumed that the amount of ammonium is proportional to the transpired water. The transpired water is obtained from crop water requirements estimated by the modified penman method. The nitrogen uptake by the plants is calculated by the following equation :

$$UTNH_4 = ET * (NH_4) \quad (5.8)$$

$UTNH_4$ = Rate of ammonium uptake by plants from the root zone, kg/ha

ET = Evapotranspiration, mm, and

NH_4 = Concentration of NH_4 present in the root zone.

h. Leaching

Nitrogen loss by leaching is considered to be mainly in nitrate form (Johnsson *et al.*, 1987; Borg *et al.*, 1990; Aulakh and Singh, 1997). Leaching of ammonium in soils is very low except when fertilizer is applied in very large quantities or the soils are coarse textured having low Cation Exchange Capacity (CEC) (Aulakh and Singh, 1997). This is because ammonium is largely fixed to soil colloids (Krantz *et al.*, 1943; Broadbent *et al.*, 1958 and Wiklander, 1977). The two major factors controlling leaching losses of nitrate are concentration of nitrate in the soil profile at the time of leaching and quantity of water leaving root zone. The amount of nitrate leached below the root zone is that fraction of the nitrate produced during nitrification process on the surface oxidized layer. For the present model, nitrification in the reduced zone is neglected, as the paddy field was under saturated anaerobic conditions throughout the crop season. The daily amount of percolation is calculated by daily water balance model for rice (Chapter 4, Section 4.2.1). Hence the amount of nitrate leached below the root zone is in proportion to the fraction of water in the root zone that percolates out of the root zone times the concentration of nitrate in the root zone. The nitrate leaching from the root zone is given as follows :

$$LEANO_3 = DP * (NO_3) \quad (5.9)$$

where,

$LEANO_3$ = Amount of nitrate leached from root zone, kg/ha,

DP = Deep percolation, mm, and

NO₃ = Concentration of nitrate present in the root zone.

5.2 SELECTION OF MODEL PARAMETERS

The model parameters are the rate constants for the different N transformation processes. These are dependent on several factors namely, urea concentration, temperature, pH, soil texture, flooding condition etc. Changes in these factors can either accelerate or decelerate specific processes (Table 5.1). The range of the rate constants for different processes are obtained from the review of literature (Chaper 2, Table 2.1) and are given in Table 5.1. Based on the conditions existing at the particular location, values of the rate constant for different N transformation processes can be selected from within the range identified in Table 5.1 and adjusted heuristically on either side of the mean of the above range. These are treated as initial estimates of model parameters. More accurate values of the parameters obtained during model calibration using observed data of leached nitrate concentration.

5.3 COMPUTER PROGRAMME

A computer programme was written in Fortran 77 for computations involved in the Nitrogen Balance Model discussed above, and is listed in Appendix D.

5.4 VALIDATION OF THE NITROGEN BALANCE MODEL

The nitrogen-balance model presented in section 5.1 is general and can be used at any location. The model parameters can be chosen based on the guidelines given in Table 5.1. The general applicability of the model is evaluated by comparing model predicted nitrogen balance components with their

Table 5.1. Rate constants for N - Transformation processes in flooded rice fields

Process	Equation	Range of rate constant (K), d^{-1}	Factors affecting process	Adjustments in rate constants in response to changes in factors
Urea hydrolysis	$\text{UNH}_4 = U (1-e^{-k_1 t})$	0.4-0.8	urea concentration Soil pH Soil temperature moisture content of soil soil texture	Increases with increase in urea conc. Faster in high pH soils increases with temperature Faster in wet conditions than dry conditions Faster in clayey soils than in sandy soils
Volatilization	$\text{UNH}_3 = \text{UNH}_4 (1-e^{-k_2 t})$	0.02-0.07	Soil pH CEC Submerged conditions NH_4^+ concentration High flood water temp	increases with pH decreases with increase in CEC Favourable Increases with increase in NH_4^+ conc. increases
Nitrification	$\text{UNO}_3 = \text{UNH}_4 (1-e^{-k_3 t})$	0.02-0.08	Low pH NH_4^+ concentration Aeration	inhibits nitrification increases with increase in NH_4^+ concentration aerobic conditions are favourable
Mineralization	$\text{MNH}_4 = N (1-e^{-k_4 t})$	0.001-0.04	Temperature Soil moisture C/N ratio CEC pH	increases with temperature drying of soils enhances N mineralization rate Smaller the ratio, mineralization is more not significantly correlated does not show marked sensitivity
Immobilization	$\text{IN} = \text{NH}_4 (1-e^{-k_5 t})$	0.08-0.15	Temperature Aeration	Rapid at low temperature Less was immobilized in anaerobic conditions as compared to aerobic conditions
Denitrification	$\text{DNI} = \text{NO}_3 (1-e^{-k_6 t})$	0.1-0.18	C/N ratio Soil pH Temperature Aeration Nitrification rate	wider the ratio, more fertilizer will be immobilized Low pH inhibits, above pH of 7, denitrification takes place at faster rate Higher the temperature, greater the denitrification Anaerobic conditions are favourable Increase with increase in nitrification rate

corresponding observed values at two locations, Pantnagar and New Delhi. The observed data sets were taken from published literature.

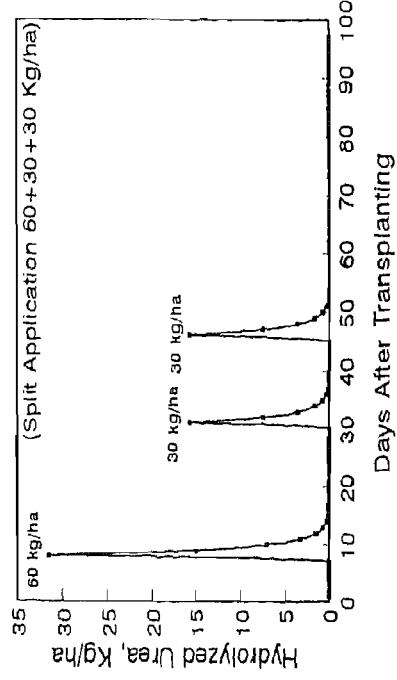
Validation with data from Pantnagar

Dhyani and Mishra (1993) reported field observations of N-balance at Pantnagar in two crop seasons, 1987 and 1988. The soil is beni silty clay loam (Aquic Hapludoll). The pH and the available N in the soil are 7.3 and 237.0 kg/ha, respectively. ^{15}N -labelled fertilizer urea (120 kg N/ha) was applied in three instalments (50 per cent basal + 25 per cent at late tillering + 25 per cent at panicle initiation). 28 day old rice seedlings (var. PD4) were transplanted in the field. The field was kept submerged with 5 cm depth of water. The measured percolation rate is 8.4 mm/day. Weekly average evapotranspiration values estimated using modified-Penman method for this location are given in Table 5.2..

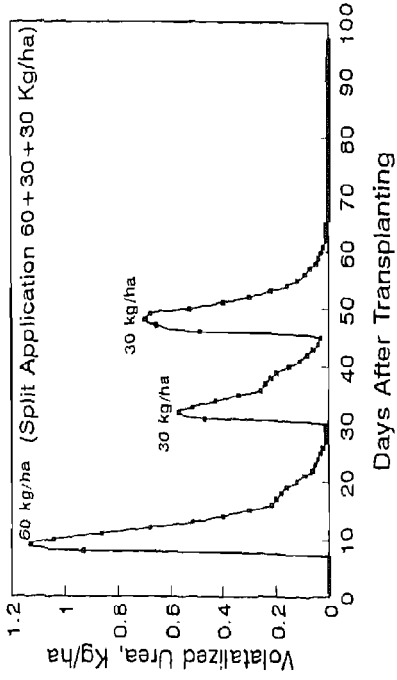
The nitrogen balance model was run using the measured percolation rates as input data instead of deriving them from the rice water balance model. Initial values of rate constants required for modelling the different N-transformation processes, urea hydrolysis, volatilization, nitrification, mineralization, immobilization and denitrification were selected from Table 5.1. The model was then calibrated with average observed data of *kharif* seasons of two years (1987 and 1988). Calibration is the process of adjusting model parameters within the expected range to minimize the difference between predicted and observed values. The nitrogen balance model was run on daily basis with the experimental conditions of Pantnagar for quantifying the N - transformation processes for the entire crop growth period. The model results of Pantnagar for different N-transformation processes (urea hydrolysis, volatilization, uptake and leaching) are represented graphically (Fig. 5.3a to 5.3d). The final values of rate constants identified for specific N-transformations are given in Table 5.3. The daily amounts of volatilization

Fig.5.3 Schematic Representation of Simulated Nitrogen Transformation Processes at Pantnagar

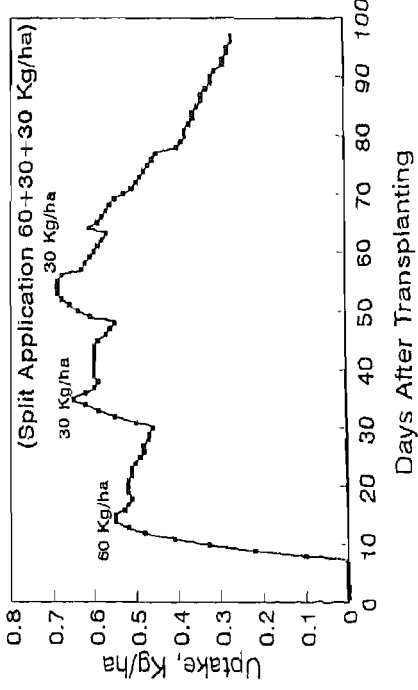
a. Urea Hydrolysis



b. Volatilization



c. N Uptake



d. Nitrate Leaching

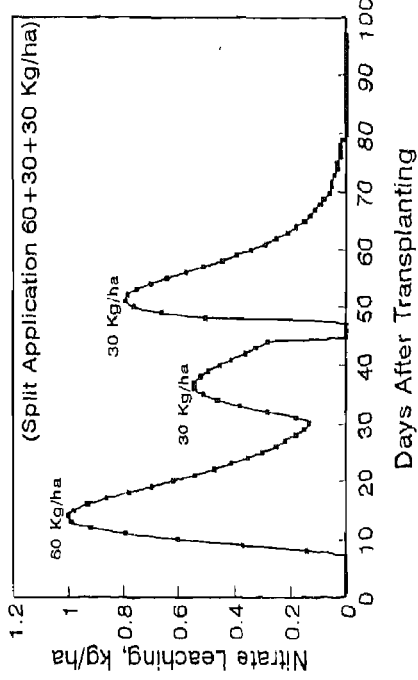


**Table 5.2 Weekly average reference evapotranspiration values (mm/day)
at Pantnagar**

Standard week No.	Reference evapotranspiration	Standard Week No.	Reference evapotranspiration
1	1.4	27	5.2
2	1.6	28	4.8
3	1.7	29	4.7
4	1.7	30	4.4
5	1.9	31	4.2
6	2.2	32	4.2
7	2.5	33	4.3
8	2.8	34	4.2
9	3.3	35	4.3
10	3.5	36	4.2
11	3.9	37	3.9
12	4.2	38	4.2
13	4.7	39	4.1
14	5.2	40	3.7
15	5.9	41	3.7
16	6.3	42	3.5
17	7.0	43	3.1
18	7.1	44	2.8
19	7.5	45	2.5
20	7.3	46	2.3
21	7.6	47	2.0
22	7.6	48	1.9
23	7.0	49	1.8
24	6.6	50	1.6
25	6.1	51	1.4
26	5.3	52	1.4

Source : Khumbate and Biswas (1992)

Table 5.3 Final values of model parameters for different N-transformation processes in rice at Pantnagar

N transformation Process	Rate constants, day ⁻¹
Urea hydrolysis	0.744
Volatilization	0.03
Nitrification	0.07
Mineralization	0.004
Immobilization	0.15
Denitrification	0.12

losses, leaching losses and uptake (Table 5.4) were summed to get seasonal totals, as only seasonal field data of these values were available for comparison. Leaching losses and denitrification losses were added and considered as unaccounted N loss. The seasonal results are given in Table 5.5.

Data of N-uptake pattern with time was available at Pantnagar for 1987 (Awasthe and Mishra, 1987). This field experiment was conducted in *kharif* season at the Crop Research Centre of the university at Pantnagar on medium duration variety. The pH and the available N in the soil are 7.3 and 237.0 kg N/ha, respectively. The field was kept flooded with constant depth of water 6 cm. Plant samples were collected from the field at 10 days interval upto 50 days and then at harvest. Total N in the plant uptake was determined by micro-kjeldahl procedure. The nitrogen balance model was run with the parameters in Table 5.3 and the measured percolation rates as inputs to find out the contribution of N to plant nutrition. The N uptake pattern obtained by N balance model and field experimental studies are given in the Table 5.6. Graphical representations of N uptake pattern for both the basal and split applications, obtained by model and experimental studies are shown in Figs. 5.4 and 5.5. From Table 5.5 and Table 5.6 it is seen that the simulated values are in close agreement

Table 5.4 Daily nitrogen balance in rice fields at Pantnagar

LOCATION PANTNAGAR, UP							
DAY	UHYDR	VOLANI	NITRI	IMMOB	DENTTR	UPTAKE	LEACHGW
all units are in kg/ha							
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	31.49	0.93	2.13	0.74	0.02	0.10	0.14
9	14.96	1.13	2.58	0.89	0.05	0.22	0.37
10	7.11	1.04	2.37	0.82	0.09	0.33	0.60
11	3.38	0.86	1.97	0.68	0.12	0.41	0.79
12	1.61	0.68	1.56	0.54	0.14	0.48	0.92
13	0.76	0.52	1.20	0.41	0.15	0.52	0.99
14	0.36	0.40	0.90	0.31	0.15	0.55	1.00
15	0.17	0.30	0.68	0.23	0.14	0.55	0.98
16	0.08	0.22	0.50	0.17	0.14	0.56	0.93
17	0.04	0.16	0.37	0.13	0.13	0.56	0.86
18	0.02	0.12	0.27	0.09	0.11	0.56	0.78
19	0.01	0.09	0.20	0.07	0.10	0.56	0.70
20	0.00	0.07	0.15	0.05	0.09	0.56	0.62
21	0.00	0.05	0.11	0.04	0.08	0.55	0.54
22	0.00	0.04	0.08	0.03	0.07	0.54	0.47
23	0.00	0.03	0.06	0.02	0.06	0.53	0.41
24	0.00	0.02	0.04	0.02	0.05	0.52	0.35
25	0.00	0.01	0.03	0.01	0.04	0.51	0.30
26	0.00	0.01	0.02	0.01	0.04	0.50	0.25
27	0.00	0.01	0.02	0.01	0.03	0.49	0.22
28	0.00	0.01	0.01	0.00	0.03	0.48	0.18
29	0.00	0.00	0.01	0.00	0.02	0.49	0.15
30	0.00	0.00	0.01	0.00	0.02	0.48	0.13
31	15.74	0.47	1.07	0.37	0.03	0.51	0.18
32	7.48	0.56	1.29	0.45	0.04	0.56	0.28
33	3.56	0.52	1.19	0.41	0.06	0.61	0.38
34	1.69	0.43	0.99	0.34	0.07	0.64	0.46
35	0.80	0.34	0.78	0.27	0.08	0.66	0.51
36	0.38	0.26	0.60	0.21	0.08	0.66	0.54
37	0.18	0.20	0.45	0.16	0.08	0.66	0.54
38	0.09	0.15	0.34	0.12	0.08	0.67	0.52
39	0.04	0.11	0.25	0.09	0.07	0.66	0.49
40	0.02	0.08	0.19	0.06	0.07	0.66	0.45
41	0.01	0.06	0.14	0.05	0.06	0.65	0.41
42	0.00	0.04	0.10	0.04	0.05	0.64	0.36
43	0.00	0.03	0.07	0.03	0.05	0.65	0.32
44	0.00	0.02	0.05	0.02	0.04	0.63	0.28
45	0.00	0.02	0.04	0.00	0.02	0.62	0.00
46	15.74	0.48	1.10	0.00	0.02	0.61	0.00
47	7.48	0.66	1.50	0.00	0.02	0.59	0.00
48	3.56	0.70	1.59	0.55	0.07	0.65	0.50
49	1.69	0.56	1.29	0.45	0.10	0.70	0.66
50	0.80	0.44	1.00	0.35	0.11	0.71	0.76
51	0.38	0.33	0.76	0.26	0.12	0.73	0.79
52	0.18	0.25	0.57	0.20	0.12	0.74	0.78
53	0.09	0.19	0.43	0.15	0.11	0.75	0.75

contd...

54	0.04	0.14	0.32	0.11	0.10	0.74	0.70
55	0.02	0.10	0.23	0.08	0.09	0.74	0.64
56	0.01	0.08	0.17	0.06	0.08	0.73	0.57
57	0.00	0.06	0.13	0.04	0.07	0.67	0.51
58	0.00	0.04	0.09	0.03	0.07	0.66	0.44
59	0.00	0.03	0.07	0.02	0.06	0.65	0.39
60	0.00	0.02	0.05	0.02	0.05	0.64	0.34
61	0.00	0.02	0.04	0.01	0.04	0.63	0.29
62	0.00	0.01	0.03	0.01	0.04	0.62	0.25
63	0.00	0.01	0.02	0.01	0.03	0.61	0.21
64	0.00	0.01	0.01	0.01	0.03	0.64	0.18
65	0.00	0.00	0.01	0.00	0.02	0.63	0.15
66	0.00	0.00	0.01	0.00	0.02	0.62	0.13
67	0.00	0.00	0.01	0.00	0.02	0.60	0.11
68	0.00	0.00	0.00	0.00	0.01	0.59	0.09
69	0.00	0.00	0.00	0.00	0.01	0.58	0.08
70	0.00	0.00	0.00	0.00	0.01	0.57	0.06
71	0.00	0.00	0.00	0.00	0.01	0.54	0.05
72	0.00	0.00	0.00	0.00	0.01	0.53	0.05
73	0.00	0.00	0.00	0.00	0.01	0.52	0.04
74	0.00	0.00	0.00	0.00	0.00	0.51	0.03
75	0.00	0.00	0.00	0.00	0.00	0.50	0.03
76	0.00	0.00	0.00	0.00	0.00	0.49	0.02
77	0.00	0.00	0.00	0.00	0.00	0.48	0.02
78	0.00	0.00	0.00	0.00	0.00	0.42	0.02
79	0.00	0.00	0.00	0.00	0.00	0.42	0.01
80	0.00	0.00	0.00	0.00	0.00	0.41	0.00
81	0.00	0.00	0.00	0.00	0.00	0.40	0.00
82	0.00	0.00	0.00	0.00	0.00	0.39	0.00
83	0.00	0.00	0.00	0.00	0.00	0.39	0.00
84	0.00	0.00	0.00	0.00	0.00	0.38	0.00
85	0.00	0.00	0.00	0.00	0.00	0.37	0.00
86	0.00	0.00	0.00	0.00	0.00	0.36	0.00
87	0.00	0.00	0.00	0.00	0.00	0.36	0.00
88	0.00	0.00	0.00	0.00	0.00	0.35	0.00
89	0.00	0.00	0.00	0.00	0.00	0.34	0.00
90	0.00	0.00	0.00	0.00	0.00	0.34	0.00
91	0.00	0.00	0.00	0.00	0.00	0.33	0.00
92	0.00	0.00	0.00	0.00	0.00	0.31	0.00
93	0.00	0.00	0.00	0.00	0.00	0.30	0.00
94	0.00	0.00	0.00	0.00	0.00	0.30	0.00
95	0.00	0.00	0.00	0.00	0.00	0.29	0.00
96	0.00	0.00	0.00	0.00	0.00	0.29	0.00
97	0.00	0.00	0.00	0.00	0.00	0.28	0.00

VOLATILIZED N = 14.11
 N UPTAKE BY PLANTS = 47.53
 N LEFT IN THE SOIL = 26.10
 UNACCOUNTED N = 32.21

Table 5.5 Seasonal nitrogen balance values at Pantnagar

Process	Observed* kg/ha	Simulated kg/ha
Plant uptake	44.0	47.53
N left in soil	27.0	26.1
Volatilization	13.3	14.11
Other losses (leaching+denitrification)	35.7	32.21

* Source : Dhyani and Mishra (1993)

with the experimental values. From the Fig. 5.4 and 5.5, it is seen that the N uptake pattern obtained by the model closely matched with the experimental values. Also higher N uptake at later growth stages predicted by the model (Fig. 5.4 and 5.5) is comparable to the experimental results (Awasthe and Mishra, 1987; Dhyani and Mishra, 1993). Similar results were obtained by De Datta *et al.* (1968) and Khind and Datta (1985).

Validation with data from IARI

The nitrogen balance model was tested with the data from experimental field of IARI farm, New Delhi for the year 1989 (Biswas, 1992). The location of the experimental site is at 28°40' N latitude and 77°12' longitude. 120 kg N/ha prilled urea was applied at three splits (50% at 7 days after transplanting (DAT) + 25% at top dressing, 30 DAT + 25% at 45 DAT). 25 day old seedlings of rice were transplanted on 21 July, 1989 and 5 cm depth of water was maintained in the field. The pH and the available N in the soil are 8.2 and 275.6 kg N/ha, respectively. Daily weather data and average weekly evaporation values were collected from IARI meteorological observatory (Table 5.7). Daily percolation losses estimated using daily soil water balance model for paddy fields (Chapter 4, Section 4.2.1) corresponding to constant depth of ponding 5 cm,

Fig.5.4 Nitrogen Uptake in rice at Pantnagar

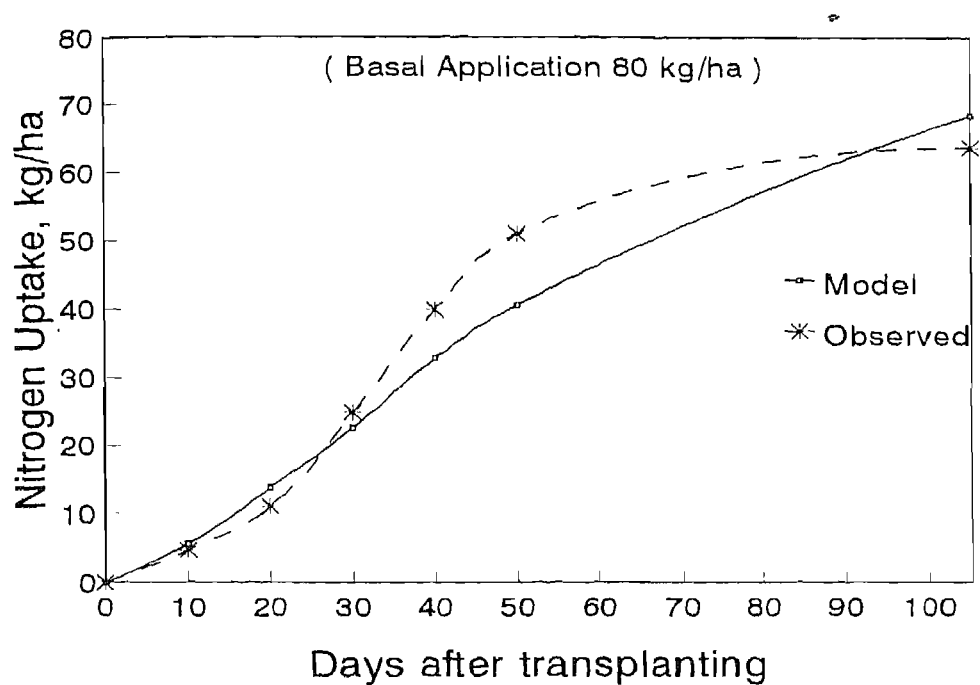


Fig.5.5 Nitrogen Uptake in rice at Pantnagar

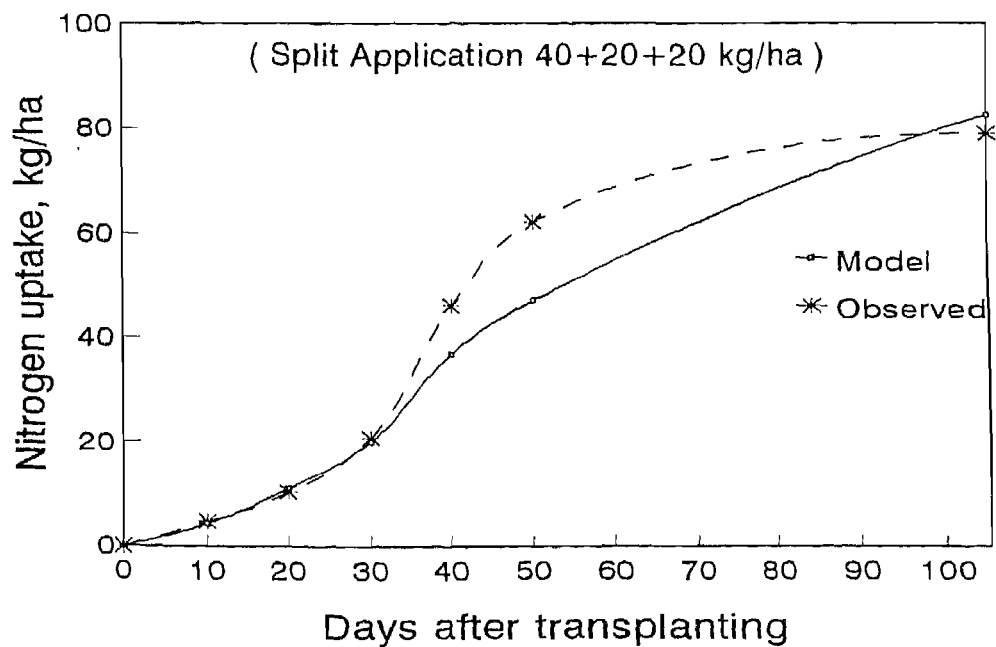


Table 5.6 N uptake pattern for Pant Nagar location

Days after transplanting	Basal application 80 kg/ha		Split application 80 kg/ha	
	N uptake kg/ha		N uptake kg/ha	
	Observed*	Simulated	Observed *	Simulated
10	5.62	4.7	4.26	4.7
20	13.74	11.0	11.2	10.4
30	22.68	25.0	20.03	20.8
40	32.86	40.0	35.83	46.2
50	40.6	51.0	47.23	62.2
105 (harvesting)	68.34	63.65	82.5	78.9

*Source : Awasthi and Mishra (1987)

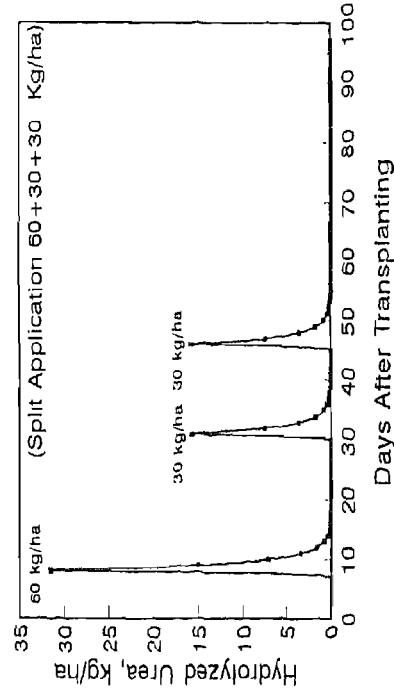
serve as data input to nitrogen balance model. The initial values of rate constants were selected from Table 5.1 and the model was calibrated by adjusting the parameters within the specified range. The value of the rate constants are given in Table 5.8. There is a slight increase in the volatilization rate constant, as pH of Delhi soil is more than for the soil at Pantnagar. The daily nitrogen balance model was run for the IARI data and the results are given in Table 5.9. Seasonal totals for individual processes are obtained by summing the daily amounts and compared with the seasonal experimental data (Table 5.10).

The model results for different N - Transformation processes like, urea hydrolysis, volatilization, leaching and uptake for IARI location are represented graphically (Fig. 5.6a to Fig. 5.6d). From Table 5.10 it is seen that the results obtained by model are in close agreement with the experimental data.

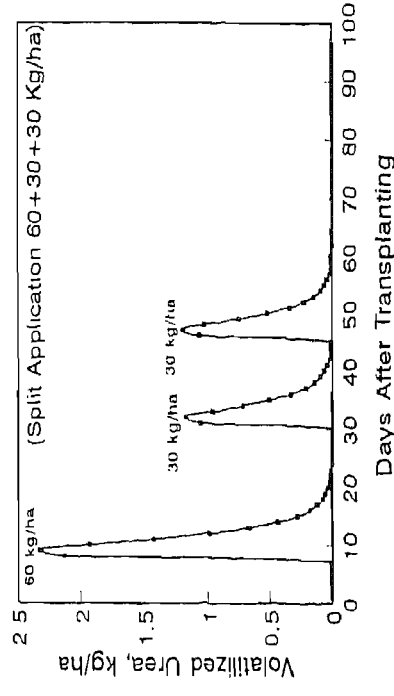
Hence the soil water balance model for paddy fields together with nitrogen balance model provide a generally applicable tool to satisfactorily estimate the nitrate pollutant loads from rice fields.

Fig.5.6 Schematic Representation of Simulated Nitrogen Transformation Processes in rice at IARI

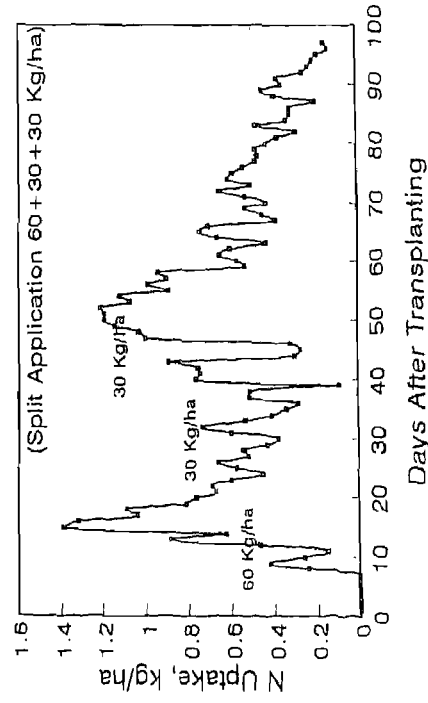
a. Urea Hydrolysis



b. Volatilization



c. N Uptake



d. Nitrate Leaching

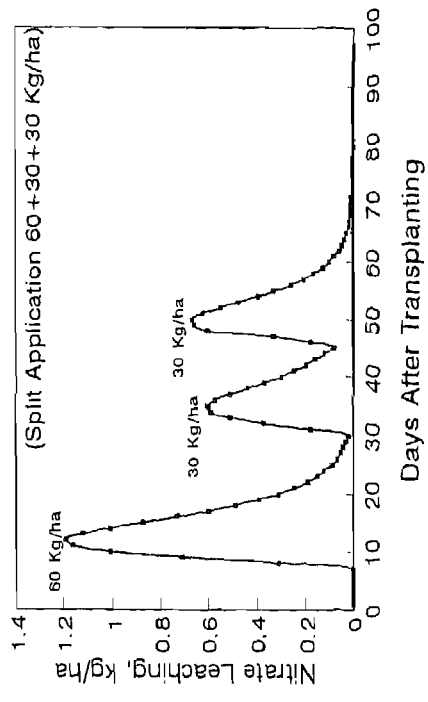


Table 5.7 Daily Pan evaporation values measured at IARI meteorological observatory, New Delhi for the year, 1989

Day/month	Pan evaporation values, mm				
	July	August	September	October	November
1	8.2	3.4	6.4	4.8	2.8
2	6.6	6.0	2.2	6.0	3.2
3	8.0	4.2	2.0	6.0	4.0
4	6.4	9.2	2.2	5.6	4.6
5	7.4	9.0	6.2	5.2	5.0
6	8.2	7.4	6.0	5.2	3.8
7	8.2	8.0	6.4	5.4	4.0
8	8.0	6.2	6.6	5.0	5.0
9	6.8	6.0	6.6	4.6	4.2
10	8.0	5.4	6.8	3.6	3.6
11	10.4	5.8	6.2	6.0	3.0
12	14.0	5.2	6.6	4.4	3.2
13	10.6	4.0	5.4	4.2	3.2
14	3.2	5.2	6.2	4.8	3.6
15	4.6	6.2	5.8	3.0	3.2
16	3.4	5.0	6.2	6.0	4.0
17	5.8	5.4	3.6	7.2	4.2
18	5.0	4.4	4.0	6.0	3.2
19	5.6	4.0	4.6	6.4	3.6
20	7.8	5.4	4.4	4.6	3.2
21	6.0	5.8	3.2	4.2	2.8
22	6.0	3.8	5.0	3.8	2.6
23	8.2	2.8	5.8	3.6	2.6
24	9.0	2.2	5.6	2.6	4.2
25	10.4	1.8	3.2	3.0	1.4
26	6.6	3.2	3.8	3.0	2.2
27	6.0	3.2	4.6	3.6	2.2
28	7.0	0.6	3.8	3.4	3.4
29	5.8	4.8	4.8	3.2	2.8
30	2.6	5.0	6.0	3.6	2.8
31	1.2	5.2	-	3.2	-

Table 5.8 Model parameters for different N-transformation processes at IARI, New Delhi

N transformation Process	Rate constants, day ⁻¹
Urea hydrolysis	0.744
Volatilization	0.06
Nitrification	0.08
Mineralization	0.002
Immobilization	0.15
Denitrification	0.12

Sensitivity analysis of N-balance model

Sensitivity analysis of the N balance model was performed first for N-transformation coefficients of the model for Delhi. From the analysis, it was observed that leachate concentration which is of primary concern in estimating NPS pollution loads to ground water was affected by slight increase or decrease in urea hydrolysis, nitrification, volatilization and denitrification rate constants (Table 5.11). The leachate concentration was less sensitive to changes in the mineralization and immobilization rate constants (Table 5.11). Hence, for the present studies, mineralization and immobilization rate constants are not considered important in the calibration procedure. This is because losses from mineralization process in the reduced layer has negligible contribution to nitrate leaching.

5.5 ESTIMATION OF NITRATE POLLUTANT LOADS TO GROUND WATER IN THE CASE STUDY AREA

Detailed description of the study area is given in Chapter 3. The nitrate pollutant loads vary spatially and temporally, as daily percolation losses and standing water depths vary with weather, soil and water supply conditions. The

Table S.9 Daily nitrogen balance in rice fields at IARI

LOCATION : I A R I, NEW DELHI							
DAY	UHYDR	VOLATI	NITRI	IMMOB	DENITR	UPTAKE	LEACHGW
all units are in kg/ha							
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	31.49	1.83	2.42	1.22	0.03	0.24	0.31
9	14.96	2.03	2.68	1.35	0.07	0.41	0.71
10	7.11	1.69	2.23	1.12	0.11	0.26	1.01
11	3.38	1.26	1.67	0.84	0.12	0.15	1.18
12	1.61	0.89	1.17	0.59	0.13	0.47	1.21
13	0.76	0.61	0.80	0.40	0.12	0.87	1.15
14	0.36	0.40	0.53	0.27	0.11	0.62	1.03
15	0.17	0.26	0.35	0.18	0.09	1.38	0.90
16	0.08	0.17	0.23	0.11	0.08	1.31	0.76
17	0.04	0.11	0.15	0.07	0.07	1.04	0.63
18	0.02	0.07	0.09	0.05	0.05	1.09	0.51
19	0.01	0.04	0.06	0.03	0.04	0.81	0.41
20	0.00	0.03	0.04	0.02	0.03	0.76	0.33
21	0.00	0.02	0.02	0.01	0.03	0.66	0.26
22	0.00	0.01	0.02	0.01	0.02	0.69	0.20
23	0.00	0.01	0.01	0.00	0.02	0.60	0.16
24	0.00	0.00	0.01	0.00	0.01	0.45	0.12
25	0.00	0.00	0.00	0.00	0.01	0.57	0.10
26	0.00	0.00	0.00	0.00	0.01	0.66	0.07
27	0.00	0.00	0.00	0.00	0.01	0.52	0.06
28	0.00	0.00	0.00	0.00	0.00	0.54	0.04
29	0.00	0.00	0.00	0.00	0.00	0.43	0.03
30	0.00	0.00	0.00	0.00	0.00	0.38	0.03
31	15.74	0.92	1.21	0.61	0.02	0.59	0.18
32	7.48	1.01	1.34	0.67	0.04	0.73	0.37
33	3.56	0.85	1.12	0.56	0.05	0.52	0.52
34	1.69	0.63	0.83	0.42	0.06	0.41	0.60
35	0.80	0.44	0.59	0.30	0.06	0.33	0.61
36	0.38	0.30	0.40	0.20	0.06	0.28	0.58
37	0.18	0.20	0.27	0.13	0.05	0.51	0.52
38	0.09	0.13	0.17	0.09	0.05	0.50	0.45
39	0.04	0.09	0.11	0.06	0.04	0.09	0.38
40	0.02	0.06	0.07	0.04	0.03	0.75	0.31
41	0.01	0.04	0.05	0.02	0.03	0.73	0.26
42	0.00	0.02	0.03	0.01	0.02	0.74	0.21
43	0.00	0.01	0.02	0.01	0.02	0.89	0.16
44	0.00	0.01	0.01	0.01	0.01	0.30	0.13
45	0.00	0.01	0.01	0.00	0.01	0.27	0.08
46	15.74	0.92	1.22	0.52	0.02	0.32	0.18
47	7.48	1.05	1.38	0.60	0.04	0.99	0.33
48	3.56	0.90	1.19	0.60	0.06	1.02	0.61
49	1.69	0.67	0.88	0.44	0.07	1.13	0.67
50	0.80	0.47	0.62	0.31	0.07	1.18	0.68
51	0.38	0.32	0.42	0.21	0.07	1.18	0.64
52	0.18	0.21	0.28	0.14	0.06	1.20	0.57
53	0.09	0.14	0.18	0.09	0.05	1.07	0.49
54	0.04	0.09	0.12	0.06	0.04	1.11	0.41
55	0.02	0.06	0.08	0.04	0.04	0.88	0.34
56	0.01	0.04	0.05	0.02	0.03	0.99	0.28
57	0.00	0.02	0.03	0.02	0.02	0.90	0.22
58	0.00	0.01	0.02	0.01	0.02	0.93	0.18
59	0.00	0.01	0.01	0.01	0.01	0.52	0.14

60	0.00	0.01	0.01	0.00	0.01	0.57	0.11
61	0.00	0.00	0.00	0.00	0.01	0.64	0.08
62	0.00	0.00	0.00	0.00	0.01	0.60	0.07
63	0.00	0.00	0.00	0.00	0.01	0.43	0.05
64	0.00	0.00	0.00	0.00	0.00	0.66	0.04
65	0.00	0.00	0.00	0.00	0.00	0.74	0.03
66	0.00	0.00	0.00	0.00	0.00	0.69	0.02
67	0.00	0.00	0.00	0.00	0.00	0.39	0.02
68	0.00	0.00	0.00	0.00	0.00	0.45	0.01
69	0.00	0.00	0.00	0.00	0.00	0.53	0.01
70	0.00	0.00	0.00	0.00	0.00	0.43	0.01
71	0.00	0.00	0.00	0.00	0.00	0.53	0.01
72	0.00	0.00	0.00	0.00	0.00	0.65	0.00
73	0.00	0.00	0.00	0.00	0.00	0.50	0.00
74	0.00	0.00	0.00	0.00	0.00	0.61	0.00
75	0.00	0.00	0.00	0.00	0.00	0.59	0.00
76	0.00	0.00	0.00	0.00	0.00	0.54	0.00
77	0.00	0.00	0.00	0.00	0.00	0.48	0.00
78	0.00	0.00	0.00	0.00	0.00	0.47	0.00
79	0.00	0.00	0.00	0.00	0.00	0.47	0.00
80	0.00	0.00	0.00	0.00	0.00	0.43	0.00
81	0.00	0.00	0.00	0.00	0.00	0.38	0.00
82	0.00	0.00	0.00	0.00	0.00	0.29	0.00
83	0.00	0.00	0.00	0.00	0.00	0.48	0.00
84	0.00	0.00	0.00	0.00	0.00	0.34	0.00
85	0.00	0.00	0.00	0.00	0.00	0.32	0.00
86	0.00	0.00	0.00	0.00	0.00	0.32	0.00
87	0.00	0.00	0.00	0.00	0.00	0.20	0.00
88	0.00	0.00	0.00	0.00	0.00	0.39	0.00
89	0.00	0.00	0.00	0.00	0.00	0.45	0.00
90	0.00	0.00	0.00	0.00	0.00	0.36	0.00
91	0.00	0.00	0.00	0.00	0.00	0.37	0.00
92	0.00	0.00	0.00	0.00	0.00	0.26	0.00
93	0.00	0.00	0.00	0.00	0.00	0.23	0.00
94	0.00	0.00	0.00	0.00	0.00	0.21	0.00
95	0.00	0.00	0.00	0.00	0.00	0.19	0.00
96	0.00	0.00	0.00	0.00	0.00	0.14	0.00
97	0.00	0.00	0.00	0.00	0.00	0.16	0.00
VOLATILIZED N	=	19.08					
N UPTAKE BY PLANTS	=	52.48					
N LEFT IN THE SOIL	=	23.24					
UNACCOUNTED N	=	25.19					

Table 5.10 Seasonal nitrogen balance values at IARI, New Delhi

Process	Observed* kg/ha	Simulated kg/ha
Plant uptake	49.1	52.48
N left in soil	22.7	23.24
Other losses (Volatilization leaching+denitrification)	47.2	44.27

* Source : Dhyani and Mishra (1993)

spatial and temporal variability of these factors for the study area were considered, while estimating daily percolation losses and daily standing water depths by running the soil water balance model for basic simulation units (Fig. 3.7) identified by GIS. The assessment of spatial variability of NO_3 leaching is also done by running the nitrogen balance model for the same basic simulation units (BSU) of Fig. 3.7

5.5.1 Input Data and Model Parameters

The input data required for each BSU for running the nitrogen balance model are given below.

- 1) Daily percolation losses for rice fields
- 2) Daily standing water depths
- 3) Daily evapotranspiration values
- 4) Soil parameters
- 5) Area under paddy crop for each BSU (Table 4.10)
- 6) Rate constants for N-Transformation processes (Table 5.1)

1 to 3 are output from the daily soil water balance model for rice. 4 is the same as for the input data for soil water balance model. There are two main soil textural groups in the study area, clayloam and sandy clayloam. The value of rate constants of N-transformation processes in rice for these two soils are selected based on the procedure of Section 5.2 and are given in Table (5.12)

Table 5.11 Sensitivity analysis of the rate constants on N- transformation processes.

Urea hydrolysis		Volatilization		Nitrification		Denitrification		Mineralization		Immobilization	
rate constants day ⁻¹	NO ₃ leached Kg/ha	rate constants day ⁻¹	NO ₃ leached Kg/ha	rate constants day ⁻¹	NO ₃ leached Kg/ha	rate constants day ⁻¹	NO ₃ leached Kg/ha	rate constants day ⁻¹	NO ₃ leached Kg/ha	rate constants day ⁻¹	NO ₃ leached Kg/ha
0.4	22.7	0.02	25.43	0.02	6.93	0.1	25.1	0.001	22.7	0.008	22.7
0.5	21.7	0.03	24.68	0.03	10.04	0.12	24.2	0.002	22.7	0.009	22.7
0.6	18.4	0.04	23.2	0.04	12.94	0.14	23.4	0.003	22.7	0.1	22.7
0.7	16.7	0.05	21.3	0.05	15.64	0.16	21.2	0.004	22.7	0.15	22.7
0.8	14.2	0.06	20.7	0.06	18.17	0.18	17.5				
		0.07	18.0	0.07	20.55						
		0.08	16.1	0.08	22.78						

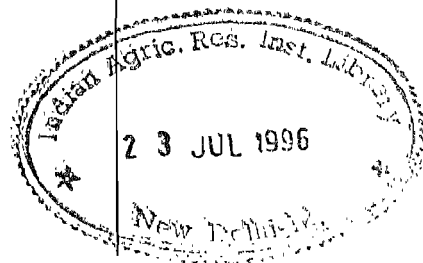


Table 5.12 Model parameters for different N-transformation processes in rice for the soils of Central Godavari Delta Irrigation Project

N-transformation process	Rate constants (day ⁻¹)	
	Clay loam	Sandy clay loam
Urea hydrolysis	0.744	0.744
Volatilization	0.06	0.07
Nitrification	0.06	0.07
Mineralization	0.006	0.006
Immobilization	0.15	0.15
Denitrification	0.12	0.12

There are marginal changes compared to Pantnagar were made for soil texture and pH. The model was calibrated with observed values of N-uptake by plants in the study area. Data of only this component of the N-balance was available from the study area (Satyanarayana, 1997, Maruteru, A.P.A.U. research station, personal communication). The model predicted N-uptake of 87.3 kg/ha against the observed 90 kg/ha for the varieties grown in the area. The dynamics of different N-transformation process are shown in Figs. 5.7a to 5.7d. A more detailed validation of the spatial distribution of the pollutant loads calculated by the model is presented in Chapter 6 in which the nitrate concentrations in ground water as a result of the above loadings are simulated for the year 1995

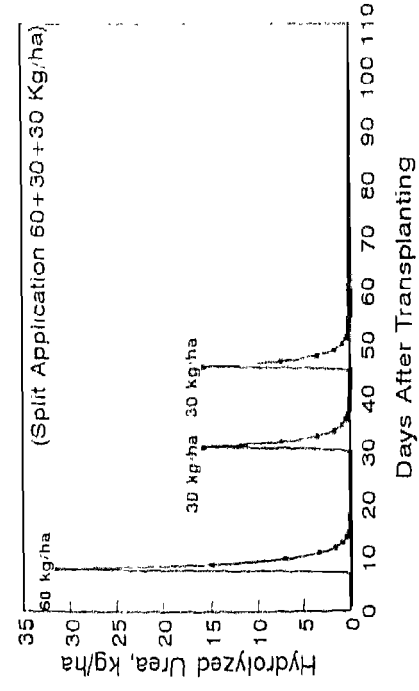
5.5.2 Interface Between the Nitrogen Balance Model and GIS

The general flow of information between the GIS and the models is same as described in Chapter 4, Section 4.7 (Fig. 4.5)

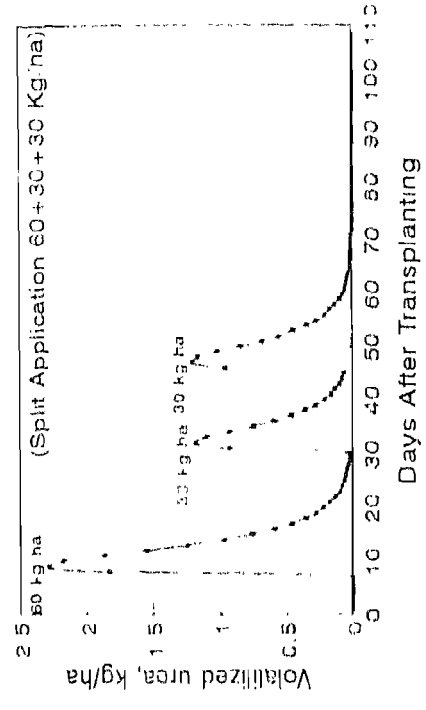
The coupled soil water balance-nitrogen balance model was run for each of the 38 BSU's to obtain the daily nitrogen balance in the paddy fields. A sample result of the model run for one BSU's during the year 1995, *kharif* season

Fig.5.7 Schematic Representation of Simulated Nitrogen Transformation Processes in rice at Study Area

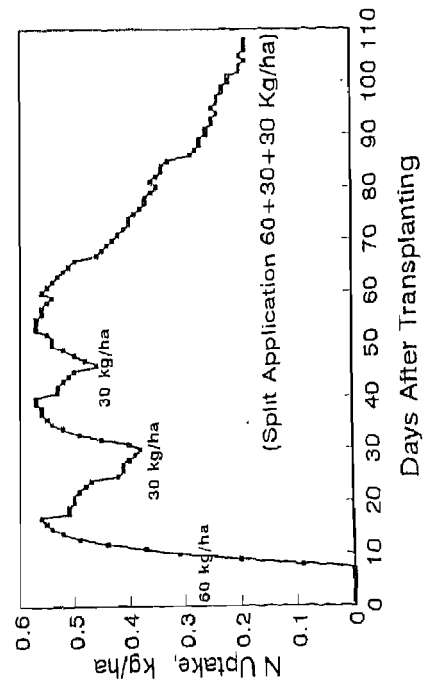
a. Urea Hydrolysis



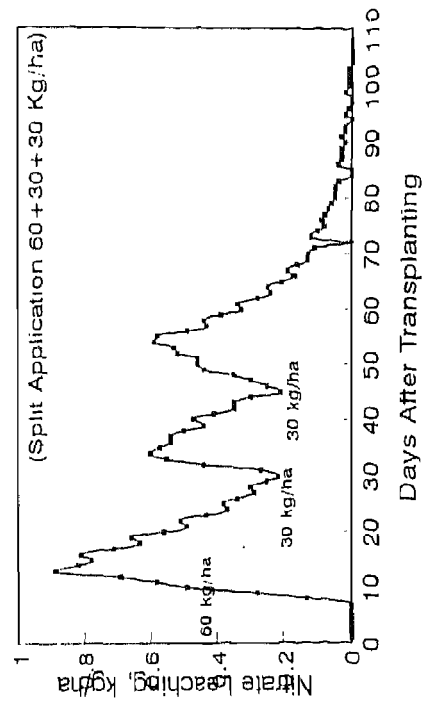
b. Volatilization



c. N Uptake



d. Nitrate Leaching



is given in Table 5.13. The seasonal nitrogen balance for all 38 basic simulation units is given in Table 5.14. The monthly and seasonal nitrate pollution loads from all the 38 basic simulation units for the year, 1995, *kharif* season are given (Table 5.15). The monthly and seasonal percolation losses for each BSU were also calculated for the period 1987 to 1995 and the sample results for 1995 were given in Table 4.9. Thematic maps of the spatial distribution of pollutant loadings and seasonal percolation values for each year were generated by transferring the above results to GIS. The distribution of the seasonal percolation losses and the pollution potential of the irrigation project area for the year 1995 are displayed on GIS (Fig. 5.8 and Fig. 5.9). The seasonal nitrate pollution loadings (Table 5.15) for the year 1995, *kharif* season vary between 225 to 460 ppm. These variations reflect variations in weather, soils, water supply and fertilizer use over the command area of the irrigation project.

5.6 DISCUSSION

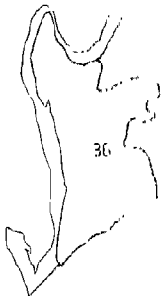
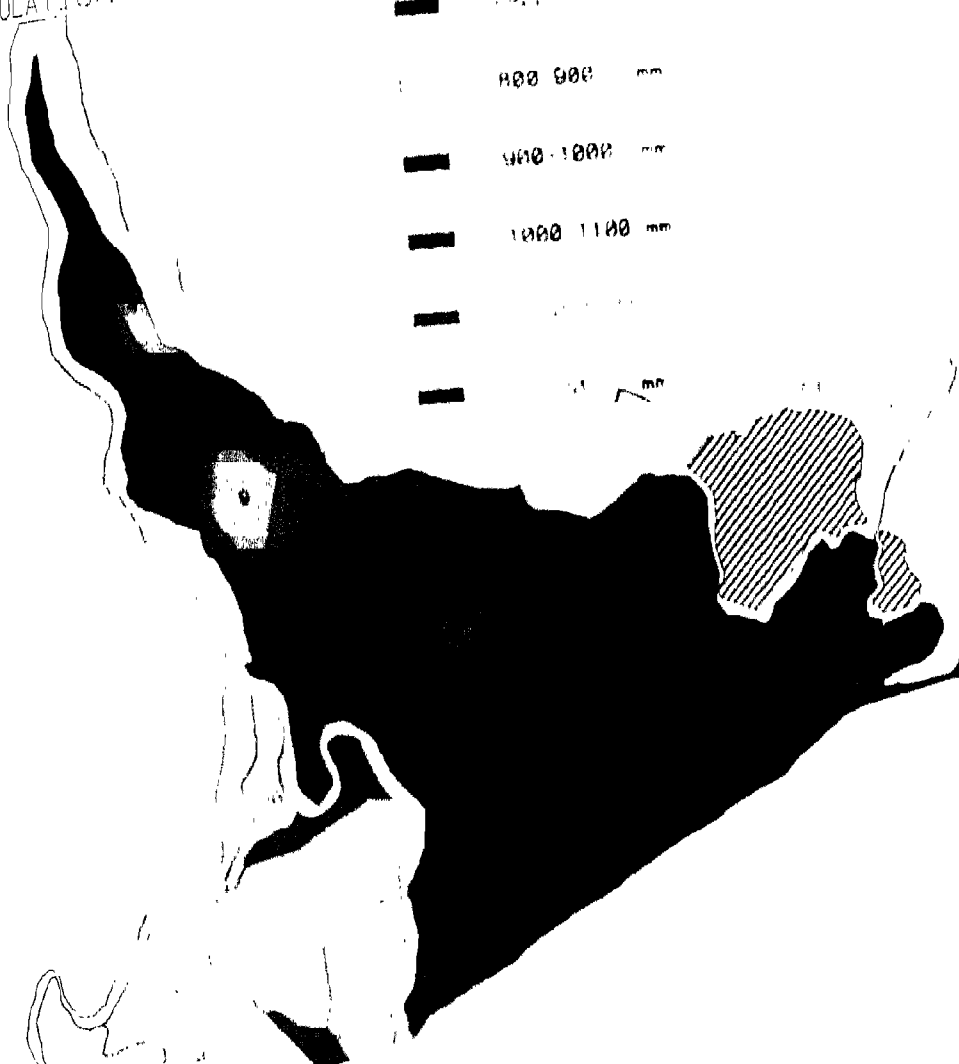
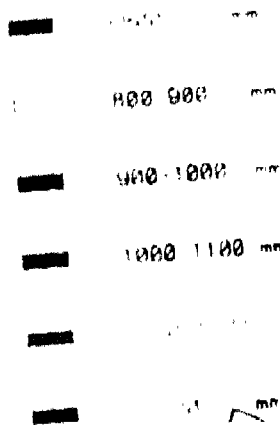
Nitrate is a major contributor of non point source pollution of surface and groundwater systems in agricultural areas. This is because nitrogen fertilizers are quite water soluble and are more likely to be leached out of the root zone in the form of nitrate. To devise strategies to control non point source pollution from fertilizers, planners need an evaluation and management model to assess pollutant loads and fertilizer leaching. A primary requirement is an easy procedure for transfer of model to different locations, for different data sets and parameters which vary spatially and temporally. This can be accomplished by integrating water and nitrogen balance models with spatial software like GIS.

Many comprehensive models have been developed for estimating the movement and transformations of nitrogen in the unsaturated zone. However, these models often require extensive and detailed input data, making them

Fig. 5.8

PERCOLATION

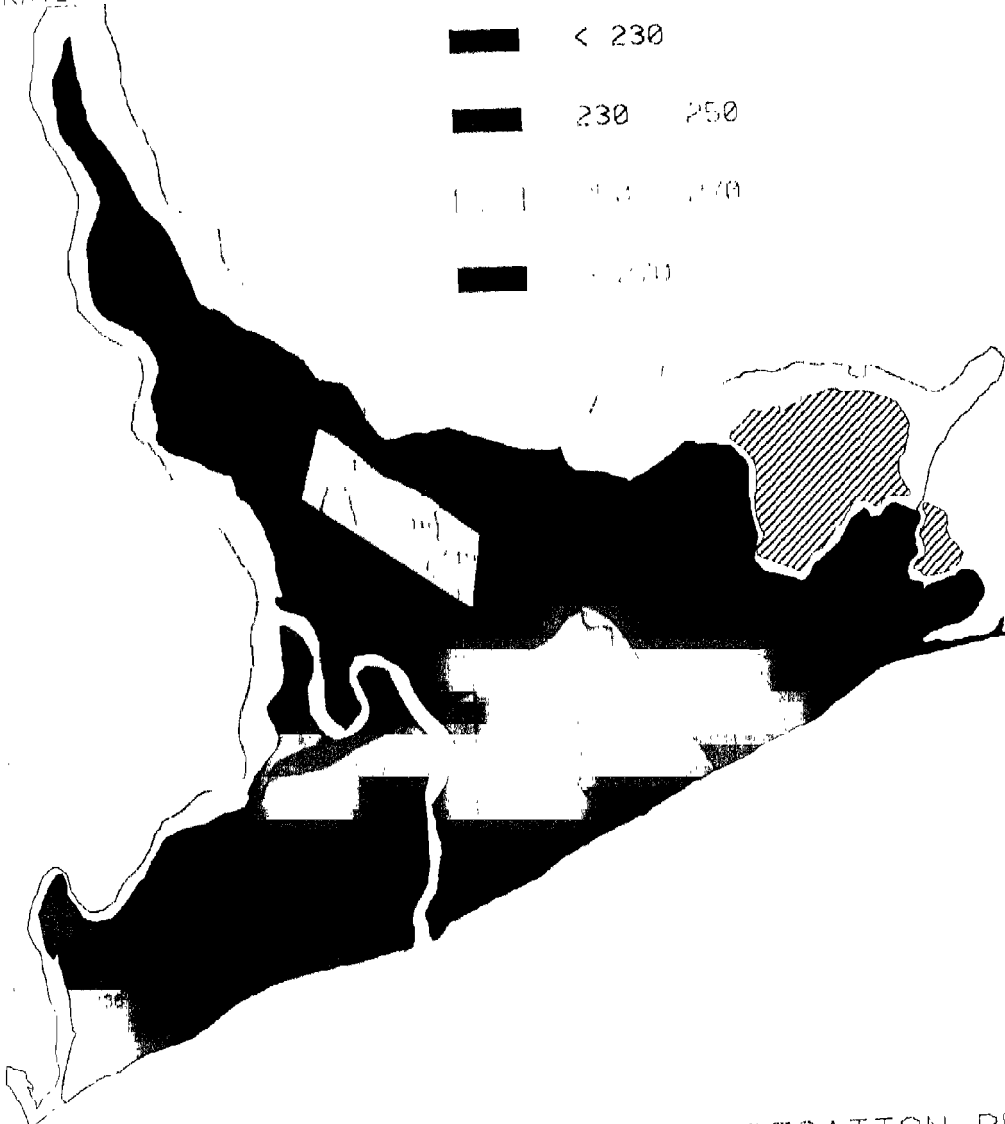
IELDS (KHARIF 1995)



GODAVARI VALLEY IRRIGATION PROJECT

Fig. 5.9

NITRATE LOADS (GGM) FROM FIELD TIELDS (KHARIF 1995)



GODAVARI DELTA CENTRAL CANAL IRRIGATION PROJECT

Table 5.13 Daily nitrogen balance for BSU 1 of the study area

(Kharif season, 1995)							
DAY	CHYDR	NOMIN	NUTRI	PMONH	DENITR	UPTAKE	LEACHGW
all units are in kg/ha							
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	31.49	1.53	1.53	0.51	0.01	0.09	0.13
9	14.96	2.28	2.28	0.60	0.03	0.20	0.28
10	7.11	2.18	2.18	0.59	0.05	0.31	0.49
11	3.38	1.87	1.87	0.48	0.06	0.37	0.58
12	1.61	1.55	1.55	0.40	0.07	0.44	0.69
13	0.76	1.24	1.24	0.36	0.08	0.49	0.89
14	0.36	0.97	0.97	0.26	0.08	0.52	0.82
15	0.17	0.76	0.76	0.20	0.08	0.54	0.78
16	0.08	0.59	0.59	0.16	0.08	0.55	0.81
17	0.04	0.46	0.46	0.12	0.07	0.56	0.71
18	0.02	0.36	0.36	0.09	0.07	0.51	0.63
19	0.01	0.28	0.28	0.07	0.07	0.51	0.66
20	0.00	0.22	0.22	0.05	0.06	0.50	0.56
21	0.00	0.17	0.17	0.04	0.06	0.50	0.49
22	0.00	0.13	0.13	0.03	0.06	0.49	0.51
23	0.00	0.10	0.10	0.02	0.05	0.48	0.43
24	0.00	0.08	0.08	0.02	0.04	0.47	0.37
25	0.00	0.06	0.06	0.02	0.04	0.42	0.38
26	0.00	0.05	0.05	0.01	0.04	0.41	0.34
27	0.00	0.04	0.04	0.01	0.03	0.41	0.29
28	0.00	0.03	0.03	0.01	0.03	0.40	0.30
29	0.00	0.02	0.02	0.01	0.03	0.39	0.25
30	0.00	0.02	0.02	0.00	0.03	0.38	0.22
31	15.74	0.93	0.93	0.22	0.03	0.40	0.27
32	7.48	1.17	1.17	0.33	0.03	0.45	0.44
33	3.56	1.10	1.10	0.33	0.05	0.49	0.55
34	1.69	0.93	0.93	0.29	0.05	0.52	0.60
35	0.80	0.75	0.75	0.22	0.05	0.54	0.57
36	0.38	0.59	0.59	0.17	0.05	0.55	0.54
37	0.18	0.46	0.46	0.13	0.05	0.56	0.54
38	0.09	0.36	0.36	0.10	0.05	0.56	0.50
39	0.04	0.28	0.28	0.07	0.04	0.57	0.44
40	0.02	0.21	0.21	0.06	0.04	0.57	0.47
41	0.01	0.16	0.16	0.05	0.04	0.53	0.41
42	0.00	0.13	0.13	0.03	0.04	0.53	0.35
43	0.00	0.10	0.10	0.03	0.03	0.52	0.35
44	0.00	0.08	0.08	0.02	0.03	0.51	0.30
45	0.00	0.06	0.06	0.01	0.03	0.50	0.21
46	15.74	0.96	0.96	0.21	0.03	0.46	0.25
47	7.48	1.20	1.20	0.26	0.04	0.48	0.30
48	3.56	1.16	1.16	0.25	0.04	0.50	0.35
49	1.69	1.02	1.02	0.23	0.05	0.52	0.44
50	0.80	0.85	0.85	0.19	0.06	0.54	0.46
51	0.38	0.69	0.69	0.15	0.06	0.54	0.46
52	0.18	0.56	0.56	0.13	0.06	0.55	0.52
53	0.09	0.45	0.45	0.10	0.06	0.57	0.53
54	0.04	0.35	0.35	0.09	0.06	0.57	0.59
55	0.02	0.28	0.28	0.07	0.06	0.57	0.58
56	0.01	0.21	0.21	0.05	0.05	0.56	0.49
57	0.00	0.17	0.17	0.04	0.05	0.56	0.43
58	0.00	0.13	0.13	0.03	0.05	0.55	0.44
59	0.00	0.10	0.10	0.02	0.04	0.54	0.39

[illegible]

Table 5.14 Seasonal nitrogen balance from all the BSU'S of the study area

(Kharif season, 1995)

BSU	PMN	Vol IAI	DI NURI	UPTAKE	LEACHGW	SOILADS	NH ₄ LEFT	NO ₃ LEFT
all units are in kg/ha								
1	0.00	31.10	3.01	41.70	27.98	8.05	8.05	0.01
2	0.00	30.73	2.97	42.26	27.65	8.16	8.13	0.01
4	0.00	30.57	2.86	42.52	27.57	8.20	8.13	0.01
3	0.00	30.99	3.11	41.93	27.74	8.08	8.00	0.01
7	0.00	30.80	2.79	42.13	27.97	8.13	8.14	0.00
6	0.00	31.21	3.02	41.56	28.15	8.02	8.00	0.00
5	0.00	30.93	2.91	41.90	28.00	8.10	8.14	0.00
10	0.00	30.80	2.79	42.13	27.97	8.13	8.14	0.00
14	0.00	32.04	3.09	40.41	28.81	7.79	7.73	0.01
9	0.00	31.21	3.02	41.56	28.15	8.02	8.00	0.00
13	0.00	33.26	3.50	38.64	29.60	7.45	7.40	0.01
17	0.00	32.04	3.09	40.41	28.81	7.79	7.73	0.01
8	0.00	30.93	2.91	41.90	28.00	8.10	8.14	0.00
22	0.00	30.82	2.81	42.16	27.95	8.13	8.08	0.00
23	0.00	30.82	2.81	42.16	27.95	8.13	8.08	0.00
24	0.00	30.74	2.90	42.33	27.54	8.15	8.05	0.01
16	0.00	33.26	3.50	38.64	29.60	7.45	7.40	0.01
12	0.00	31.58	3.12	41.05	28.27	7.92	7.87	0.01
11	0.00	31.39	3.02	41.27	28.25	7.97	7.99	0.01
19	0.00	33.26	3.50	38.64	29.60	7.45	7.40	0.01
15	0.00	31.58	3.12	41.05	28.27	7.92	7.87	0.01
29	0.00	30.74	2.90	42.33	27.54	8.15	8.05	0.01
21	0.00	31.14	3.01	41.72	28.06	8.04	7.97	0.01
20	0.00	30.76	3.10	42.28	27.29	8.15	8.06	0.01
28	0.00	30.74	2.90	42.33	27.54	8.15	8.05	0.01
18	0.00	31.58	3.12	41.05	28.27	7.92	7.87	0.01
27	0.00	40.58	5.67	28.03	34.29	5.41	5.40	0.06
25	0.00	40.34	5.75	28.38	33.80	5.48	5.46	0.06
30	0.00	40.78	5.55	27.68	34.85	5.35	5.40	0.04
31	0.00	31.39	3.02	41.27	28.25	7.97	7.99	0.01
38	0.00	40.34	5.75	28.38	33.80	5.48	5.46	0.06
26	0.00	40.34	5.75	28.38	33.80	5.48	5.46	0.06
32	0.00	40.78	5.55	27.68	34.85	5.35	5.40	0.04
33	0.00	40.78	5.55	27.68	34.85	5.35	5.40	0.04
34	0.00	40.56	5.62	28.09	34.47	5.42	5.38	0.05
35	0.00	40.56	5.62	28.09	34.47	5.42	5.38	0.05
36	0.00	40.56	5.62	28.09	34.47	5.42	5.38	0.05
37	0.00	40.58	5.67	28.03	34.29	5.41	5.40	0.06

Table 5.15 Monthly and seasonal nitrate loads from all the BSU's, ppm

(Kharif season, 1995)

BSU	Nitrate concentration loads, ppm						SEASONAL TOTAL
	JUNE	JULY	AUG	SEPT	OCT	NOV	
1	0.00	125.50	101.84	13.83	0.58	0.00	241.74
2	0.00	123.03	101.41	14.17	0.20	0.00	238.80
4	0.00	115.52	98.39	15.61	0.12	0.00	229.64
3	0.00	124.86	107.24	14.67	0.28	0.00	247.05
7	0.00	119.41	96.20	10.19	0.06	0.00	225.86
6	0.00	128.16	104.09	10.81	0.06	0.00	243.12
5	0.00	127.50	98.29	9.16	0.07	0.00	235.01
10	0.00	119.41	96.20	10.19	0.06	0.00	225.86
14	0.00	119.59	113.80	12.11	0.19	0.00	245.70
9	0.00	128.16	104.09	10.81	0.06	0.00	243.12
13	0.00	120.70	133.56	12.92	0.25	0.00	267.43
17	0.00	119.59	113.80	12.11	0.19	0.00	245.70
8	0.00	127.50	98.29	9.16	0.07	0.00	235.01
22	0.00	115.86	97.53	13.17	0.09	0.00	226.65
23	0.00	115.86	97.53	13.17	0.09	0.00	226.65
24	0.00	116.26	95.17	17.93	0.00	0.00	229.37
16	0.00	120.70	133.56	12.92	0.25	0.00	267.43
12	0.00	129.05	107.58	12.65	0.00	0.00	249.28
11	0.00	128.45	104.02	10.85	0.00	0.00	243.32
19	0.00	120.70	133.56	12.92	0.25	0.00	267.43
15	0.00	129.05	107.58	12.65	0.00	0.00	249.28
29	0.00	116.26	95.17	17.93	0.00	0.00	229.37
21	0.00	123.87	103.08	13.90	0.12	0.00	240.96
20	0.00	125.44	96.70	19.50	0.00	0.00	241.64
28	0.00	116.26	95.17	17.93	0.00	0.00	229.37
18	0.00	129.05	107.58	12.65	0.00	0.00	249.28
27	0.00	190.84	198.18	64.94	4.29	0.00	458.25
25	0.00	193.66	198.98	67.43	2.61	0.00	462.68
30	0.00	194.28	199.14	52.18	3.55	0.00	449.15
31	0.00	128.45	104.02	10.85	0.00	0.00	243.32
38	0.00	193.66	198.98	67.43	2.61	0.00	462.68
26	0.00	193.66	198.98	67.43	2.61	0.00	462.68
32	0.00	194.28	199.14	52.18	3.55	0.00	449.15
33	0.00	194.28	199.14	52.18	3.55	0.00	449.15
34	0.00	185.87	198.74	65.54	4.51	0.00	454.66
35	0.00	185.87	198.74	65.54	4.51	0.00	454.66
36	0.00	185.87	198.74	65.54	4.51	0.00	454.66
37	0.00	190.84	198.18	64.94	4.29	0.00	458.25

impractical to use in a large geographical area. Such models generally address certain specific issues of water quality concern, but often limit solutions because of specific limitations in a given model. For example, models are either non-spatially distributed (e.g. EPIC, CREAMS, GLEAMS) or spatially distributed (e.g. ANSWERS, AGNPS), single event (e.g. AGNPS, ANSWERS), or continuous scale (e.g. EPIC, CREAMS), field scale (e.g. EPIC, CREAMS, GLEAMS), or watershed / basin scale (e.g. ANSWERS, AGNPS). Many models consider nitrification, denitrification, mineralization, immobilization and plant uptake, but some do not consider one or more of these. Nearly all of these models were developed for crops other than rice, and describe the processes under aerobic conditions. Some other limitations of existing models include their inability to handle and manage large amounts of model input data, difficulties in determining model parameters and accounting for the spatial variability and heterogeneity that are often present in regional scale.

The model developed in the present study is simple and comprehensive as it includes all the important nitrogen transformation processes that occur in both soil and flood water zones. The model development and data input are such that simulations can be carried out simultaneously for a wide range of weather regimes, soil types and irrigation application. The development also facilitates efficient linkages with other hydrologic (soil water balance, groundwater flow) and pollutant transport (groundwater transport) models, and GIS. Further, the nitrogen balance model developed in this study considers all the important N-transformation processes (urea hydrolysis, volatilization, nitrification, mineralization, immobilization, uptake, denitrification and leaching) under anaerobic conditions. The model is based on minimum number of relations and parameters and provides an acceptable estimate of the pollutant loadings to

groundwater. The model can be applied at different locations easily. The spatially and temporally distributed attributes are included by interfacing with a soil water balance model (Chapter 4, Section 4.2) and GIS for the study area.

For the present study, paddy fields were divided into three distinct zones, namely, flood water zone, oxidized zone and reduced zone depending on the oxidation-reduction or redox potential of the system. Transformation reactions that occur in the different redox zones of an idealized flooded soil water system were also identified. All these transformations except plant uptake and leaching were considered to follow first order kinetics. Nitrification process was ignored in the reduced layer, as paddy field will be under saturated conditions throughout the crop season. Exhaustive literature search was made to identify range of rate constants for different N-Transformations and a heuristic procedure for selection of this rate constant within the observed change was also given.

It was shown that the urea hydrolysis was completed within 7 days of fertilizer application (Fig. 5.7a). Similar results were reported by Craswell and Vlek (1982), Sannigrahi and Mandal (1987) and Praveen Kumar *et al.* (1990).

It was observed that the gaseous loss of nitrogen varies from 25 % to 33 % of the applied fertilizer (Table 5.14). The losses of nitrogen through volatilization simulated by model in the present study were in conformity with the earlier findings (Table 2.1). From the Fig. 5.7b it is clear that 75% of the total volatilization loss occurred within 7 days of urea application and this process continues for about 15 days after fertilizer application. Similar results were obtained by many researchers (Reddy *et al.*, 1986; Balwinder Singh and Bajwa, 1987; Mishra *et al.*, 1990; Singh and Prasad, 1992; Joseph *et al.*, 1993). This may be due to formation of ammonium carbonate from urea hydrolysis, which increases the pH of the flood water.

Daily N use by rice crop was determined by considering daily volatilization losses, daily leaching losses and daily denitrification losses. From the Fig. 5.7c it was observed that the nitrogen uptake increased immediately after the application of fertilizer and decreased at 70 days after transplanting. This could be due to the increased availability of nitrogen and better plant growth and activity of roots reflected in higher ET. Nitrogen content at 70 days after planting decreased due to dilution effect caused by higher dry matter production in comparison to adsorption, and mobilization of nitrogen towards developing grains (Dubey and Bisin, 1989; Dhyani and Mishra, 1993).

Leaching losses varied from 20% to 30% of applied nitrogen (Table 5.14). It is seen that as percolation rate increases, leaching losses also increased (Fig. 5.7d). This direct association between the flood water percolation rate and nitrogen loss by leaching is expected. Leaching loss of nitrogen was observed to be higher during the first week of fertilizer application and it decreased as the time advanced. Higher loss of nitrogen immediately after the application of fertilizer was due to the increase in concentration of dissolved nitrogen soil solution.

The major assumption in the present analysis is that conversion of the different forms of N in the soil-water-plant system follows first-order kinetics. Most of the literature cited here and in chapter 2 support the validity of this assumption, at least in the range of rate constants under study. Evaluation of the rate coefficients under known environmental conditions is of great importance in quantifying the N-Transformation processes. The present analysis assumes that the rate constants are constants although it is evident (Ardakani *et al.*, 1973) that numerical values depend on the number of microorganisms participating in the transformation process. Therefore, development of functional relations

between rate constants and other dependent variables seems to be essential for better predictions of N - Transformations (Shaffer and Dutt, 1973). Such functions can be added to the present numerical scheme by introducing a subroutine and thus changing the rate constant from a constant to a variable values.

One of the major problems in using secondary data for verification of the proposed models is that not all the input parameters required by the model are known and hence had to be assumed. Similarly for the validation of the model, information on all the transformation processes may not be available. For example, the validation of the model was carried out with observed data of three components of N-balance at Pantnagar and two at Delhi out of possible measured data for five components. But in both cases data of atleast two components were available. However, for the study area data of only plant uptake were available for comparison with model prediction. A more formal validation of the nitrogen-balance model for the study area is carried out in Chapter 6 where the predicted nitrate loads are used as input to the groundwater transport model.

6. SIMULATION OF GROUNDWATER FLOW AND POLLUTANT TRANSPORT IN THE STUDY AREA

The spatially variable nitrate loads from rice fields were estimated as described in Chapter 5. Once the leached nitrate reach the water table its retention or dispersal in the aquifer is governed by the flow conditions in the aquifer. To study the movement of the nitrate in the aquifer, it is necessary to simulate the groundwater flow conditions. A sequential solution of the groundwater flow and transport problems is therefore necessary.

6.1 DEVELOPMENT OF GROUNDWATER BASIN SIMULATION MODEL

a. Equation governing the groundwater flow

The equation for a two dimensional transient flow of ground water through a porous matrix, which is considered in this study is .

$$\frac{\partial}{\partial x} \left(T \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(T \frac{\partial h}{\partial y} \right) + N = S \frac{\partial h}{\partial t} \quad (6.1)$$

Where

$T = T(x,y)$ transmissivity of the aquifer, = kb, m²/sec.

b = average thickness of the aquifer, m

$S = S(x,y)$, storage coefficient of the aquifer

$h = h(x,y,t)$, hydraulic head in the aquifer, m

$N = N(x,y,t)$, net recharge rate per unit area, m³/sec/m²

t = time, and

x,y are cartesian co-ordinates in a horizontal plane

Equation 6.1 is valid strictly only for confined aquifer. But under the assumption that the values of drawdown involved are far less than the total

saturated thickness of the unconfined aquifer, the equation can be applied to unconfined flow also

Equation 6.1 is a non-linear equation, hence closed form solutions are not feasible particularly for the boundary conditions of the groundwater basin problem. Hence the application of the numerical methods to obtain approximate solutions becomes imperative. Additional specifications of the groundwater problem are required to solve it. The solution depends on the definition of solution domain, initial conditions, aquifer parameters, source and sinks and boundary conditions.

b. Problem domain

The problem domain is the space-time domain for which a solution of Eqn 6.1 is to be obtained. The spatial or flow domain is the geographical area included in the groundwater model

c. Aquifer parameters

The aquifer parameters of interest are the transmissivity and specific yield and their spatial variations over the flow domain. These values were estimated in part from interpretation of aquifer tests, geologic logs for wells, and other geohydrologic data and information concerning the ground water system.

d. Boundary conditions

In general, these conditions are of two types : Specified flux and specified head boundaries. A specified flux boundary is either a recharge or barrier boundary and is described by the relation

$$T \frac{dh}{dn} = q_b(r, t) \quad (6.2)$$

Where $\frac{d}{dn}$ = Outward normal derivative to the boundary, and

q_b = specified discharge into or out of the flow domain per unit length of boundary, and is a function of position and time.

The specified head boundary condition is given by the relation

$$h = h_b(\Gamma, t) \quad (6.3)$$

where

h_b = specified head on the boundary and is a function of position and time.

Γ = boundary

e. Initial conditions

Initial conditions are the specifications of the values of the hydraulic heads at different locations over the flow domain at the start of the time domain. For each point in the flow domain, water levels in the region are specified. These are obtained from the water table contour maps based upon water level measurements in the flow domain

e. Sources and Sinks

Sources and sinks specify the recharge and discharge respectively for the groundwater system over the time domain to be simulated. Procedures for estimating recharge were presented in chapter 4.

6.1.1 Solution to the Equation of Groundwater Flow

In this method, it is assumed that the values of T and S are invariant within the discretized subdomain or element. This approximation is valid since

in the final converged solution, the area of the element forms only a fraction of the total region. FEM also facilitates assigning different values of T and S in different elements which are interconnected to give the solution of the entire continuum of the region of flow.

6.2 COMPUTER PROGRAM

The program developed by Swain (1978) and the finite element algorithm of Pinder (1974) was used. Modifications to the programme were made mainly for the input and output to solve the two-dimensional transient state problem of groundwater flow in an unconfined aquifer. The program utilizes triangular elements and linear trial functions and allows specified flux and specified head boundaries. Source and sinks are allowed at nodal points, and flow rates may vary with time step.

6.2.1 Program Structure

The program has three basic modules : a main driver module, a data-input module, and a solution and output module. These modules are shown schematically in Fig 6.1. The main driver program, "**Flow**", calls the subroutine FDATA, which reads data defining the geometry of the flow domain, initial conditions, boundary conditions, aquifer parameters, and sources and sinks. The main program then calls the subroutine FMODEL, which is the solution and output module.

A brief description of modules and submodules are described below. The source code listing in standard FORTRAN 77 and variables identified in each case are given in Appendix F.

a) Main program FLOW

The function of main program is to call subroutines FDATA and FMODEL, and the module consists essentially of call statements to these subroutines.

b. Subroutine FDATA

This enables to input data that describes groundwater problem to be solved. The input data is in three basic groups : definition of the basic solution domain, specification of constant head boundaries and specification of sources and sinks

In the first data-input group, the flow domain is described. This is accomplished by establishing a grid of triangular elements over the flow domain. The grid is defined by specifying the number of nodes in the grid NN and the x-y coordinates of each node X(I) and Y(I). Association of nodes to elements is specified by the element incidences IN (I, J). The incidences indicate the nodal number of the three nodes of a triangular element and listed in a counter-clockwise direction around an element starting with any node. An important feature of the grid is the half-band width that it generates. For a properly designed grid, the Galerkin method generates symmetric stiffness and mass matrices and these are banded. This property is utilized to decrease computer memory requirements by storing memory only for the half band. Half band width depends on numbering of the nodes in the grid. It is determined by the numerical difference plus one between the nodes in an element with the highest and lowest nodal number. Half-band width should be minimum as far as possible, and this is partially accomplished by labelling the nodes across the shortest dimension of the body. For example, if the node numbers of the triangular element are 2, 31 and 17 then the half band width is $(31-2) + 1 = 30$.

c. Subroutine FMODEL

Subroutine FMODEL includes three basic loops, and marches the solution through time (fig. 6.2). The outer most loop is the time-step loop which controls the march through time. Next is the iteration loop, which controls the iterative update of transmissivity. The innermost loop is the element loop. In this loop, the integrations of equation E.22 given in Appendix E are evaluated on an elemental basis, and the elemental contributions are made to the stiffness mass matrices (A) and (B). A compressed storage is used in subroutine FMODEL for matrices (A), (B), and (I) which are symmetric and banded.

d. Subroutine FSBAND

The purpose of this subroutine is to solve system of linear equations

$$[L] \{H^{(A)}\} = \{R\} \quad (6.4)$$

For $\{H^{(A)}\}$, the matrix [L] and the vector {R} are passed from FMODEL to subroutine FSBAND. FSBAND uses Cholesky method (Churchhouse, 1981) to solve the system of equations. The solution vector $\{H^{(A)}\}$ is passed back to the calling subroutine FMODEL.

e. Subroutine FSHAPE

It constructs the elemental stiffness and mass matrices $[A^e]$ and $[B^e]$ using the coordinates of elemental nodes, transmissivity, and storage coefficient, which are passed to FSHAPE from FMODEL, and in turn the subroutine FSHAPE returns $[A^e]$ and $[B^e]$ to FMODEL.

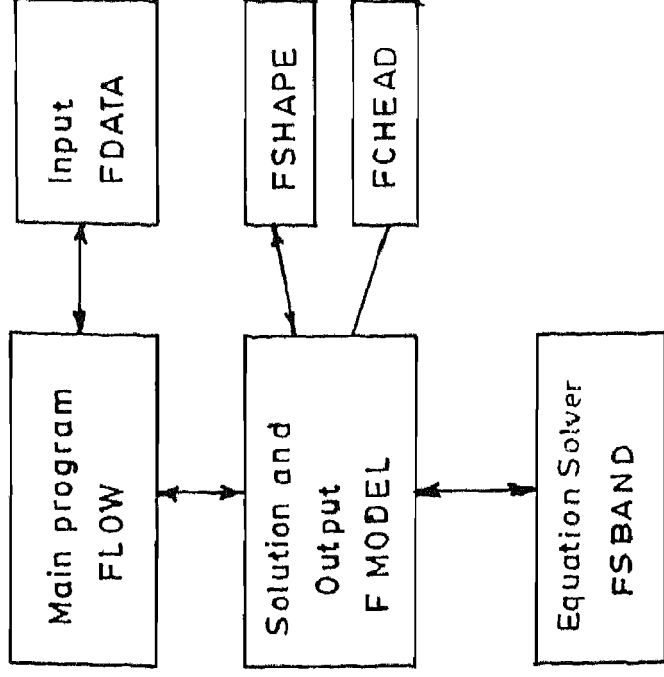


Fig.6.1 General configuration of finite element program

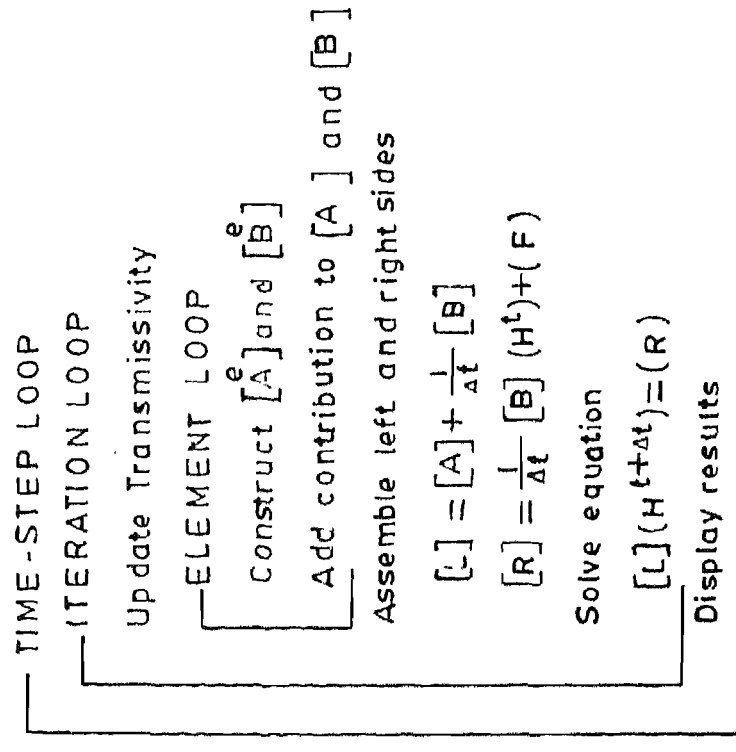


Fig.6.2 Generalised flow diagram for sub routine F model

f) Subroutine FCHEAD

The subroutine computes the flux rate at constant head nodes. The flux at the constant head nodes is treated in the model as leakage against a specified head. The relationship used in the model is

$$Q_{bi} = C [H_i^{t+\Delta t} - H_{bi}] \delta (x-x_i, y - y_i) \quad (6.5)$$

Where Q_{bi} is the flux rate at node i , C is a constant, H_i is the hydraulic head in the aquifer, H_{bi} is the specified constant head value, and δ is the Dirac Delta function. For large C , the head H_i will be closer to H_{bi} . Constant head nodes are incorporated in the model by adding

$$Q_{bi} = C [H_i^{t+\Delta t} - H_{bi}] \quad (6.6)$$

to the vector $\{R\}$ of equation E-46 given in Appendix E

Once the head in the aquifer is computed, the flux rates at constant head nodes can be computed.

6.3 EVALUATION OF PERFORMANCE OF THE GROUNDWATER MODEL

Before a groundwater model is used for predicting the future water table behaviour, it must be evaluated in terms of its performance. This is done by examining whether the model can generate the past behaviour of the water table as it is known reasonably well from the historical records. The reliability and quality of performance of a model is normally evaluated through either a calibration procedure or a sensitivity analysis. Calibration procedure essentially consists of adjusting the input parameters until computed hydraulic heads match with the observed values. Since the aquifer response is a function of number of different parameters (transmissivity, storage coefficient, recharge) and boundary conditions, etc., it is possible that either wrong parameters may be varied to

give a reasonable fit or a large number of possible combinations, none of which may be close to reality in the field may produce acceptable results (Sarma and Immaraj, 1990) The model could then give totally incorrect results when used for purposes of prediction.

Sensitivity analysis technique offers an alternative method to evaluate the model performance. In this, individual parameters are allowed to vary over the range to which they are known to vary in separate simulation runs of the model which leads to corresponding changes in the output emphasising the sensitivity of the model to the variation of that particular parameter. More attention could be paid to the quality of the data of only those parameters to which the model is sensitive. This technique was used in the present study.

6.4 APPLICATION OF GROUND WATER BASIN SIMULATION MODEL TO THE STUDY AREA

6.4.1 Organisation of Input Data

a Solution Domain

The part of the command area selected for groundwater flow simulation is shown in Fig 6.3. This area is of about 84000 ha and is divided into 107 triangular elements with 87 nodal points. The size of the triangle is adjusted to conform to the shape of the boundary. The size of the triangular elements is also reduced near boundaries to enable better approximation. Nodes are numbered in North-South direction, since this is the shortest distance, so as to produce minimum half-band width. The nodes are identified by their X and Y coordinates (X (I), Y(I) as given in Appendix F The elements are numbered as shown in Fig 6.3 Association of nodes to elements is specified by the element incidences (IN (I, J)) in counter - clock wise direction around the elements as given in Appendix F.

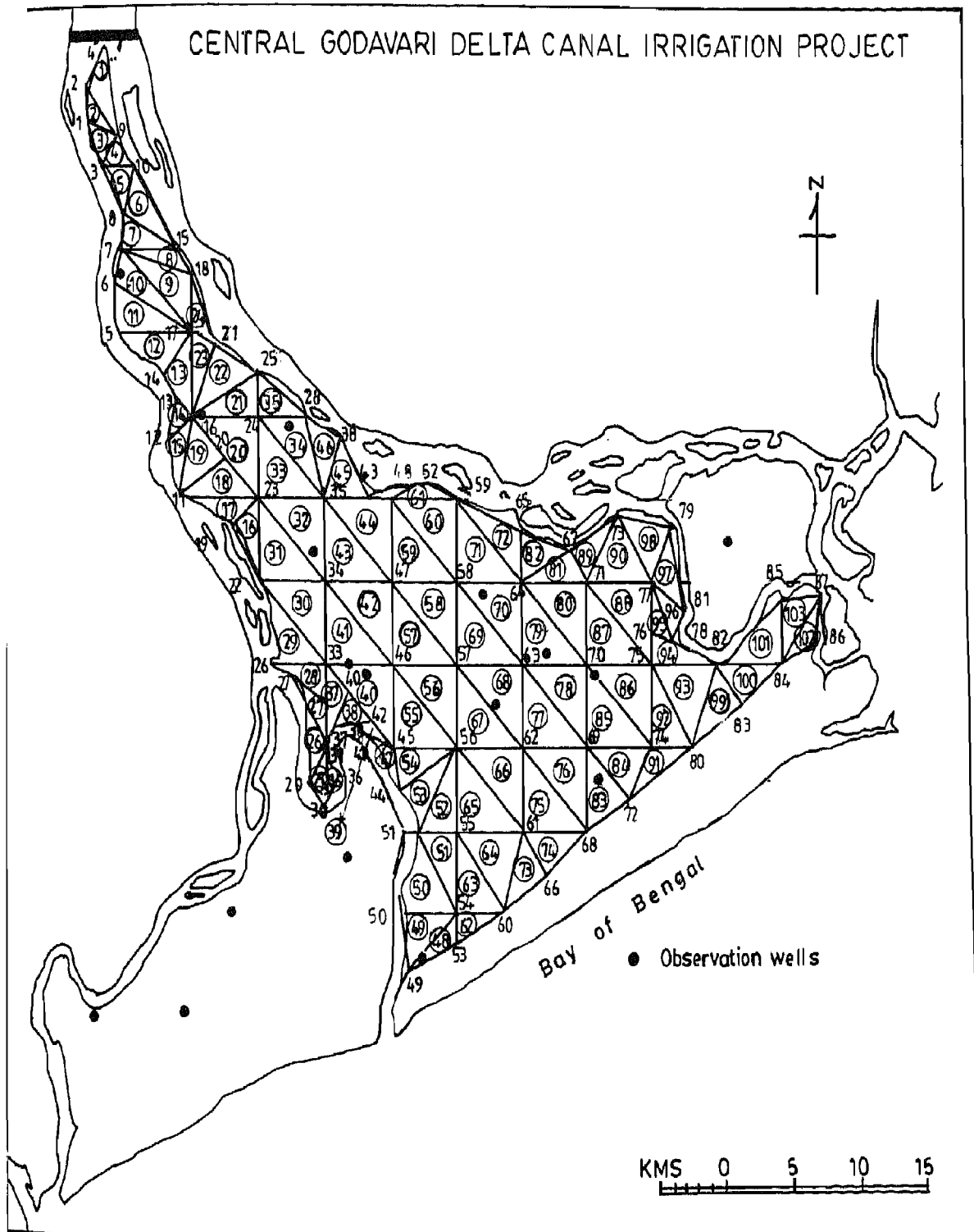


Fig.6.3 Finite Element Grid

b Aquifer parameters

Aquifer parameters required by model as input are hydraulic conductivity 'K' and specific yield ' S_y '. Most of the study area is under deltaic alluvial formations and groundwater in these formations occurs generally in water table conditions. As there was no major variation in geological properties, the study area was considered to be a homogeneous region. Accordingly, aquifer of the study area is considered to be a weathered zone with a thickness of 40 m, with an average transmissivity value of 4000 m²/day and average specific yield of 0.18 (CGWB, 1993 and NIH, 1992). Hence hydraulic conductivity of 100 m/day and specific yield of 0.18 are assigned to each of the 107 elements in the area (Appendix F).

c Initial and Boundary conditions

(i) *Initial conditions* : The time period considered in this study is 1992-93 to 1995-96. As the first step, the model is used to simulate the ground water levels in the year 1992-93. Hence, the time period considered in the model is one year divided into 12 time steps, each consisting of 30 days (a month). The observed water table contours in the month of May, 1992 (Fig. 6.4) are considered to describe the initial conditions. A finite element grid with 107 triangular elements and 87 nodes is superposed over water table contour map for May 1992 (Fig. 6.4). Each of the 87 nodes in the flow domain is assigned an initial hydraulic head obtained by interpolation from the fig 6.4. The initial conditions at all nodes are given in Appendix F.

To estimate the saturated aquifer thickness, which would be used by the model for further computations, the depth to the base of the aquifer at each node is required. The average aquifer thickness of 40 m was subtracted from the reduced level of ground surface at each node to obtain the depth to the

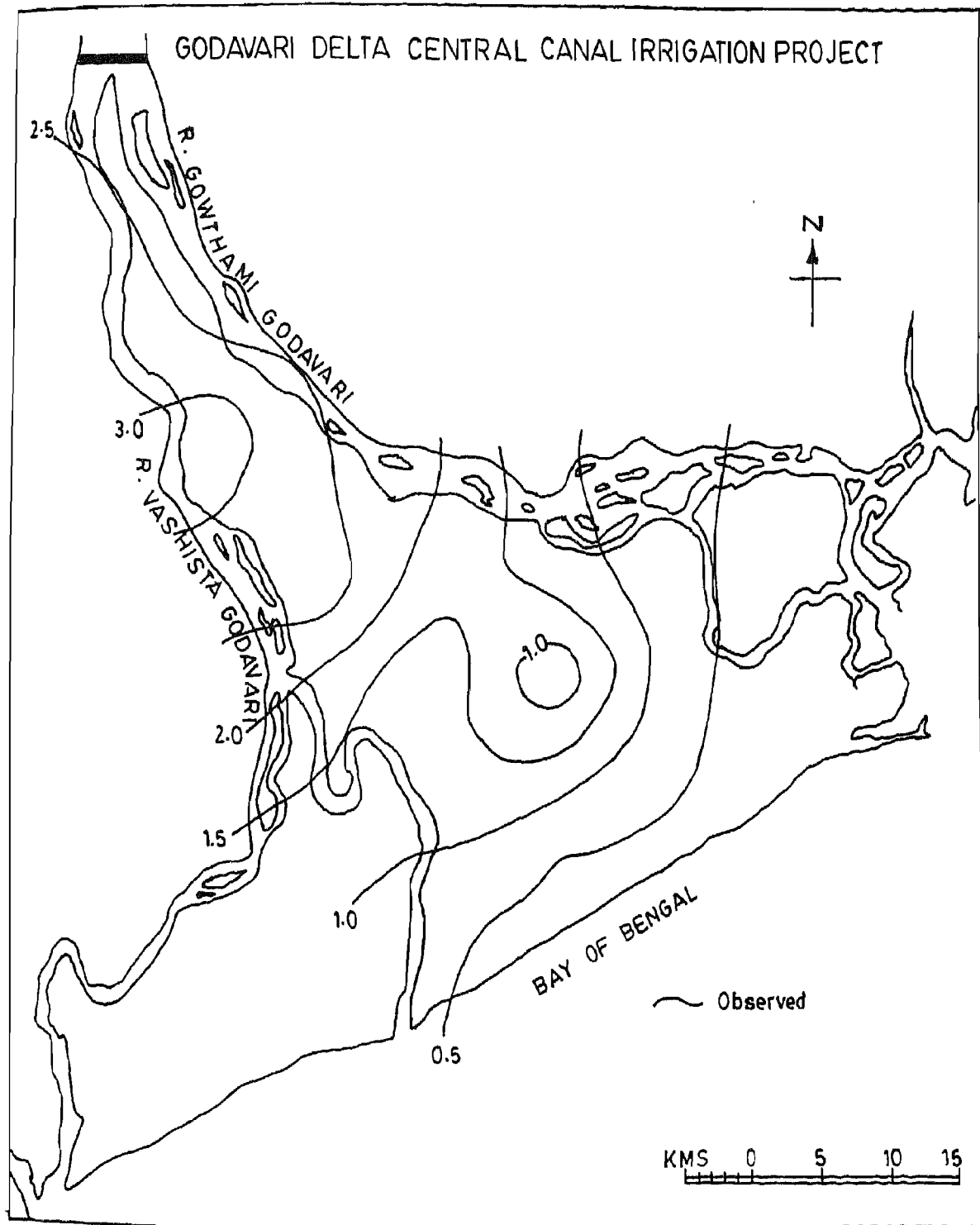


Fig.6.4 Observed groundwater levels, m (May 1992)

bottom of the aquifer. The reduced level of the ground surface is given as input to the model (Appendix F)

(ii) *Boundary conditions* : Hydrological boundaries of the study area are, the river Gowthami Godavari in the east, river Vasistha godavari and its branch Vainateya in the west and Bay of Bengal in the south. The general nature and extent of the aquifer boundaries are shown in Fig. 3.1. There were 57 nodes along the boundary. Since the present study area is surrounded by natural boundaries on all sides, constant head boundary conditions were designated along the boundaries. The constant - head boundary condition was incorporated in the model by specifying hydraulic heads at those nodes, as given in the specimen input file (Appendix F).

(d) Sources and sinks

(i) *Pumping rates* : Tube wells and filter point wells are the main source of groundwater in the study area. The total number of wells and filter points in the area is known with some degree of certainty. Their spatial distribution at different nodes of the finite element grid is not known. The exact time distribution of the pumpage (total draft) was also not known. So, for the initial model runs, the total draft for the entire area was uniformly distributed over all the internal nodes within the command area. The annual draft was distributed uniformly throughout the year, i.e. from June to next May. Subsequently pumping distribution coefficients were developed based on deviation between the observed and model calculated groundwater heads at the end of the year. This is explained in the section (6.4.2) which deals with model calibration. The norms adopted in the development of uniform pumping rate are as follows :

Estimation of uniform pumping rate:

Total number of wells in the study area	=	5052
Average rate of pumping/well	=	33 m ³ /hr
Number of operating hours per annum	=	1200 hrs
Number of pumping nodes	=	30 (all internal nodes)
Uniform (averaged over 24 hrs) pumping rate at each internal node	=	

$$\frac{33 \times 1200 \times 5052}{365 \times 24 \times 60 \times 60 \times 30} = 0.2112 \text{ m}^3/\text{sec.}$$

(ii) *Recharge rates* : The recharge rates at each node were derived from the calculated recharge for the basic simulation units (Tables 4.11 to 4.14). Nodes falling under each BSU were identified by overlaying of finite element grid (Fig. 6.3) on the BSUs (Fig.3.7, Table 6.1).

6.4.2 Spatial Distribution of Pumping Rates

The groundwater model is run with the specified boundary conditions, initial conditions, recharge rates at each node and the specified uniform pumping rates at all internal nodes for all the years. It was observed that the observed and predicted heads were randomly distributed about the 45° line. In general, if the pumping rates are near to actual values, the observed and simulated water table levels should agree within reasonable limits. Otherwise if the pumping rates used are higher than actual values, the resulting simulated groundwater levels could be lower than the observed values and vice versa. Since the recharge values are estimated using the analytical method, namely the soil water balance model, any discrepancies between observed and simulated water table levels can be attributed to the differences in the pumping rates from actual values. Accordingly it is proposed to suitably modify the pumping rates as per the following norms

Table 6.1 **Distribution of nodes within each basic simulation unit**

<i>Mandall</i> Administrative Block	Nodes Falling under each BSU	Pumping nodes within each each BSU
Atreyapuram	1,2,3,4,7,8,9,10,15 6,5 17 18,21	17
Ravulapalem	14,13,12,11, 20, 16 24,25	16, 20 24
Kothapeta	23 28 35 38,43,48	23 35
P Gannavaram	19 22,26,27,29,30,31,32, 36,37 33,40	32 33,40
Amavilli	52 0 57 59,67,58,64,65	57 58,64
Ambajipeta	39,46,42,41 34,47	42,46 34,47
Amalapuram	44,45 56,63 62	45 56,63 62
Munmidivaram	71,73,79 77,76,81,78	71 76,77
Katritikona	74,80,82,83,84,85	75,74 86,87,75
Uppatagupam	61,66,68 72,69,70	61 69,70
Allavaram	60 54,55,53,49,51,50	54,55

Table 6.2. The uniform pumping rate at each internal node was then adjusted by a pumping factor (PF) based on the deviation of the model predicted heads and the observed heads at the end of year 1992-93, (May, 1993) at each node. In doing so, it was ensured that the total draft for the area remains the same as derived from the total number of wells in the study area. Thus, if the predicted heads are within ± 0.5 m of the observed heads, $PF = 1$, if the deviations are above the observed heads, pumping rates were increased and if the deviations are below the observed heads, pumping rates were reduced using the norms of Table 6.2.

Table 6.2 Norms adopted in derivation of pumping rate coefficients

Deviation between observed and predicted head at each node, m	Pumping Factor (PF) (if computed water table is lower than observed water table level)	Pumping Factor (PF) (if computed water table is higher than observed water table level)
0 - 0.5	1.0	1.0
0.5 - 1.0	0.5	1.5
1.0 - 1.5	0	2.0

To ensure that the total pumping for the area remain the same, the pumping rate coefficients for all the internal nodes were normalized. The following equation is used to derive the normalized pumping rate coefficients.

$$\text{Normalized pumping factor at a node } i, (NPF)_i = \frac{(UPR \times INODE)}{TPN} \times PF_i \quad (6.7)$$

Where,

UPR = Uniform pumping rate at each internal node, m^3/sec

INODE = Total number of internal nodes

PF = Pumping factor at the node, i

$$TPN = UPR \times (N1 \times 0 + N2 \times 0.5 + N3 \times 1 + N4 \times 1.5 + N5 \times 2.0) \quad (6.8)$$

Where,

- N1 = Number of nodes with pumping factor zero
- N2 = Number of nodes with pumping factor 0.5
- N3 = Number of nodes with pumping factor 1.0
- N4 = Number of nodes with pumping factor 1.5
- N5 = Number of nodes with pumping factor 2.0

The pumping rates derived as above for 1992-93 were adopted for the years 1993-94, 1994-95 and 1995-96 also. Pumping is an extraction from the groundwater basin, and hence a (-ve) sign was assigned to the pumping rates at each node. Pumping nodes in each BSU are listed in Table 6.1. The typical data input for the model for the year 1995-96 is listed in Appendix F.

6.4.3 Simulation of Groundwater Levels

The model is run again for the year 1992-93 with the modified pumping rates and the results were given in the Table 6.3. From the Table 6.3, it is clear that the simulated water levels closely matched with the observed waterlevels, indicating the suitability of these pumping rates for the study area. It is also seen from the Table 6.3 that the correlation coefficient improved from 0.49 to 0.92 with the introduction of spatially distributed pumping rate coefficients for all the internal nodes. Hence for the present study, the model was run for the years 1992-93, 1993-94, 1994-95, 1995-96 with the corresponding monthly recharge rates (Table 4.11 to Table 4.14) and pumping rates derived on the basis of 1992-93 data Table 6.3. Monthly recharge rates were equally distributed among all nodes coming under that particular BSU. The observed and simulated

Table 6.3 Simulated water table levels, m for the year 1992-93

Node	Uniform pumping rates			Modified Pumping rates		
	Observed	Simulated	Deviation	Pumping rates (m ³ /sec)	Simulated	Deviation
16	3.5	3.13	0.37	0.2112	3.24	0.27
17	2.8	2.00	0.80	0.1056	2.39	0.41
20	3.5	2.55	0.95	0.1056	3.39	0.11
23	3.5	3.58	-0.08	0.2112	3.70	-0.19
24	2.6	2.74	-0.14	0.2112	2.71	-0.11
32	2.1	0.53	1.57	0.0	2.29	-0.19
33	2.45	1.74	0.71	0.1056	2.78	-0.33
34	3.25	2.39	0.86	0.1056	2.97	0.28
35	3.00	2.76	0.24	0.2112	2.85	0.15
40	1.80	0.67	1.13	0.1056	2.02	-0.22
42	1.90	0.57	1.33	0.0	1.77	0.13
45	1.75	1.52	0.23	0.2112	1.72	0.03
46	1.85	1.67	0.18	0.2112	1.89	-0.04
47	2.20	1.89	0.31	0.2112	1.94	0.26
54	0.40	-0.07	0.47	0.2112	-0.09	0.49
55	1.20	0.92	0.28	0.2112	0.74	0.46
56	1.75	2.31	-0.56	0.3168	1.75	0.00
57	1.80	1.94	-0.14	0.2112	1.80	0.00
58	1.40	1.98	-0.58	0.3168	1.52	-0.12
61	1.00	1.53	-0.53	0.2112	0.94	0.06
62	1.80	3.14	-1.34	0.4224	2.08	-0.28
63	3.00	2.93	0.07	0.2112	2.60	0.40
64	1.50	2.06	-0.56	0.3168	1.60	-0.10
69	1.20	1.97	-0.77	0.3168	1.32	-0.12
70	1.75	2.60	-0.85	0.3168	2.00	-0.25
71	1.40	1.64	-0.24	0.2112	1.51	-0.11
74	0.80	0.65	0.15	0.2112	0.51	0.29
75	0.90	1.43	-0.53	0.3168	0.92	-0.02
76	0.90	0.97	-0.07	0.2112	0.76	0.14
77	0.90	1.25	-0.35	0.2112	1.16	-0.26
Correlation coefficient R^2			0.49			0.92
Mean square error (MSE)			0.46			0.055
Mean per cent error (MPE)			-0.016			-0.050
Mean average per cent error (MAPE)			0.341			0.143

watertable levels at all the internal nodes for this time period is given in Table 6.4.

Since the time domain in the finite element model was approximated using implicit finite difference scheme, it is unconditionally stable regardless of the size of the time increment (Narasimhan and Witherspoon, 1982). Convergence can be tested in terms of four types of error checks (Prickett and Lonquist, 1971) depending on the problem under study. In the present study the method of limiting the sum of the changes in hydraulic potentials during iterations over the entire model to a pre assigned value was used (i.e. iteration closer criterion). A typical output file contains information on time domain, i.e. time step duration and number of time steps, and also the number of iterations required for the convergence of solution and the iteration closer criterion. In this model, considering the analytical approach used in estimating various components of recharge, number of iterations allowed were 8 and 0.1 was taken as iteration closure criterion, such that it will not require too much of computer time for convergence. Finally, the water levels at each node at the end of the period are also given in the output file. A specimen output file for the year 1995-96 is given in Appendix F.

6.4.4 Regional Water Balance of the Study Area

The finite element groundwater model also computes the groundwater outflow from the basin at each node. This is used to further validate the prediction of the model, and the regional groundwater balance. The net recharge (R_n) to groundwater basin during any time period can be estimated as given below (Sondhi *et al.*, 1989).

Table 6.4 Observed and simulated water table levels, m

Internal Node	1992-93		1993-94		1994-95		1995-96	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
16	3.5	3.24	4.0	3.44	5.0	4.44	6.0	5.59
17	2.8	2.39	3.0	2.44	3.8	3.0	4.5	3.89
20	3.5	3.39	4.0	3.67	5.5	6.19	7.5	7.90
23	2.6	3.70	4.3	4.20	5.5	5.98	7.5	7.33
24	2.6	2.71	3.2	2.82	3.5	2.92	4.5	3.82
32	2.1	2.29	2.7	2.32	3.5	3.17	4.0	3.75
33	2.45	2.78	2.9	2.91	3.7	4.38	5.2	5.16
34	3.25	2.97	4.0	3.54	4.0	4.51	5.0	4.82
35	3.0	2.85	3.4	3.23	3.9	4.63	5.8	5.31
40	1.80	2.02	2.3	1.75	4.0	4.64	5.5	5.57
42	1.90	1.77	2.1	1.62	3.0	3.89	4.0	3.69
45	1.75	1.72	2.1	1.64	3.0	3.03	4.0	4.05
46	1.85	1.89	2.3	2.39	3.4	3.32	4.0	3.91
47	2.20	1.94	2.5	2.48	3.2	3.24	4.5	3.89
54	0.40	-0.10	0.5	-0.08	1.0	0.14	1.2	0.76
55	1.20	0.74	1.4	1.05	1.7	1.13	2.25	1.65
56	1.75	1.75	1.9	2.17	2.5	2.90	4.0	3.94
57	1.80	1.80	2.25	2.47	2.9	3.20	4.0	3.93
58	1.40	1.52	1.6	2.02	2.7	2.71	4.5	3.91
61	1.00	0.94	1.0	1.34	1.5	1.52	2.5	2.72
62	1.80	2.08	1.95	2.46	2.8	3.38	4.2	4.95
63	3.00	2.60	3.0	3.05	3.0	3.71	4.5	4.56
64	1.50	1.60	1.85	1.95	3.0	2.55	4.0	3.64
69	1.20	1.32	1.30	1.77	1.5	2.10	3.0	3.28
70	1.75	2.00	2.30	2.53	2.5	2.90	4.0	4.04
71	1.40	1.51	1.50	1.81	2.5	2.32	3.0	3.06
74	0.80	0.51	0.70	0.64	1.0	0.78	1.75	1.33
75	0.90	0.92	0.90	1.14	1.5	1.38	2.50	2.76
76	0.90	0.76	0.70	0.15	1.5	2.12	2.50	2.72
77	0.90	1.16	1.10	1.02	1.7	1.84	3.20	3.34
R ²	0.92		0.89		0.88		0.94	
MSE	0.055		0.13		0.24		0.136	
MPE	-0.050		-0.065		0.016		-0.041	
MAPE	0.143		0.195		0.171		0.088	

$$R_n = R_g \pm Q_g - Q_p \quad (6.9)$$

Where,

R_g = Gross recharge to groundwater basin from all sources, MCM

Q_g = Groundwater inflow/outflow to neighbouring areas, MCM and

Q_p = Groundwater extraction through wells, MCM.

Estimation of components

Groundwater inflow / outflow (Q_g) : The inflow / outflow from the study area was estimated by simulating groundwater conditions using groundwater model, as discussed in chapter 6, section 6.1. The monthly outflow / inflow rates from the study area for the period 1992-93 to 1994-95 was given in the table 6.5. Annual outflow / inflow rates were also obtained from these monthly rates and given in the Table 6.5.

Table 6.5 Monthly outflow rates from the study area, m³/sec

	1992-93	1993-94	1994-95
June	4.61	9.59	12.50
July	24.74	26.06	27.68
Aug	24.71	26.11	25.7
Sep	26.23	27.81	25.55
Oct	17.35	25.7	26.39
Nov	15.52	18.93	26.46
Dec	16.99	22.39	23.30
Jan	18.49	20.22	23.58
Feb	12.30	12.91	16.28
Mar	6.79	7.46	9.68
Apr	3.72	4.21	5.76
May	4.22	2.90	16.25
Average monthly outflow rate	14.64	17.02	19.90

Gross recharge (R_g) : The gross recharge (R_g) to groundwater basin of the study area is given by

$$R_g = R_c + R_d + R_{ci} + R_{wi} + R_{uc} + R_{rf} \quad (6.10)$$

Where,

R_c = Recharge due to seepage from main canal and branches,

R_d = Recharge due to seepage from distributaries,

R_{ci} = Recharge due to percolation from areas irrigated by canal water, mm³ (Paddy crop, both *Kharif* and *Rabi* season)

R_{wi} = Recharge due to percolation losses from ^{cultured} irrigated by wells, (Pulses, sugarcane, coconut plantations).

R_{uc} = Recharge due to percolation losses from uncultivated soil, and

R_{rf} = Recharge due to percolation losses from rice fallow lands.

The various components involved in the estimation of gross recharge (R_g) from different sources was discussed in detail in chapter 4. The gross recharge obtained for each BSU is given in Table 4.11 to table 4.14 for the period 1992-1995. The annual gross recharge for entire study area is obtained by summing up the gross annual recharge values of all BSU's for the period 1992-93, 1993-94, 1994-95, 1995-96 (Table 6.6).

Pumping (Q_p) . Total pumping from the study area was obtained by multiplying total number of wells by average pumping rate adopted from CGWB report, 1992. and total pumping was given in the Table 6.6.

6.4.5 Annual Water Balance

The annual water balance of the study area is given in Table 6.6. The net rise in watertable levels during the period 1992 to 1995 is in close agreement with the observed average annual rise in watertable. Thus the outflow values used in the annual water balance of the study area, indicate a reasonable estimate of these outflows from the groundwater basin simulation model.

Table 6.6 Annual water balance of the study area

Year	gross recharge MCM	outflow MCM	pumping MCM	Net recharge MCM	Net rise in watertable (m)	Observed watertable rise (m)
1992-93	693.79	461.69	181.65	50.45	0.33	0.33
1993-94	760.12	538.00	181.65	40.47	0.27	0.30
1994-95	892.47	627.57	181.65	83.25	0.55	0.71

Foot note : $\therefore$ Column 6 = Column 5 $\times$ 6.62×10^{-3}

Size of the study area = 83914.89 ha

Specific yield = 0.18

$$\begin{aligned}
 \text{Net rise in watertable (m)} &= \frac{\text{Net recharge, MCM}}{\text{Area, ha} \times \text{Specific Yield}} \\
 &= \frac{\text{Net recharge} \times 10,00,000}{83914.89 \times 10,000 \times 0.18} \\
 &= \text{net recharge (MCM)} \times 6.62 \times 10^{-3}
 \end{aligned}$$

6.5 SENSITIVITY ANALYSIS AND VALIDATION OF THE SIMULATION MODEL

The simulation model of the groundwater basin has the capability to use the input data specified as discussed in the previous section and simulates the response of the groundwater basin. However, it is necessary to study the model's sensitivity to its parameters and its applicability to the study area before it is used for predictions. Hence sensitivity analysis was performed as discussed below.

The parameters of the model considered are hydraulic conductivity and storage coefficient. Separate simulations were carried out with the 1992-93 input data using the finite element model by varying the hydraulic conductivity and storage coefficient in turns. Hydraulic conductivity was varied by ± 50 per cent and the storage coefficient also by ± 50 per cent.

The typical results of sensitivity analysis for all the internal nodes of the study area are given in Tables 6.7 and 6.8. Some statistical parameters of the distributions of the observed and predicted watertable levels of the study area obtained for the sensitivity analysis are given in the Tables 6.7 and 6.8. It can be concluded from these tables, the model seems to be particularly insensitive to the variation in 'K' and 'S' within the range tested. Thus, the assumed homogeneity in values of 'K' and 'S' is not likely to introduce major errors. Similar observations were made by Rushton (1975), Gates and Kisiel (1974) and Boonstra and De Ridder (1981) in their studies. Hence, initial values of hydraulic conductivity and storage coefficient were retained for further analysis.

The computed water levels and the corresponding observed values for the period 1992-93 to 1995-96 are compared in (Figs. 6.5 to 6.8).

There is a close agreement between the observed and predicted waterlevels in all the years. For further evaluation of the capability of the model, the observed and simulated water levels for all the internal nodes during the simulation period 1992-96 are plotted in Fig 6.9 to Fig 6.13 to show comparison between observed and simulation water levels. The average difference between the observed and simulated waterlevels for most of the internal nodes varies between 0 to 0.5 m. For 1995, November model slightly underestimated water table levels (Table 6.9). This may be because, that rainfall at all raingauge stations during the year 1995 was higher as compared to other two years of study (Table 6.10). This would have led to a lowering of pumping rates by farmers in this year. But variations in pumping rates were not considered in the inputs to the model. A rerun of the model with reduction of total pumping by 25% with its spatial distribution in the study area improved the model prediction (Fig 6.13, Table 6.9) thus confirming this reasoning. For deviations within these limits

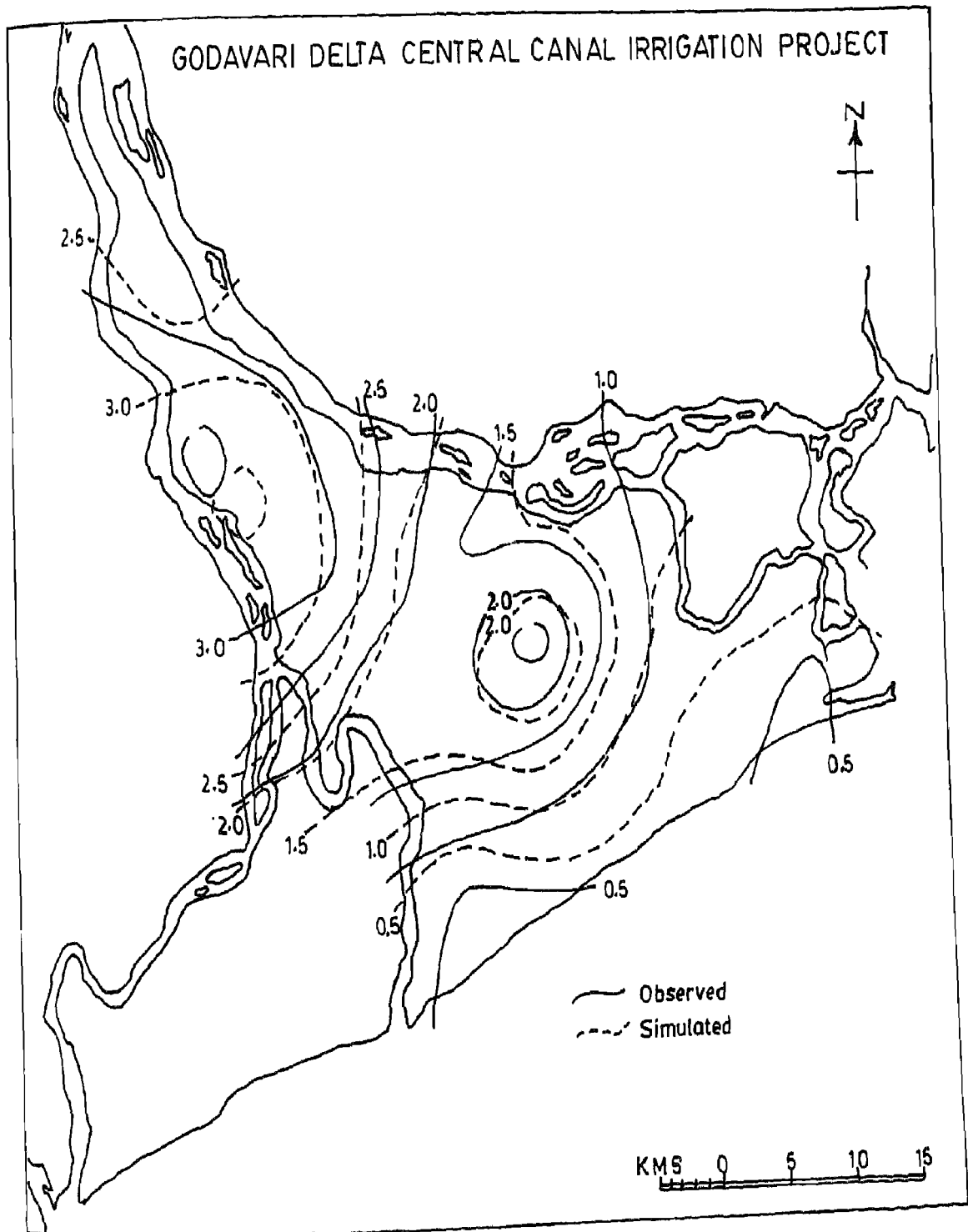


Fig.65 Observed and simulated groundwater levels, m (May 1993)

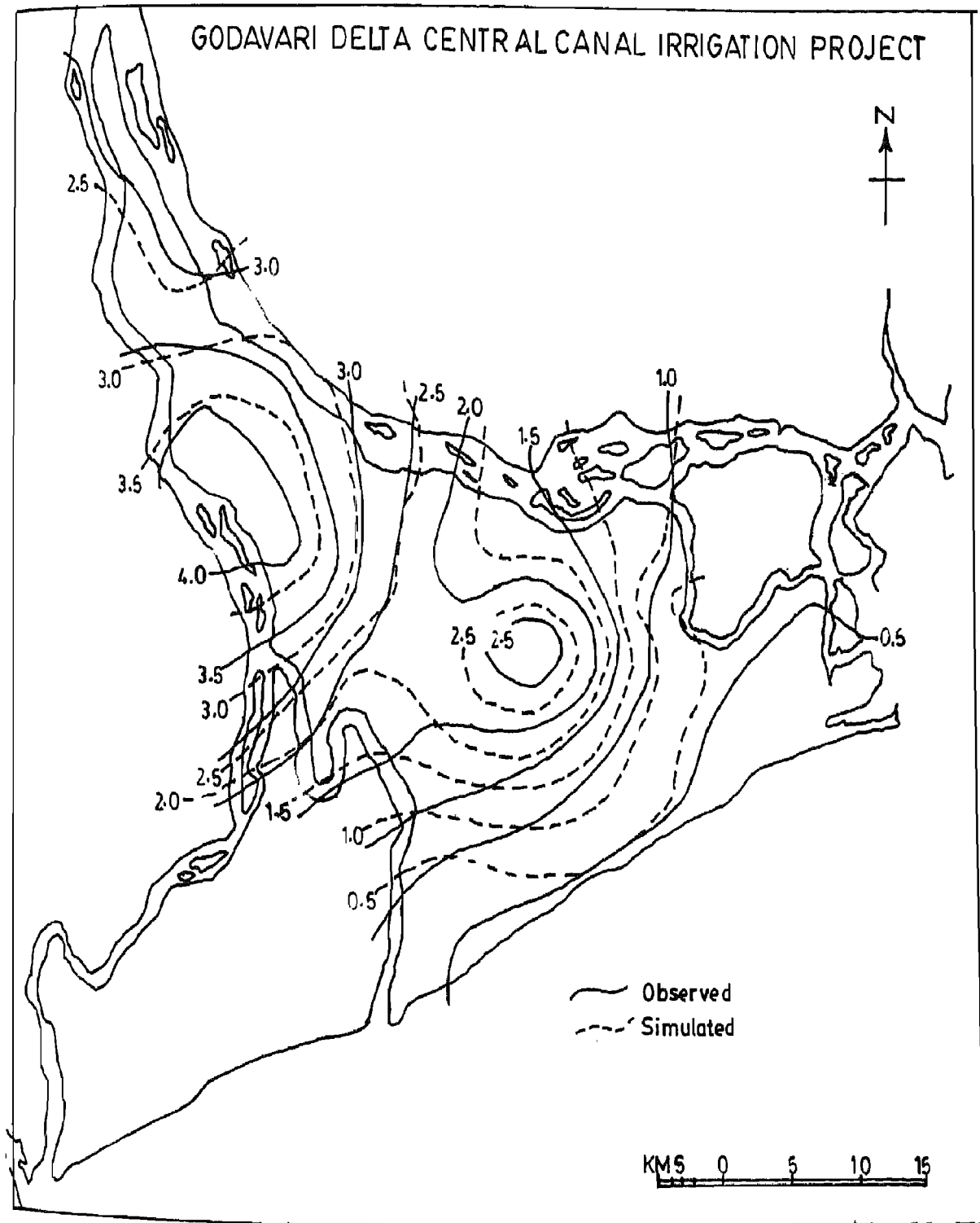


Fig6.6 Observed and simulated groundwater levels_m (May 1994)

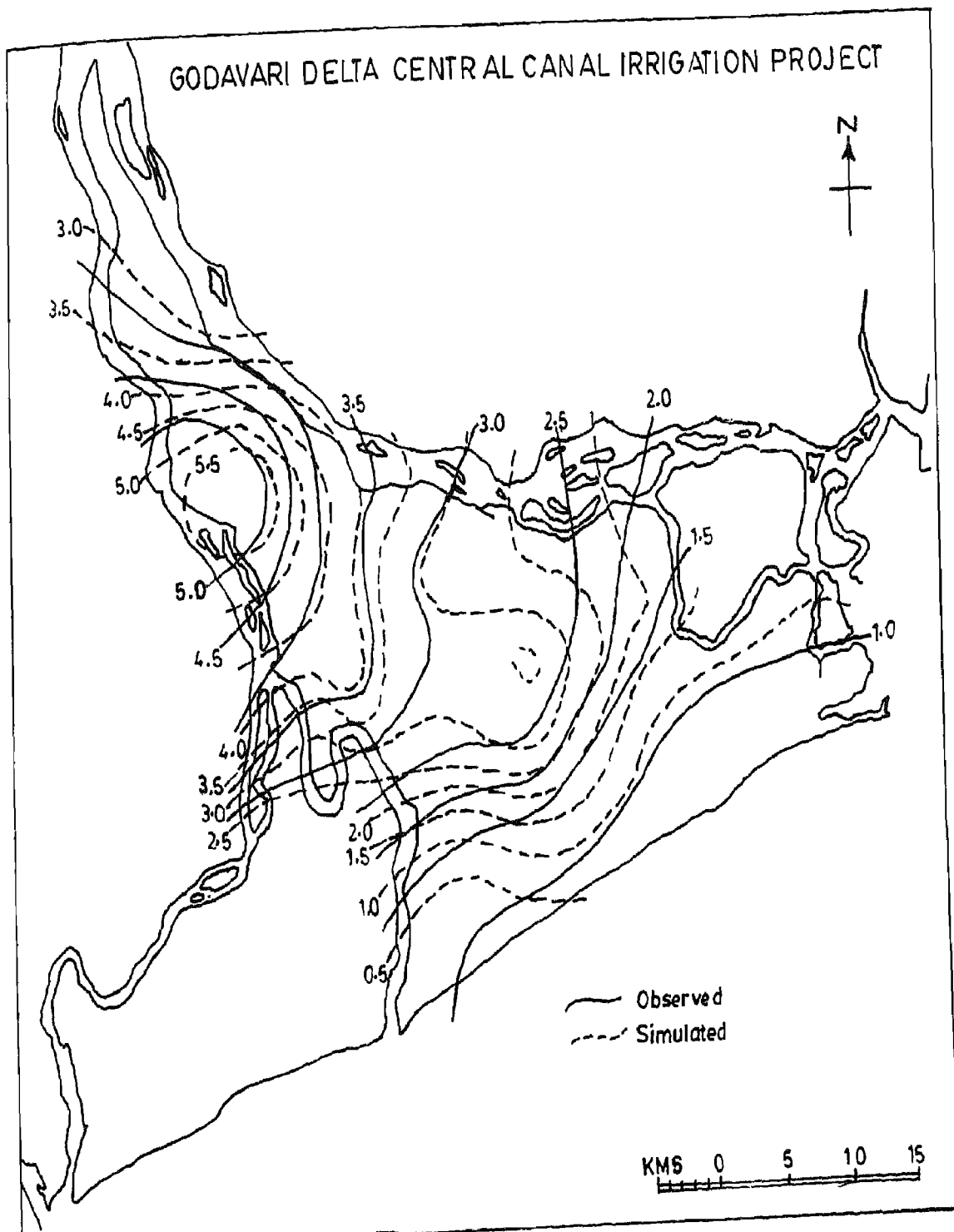


Fig. 6.7 Observed and simulated groundwater levels, m (May 1995)

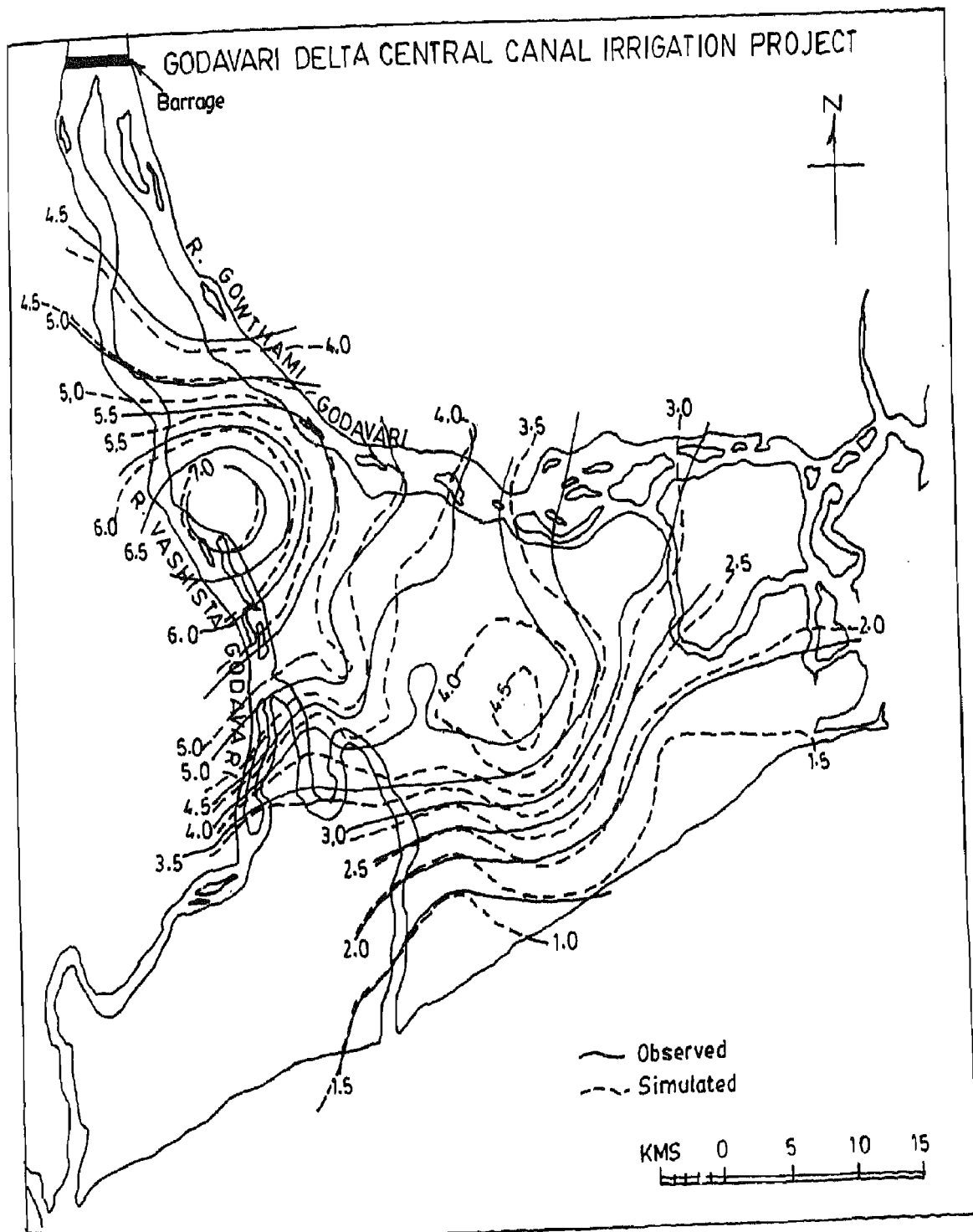


Fig.6.8 Observed and simulated groundwater levels, m (Nov, 1995)

**Fig.6.9 Observed and Simulated Groundwater levels
in the study area (May, 1993)**

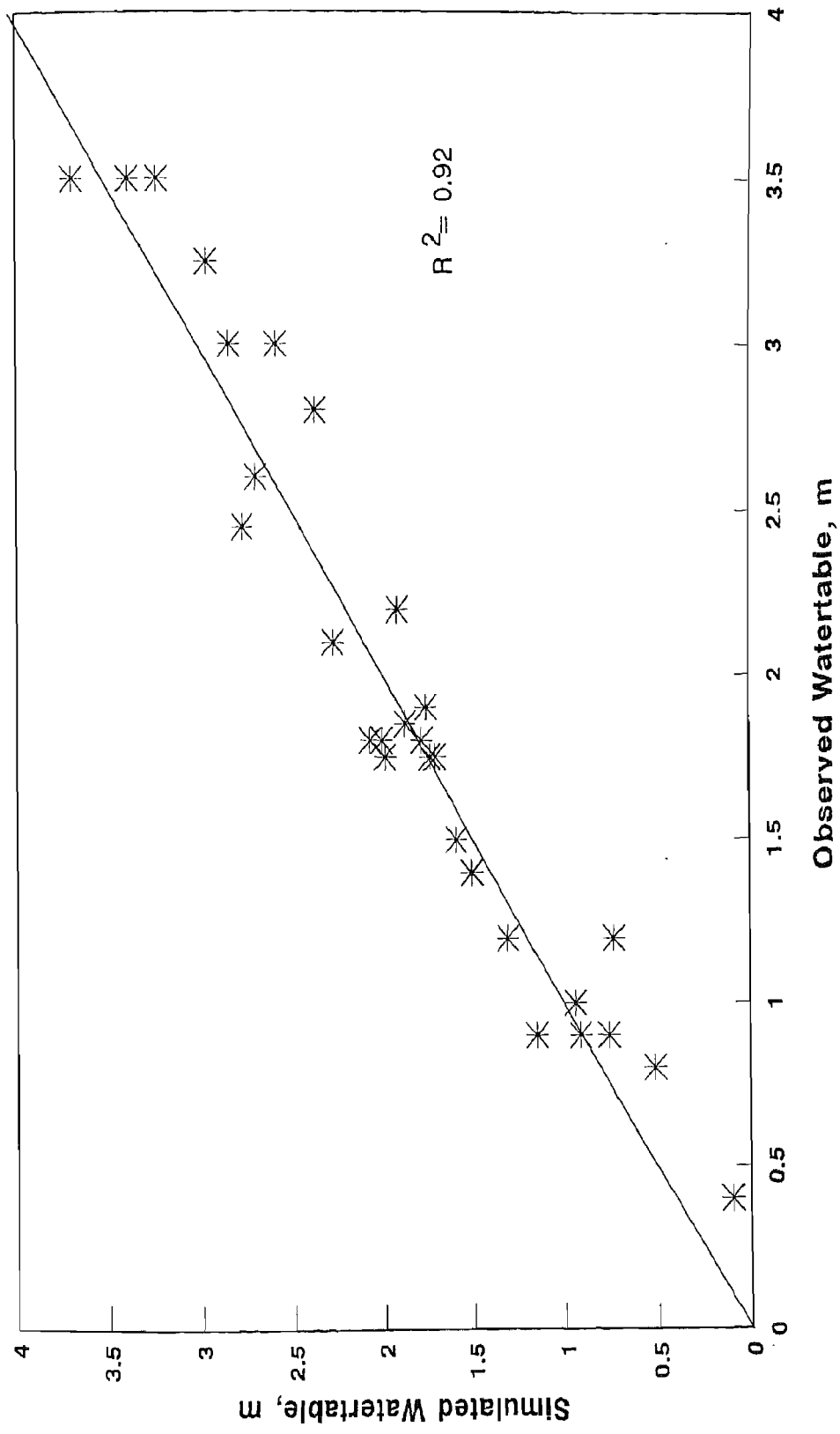


**Fig.6.10 Observed and Simulated Groundwater Levels
in the study area (May, 1994)**

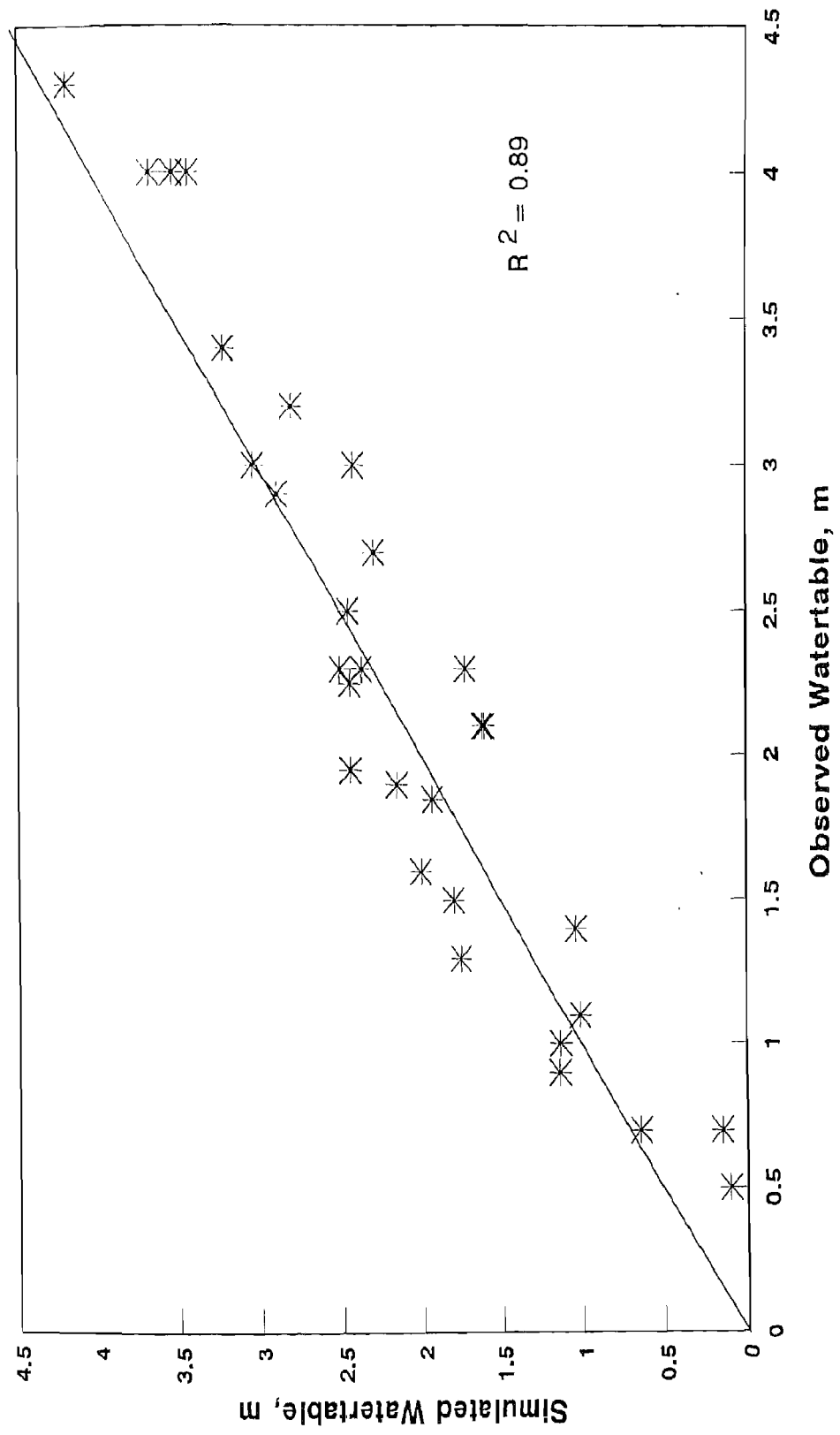


**Fig.6.11 Observed and Simulated Groundwater levels
in the study area(May, 1995)**

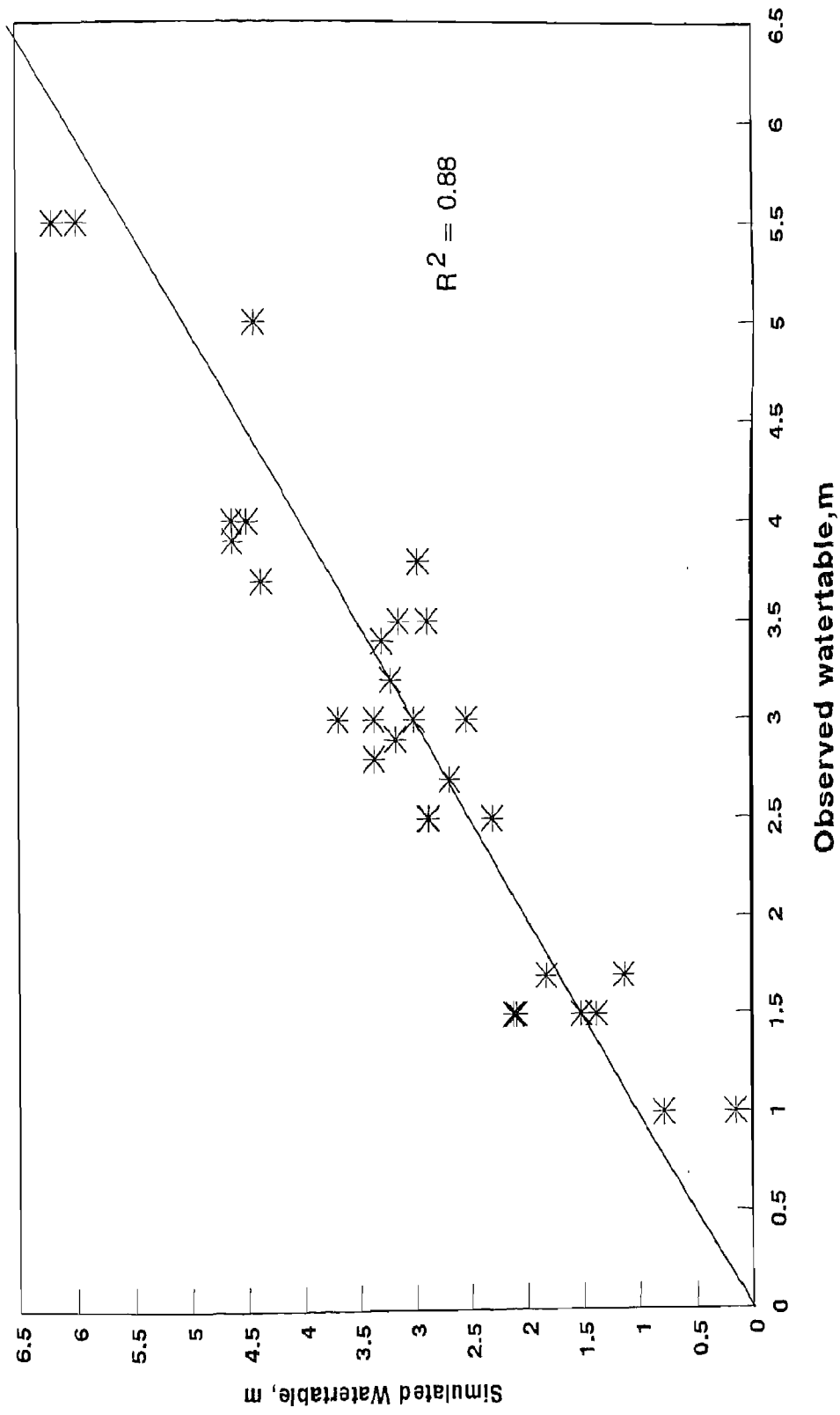


**Fig.6.12 Observed and Simulated Groundwater levels
in the study area (November, 1995)**

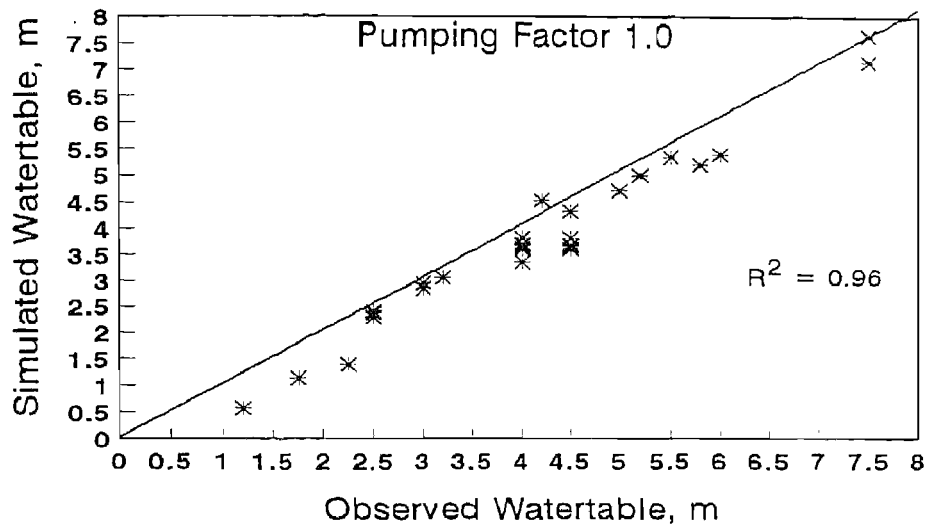


**Fig.6.13 Observed and Simulated Groundwater levels
in the study area (November, 1995)**

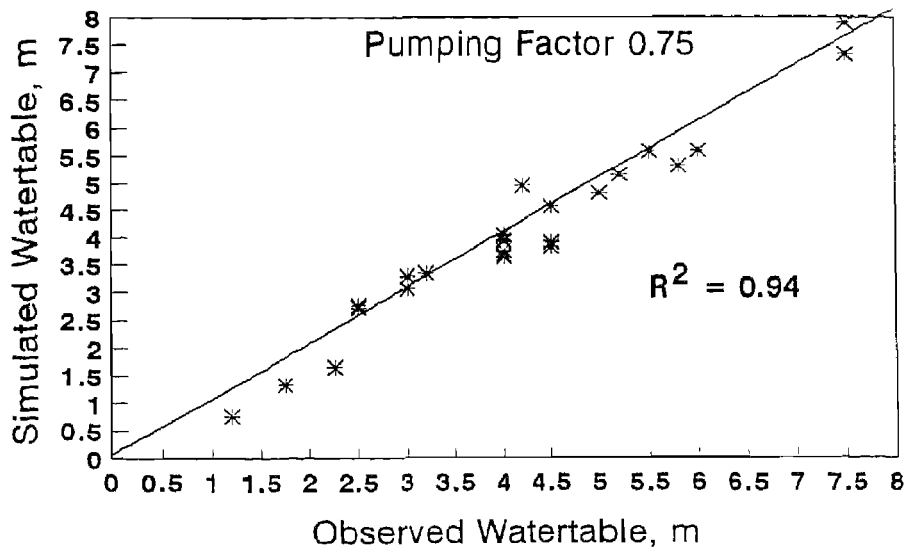


Table 6.7 **Sensitivity analysis of predicted water table levels with changes in specific yield**

Node number	Observed water table	Simulated Water table levels, m				
		With initial specific yield	25% increase in specific yield	50% increase in specific yield	25% decrease in specific yield	50% decrease in specific yield
16	3.5	3.24	3.30	3.33	3.09	2.79
17	2.8	2.39	2.46	2.51	2.30	2.19
20	3.5	3.39	3.53	3.62	3.17	2.79
23	3.5	3.70	3.76	3.78	3.53	3.15
24	2.6	2.71	2.74	2.75	2.60	2.36
32	2.1	2.29	2.31	2.32	2.26	2.21
33	2.45	2.78	2.79	2.78	2.75	2.65
34	3.25	2.97	2.89	2.82	3.04	3.02
35	3.00	2.85	2.86	2.86	2.81	2.68
40	1.80	2.02	2.09	2.14	1.92	1.78
42	1.90	1.77	1.80	1.82	1.74	1.70
45	1.75	1.72	1.72	1.72	1.73	1.73
46	1.85	1.89	1.80	1.72	2.00	2.11
47	2.20	1.94	1.87	1.81	2.03	2.11
54	0.40	-0.09	-0.04	0.01	-0.15	-0.24
55	1.20	0.74	0.76	0.77	0.68	0.55
56	1.75	0.75	1.70	1.68	1.80	1.80
57	1.80	1.80	1.71	1.64	1.92	2.05
58	1.40	1.52	1.55	1.57	1.49	1.44
61	1.00	0.94	0.98	1.00	0.86	0.67
62	1.80	2.08	2.09	2.08	2.04	1.86
63	3.00	2.60	2.52	2.46	2.68	2.67
64	1.50	1.60	1.64	1.66	1.55	1.43
69	1.20	1.32	1.34	1.35	1.25	1.03
70	1.75	2.00	1.96	1.91	1.98	1.77
71	1.40	1.51	1.54	1.54	1.43	1.24
74	0.80	0.51	0.53	0.54	0.46	0.34
75	0.90	0.92	0.95	0.97	0.82	0.58
76	0.90	0.76	0.78	0.79	0.72	0.62
77	0.90	1.16	1.24	1.30	1.04	0.87
R		0.96	0.96	0.96	0.96	0.95
MSE		0.055	0.06	0.66	0.061	0.115
MPE		-0.05	-0.037	-0.031	-0.081	-0.16
MAPE		0.143	0.148	0.152	0.15	0.194

Table 6.8 **Sensitivity analysis of predicted water table levels with changes in hydraulic conductivity**

Node number	Observed water table	Simulated Water table levels, m				
		With initial 'K'	25% increase in 'K'	50% increase in 'K'	25% decrease in 'K'	50% decrease in 'K'
16	3.5	3.41	3.11	3.02	3.41	3.65
17	2.8	2.44	2.36	2.35	2.44	2.56
20	3.5	3.69	3.21	3.10	3.69	4.29
23	3.5	4.04	3.45	3.28	4.04	4.55
24	2.6	2.75	2.66	2.61	2.75	2.76
32	2.1	2.43	2.21	2.16	2.43	2.72
33	2.45	3.04	2.62	2.51	3.04	3.51
34	3.25	3.06	2.89	2.81	3.06	3.13
35	3.00	3.02	2.74	2.66	3.02	3.27
40	1.8	2.19	1.93	1.88	2.19	2.59
42	1.9	1.88	1.72	1.69	1.88	2.13
45	1.75	1.77	1.71	1.70	1.77	1.90
46	1.85	1.80	1.94	1.96	1.80	1.60
47	2.2	1.82	2.00	2.04	1.82	1.64
54	0.4	-0.23	0.00	0.07	-0.233	-0.49
55	1.2	0.62	0.79	0.82	0.62	0.38
56	1.75	1.78	1.72	1.69	1.78	1.82
57	1.80	1.71	1.84	1.85	1.71	1.55
58	1.40	1.48	1.55	1.58	1.48	1.46
61	1.0	1.02	0.88	0.83	1.02	1.11
62	1.80	2.34	1.90	1.75	2.34	2.73
63	3.0	2.80	2.44	2.30	2.80	3.05
64	1.5	1.62	1.59	1.57	1.62	1.63
69	1.2	1.47	1.20	1.11	1.47	1.66
70	1.75	2.16	1.85	1.73	2.16	2.33
71	1.4	1.59	1.45	1.40	1.59	1.65
74	0.8	0.53	0.49	0.48	0.53	0.52
75	0.9	0.96	0.87	0.84	0.96	1.00
76	0.9	0.72	0.78	0.79	0.72	0.65
77	0.9	1.31	1.08	1.03	1.31	1.65
R		0.965	0.97	0.97	0.95	0.91
MSE		0.055	0.054	0.067	0.098	0.275
MPE		-0.050	-0.073	-0.091	-0.022	0.018
MAPE		0.143	0.126	0.125	0.188	0.298

Table 6.9 Simulated water table levels for the year 1995-96

Node	Pumping Factor 1.0			Pumping Factor 0.75	
	Water table levels, m			Water table levels, m	
	Observed	Simulated	Deviation	Simulated	Deviation
16	6.0	5.39	0.61	5.59	0.41
17	4.5	3.81	0.69	3.89	0.60
20	7.5	7.64	-0.14	7.9	-0.40
23	7.5	7.15	0.35	7.33	0.17
24	4.5	3.67	0.83	3.82	0.68
32	4.0	3.71	0.29	3.75	0.25
33	5.2	5.0	0.20	5.16	0.04
34	5.0	4.71	0.29	4.82	0.18
35	5.8	5.19	0.61	5.31	0.49
40	5.5	5.34	0.16	5.57	-0.07
42	4.0	3.60	0.40	3.69	0.31
45	4.0	3.82	0.18	4.05	-0.05
46	4.0	3.69	0.31	3.91	0.09
47	4.5	3.68	0.82	3.89	0.61
54	1.2	0.60	0.63	0.76	0.44
55	2.25	1.38	0.87	1.65	0.60
56	4.0	3.64	0.37	3.94	0.06
57	4.0	3.70	0.30	3.93	0.07
58	4.5	3.61	0.89	3.91	0.60
61	2.5	2.41	0.09	2.72	-0.22
62	4.2	4.53	-0.33	4.95	-0.75
63	4.5	4.32	0.18	4.56	-0.06
64	4.0	3.36	0.64	3.64	0.36
69	3.0	2.95	0.05	3.28	-0.28
70	4.0	3.71	0.29	4.04	-0.04
71	3.0	2.85	0.15	3.06	-0.06
74	1.75	1.13	0.62	1.33	0.42
75	2.50	2.37	0.13	2.76	-0.26
76	2.50	2.29	0.21	2.72	-0.22
77	3.20	3.05	0.15	3.34	-0.14
R ²		0.96		0.94	
MSE		0.218		0.136	
MPE		-0.11		-0.041	
MAPE		0.116		0.088	

Table 6.10 Annual (Jun-May) Rainfall, 1992-95

Raingauge station		Rainfall (mm)		
No.	Name	1992-93	1993-94	1994-95
1	Sakhinetipalli	717	1159	2237
2	Mandepalanka	825	876	1754
3	Chintalapudi	686	935	1989
4	Ainavili	776	1241	2686
5	Mukkamala	699	951	1745
6	Gopalapuram	707	1077	1678
7	Ryali	820	883	1447
Average		747	1017	1933

groundwater model performance can be considered satisfactory (Kisel *et al.*, 1972; Karanjac *et al.*, 1977; Klempt, *et al.*, 1979 and Boonstra and De Ridder, 1981). The correlation coefficient (R^2) obtained for various model simulations during the period 1992-95 vary between 0.88 to 0.94. Thus, the recharge rates obtained using soil water balance model and canal flow model and pumping rates are representative for the study area. The general agreement between the observed and predicted water levels (Fig 6.5 to Fig 6.13) is satisfactory enough to permit integration of the model with solute transport model (Section 6.6).

6.6. DEVELOPMENT OF THE GROUNDWATER TRANSPORT MODEL

The transport of a solute in groundwater can be described by combining the equation for conservation of mass for the solute and a constitutive relation for solute fluxes. The equation for conservation of mass is

$$I - 0 = \frac{\partial M}{\partial t} \quad 6.11$$

Where I is the mass inflow rate for the solute, O is the outflow rate, M is the mass of solute within the control volume, and t is time

6.6.1 General Equation of Solute Transport in Groundwater

In the present study, it was considered that solutes are transported in groundwater by the processes of advection and dispersion. Advection is the transport of solute by the moving groundwater. By this process, the solute is moved from one position in the aquifer to another with the moving groundwater according to a trajectory determined by the velocity field within the aquifer. The concentration of solute remains unchanged within a moving elemental volume of water. In contrast, dispersion is the process of mixing of solute between elemental volumes of water owing to the combined processes of molecular diffusion and hydrodynamic dispersion. The concentration of solute within a moving elemental volume of water changes during its movement from one position to another. In formalizing these concepts, it is helpful to consider first the one dimensional case and then to extend the results to the two dimensional case. For one dimensional case, the advective flux of solute is described by the product $(Q C)$. Where Q is the volumetric flux of water through a unit width of aquifer and C is the mass concentration of solute per unit volume of water. The dispersive flux of solute is described by the term

$$- b \theta D \frac{\partial C}{\partial x}$$

Where D is the dispersion coefficient, b is the aquifer thickness, θ is aquifer porosity, and $\partial C / \partial x$ is the concentration gradient. The negative sign arises because the flux of solute is in the direction of decreasing concentration gradient. The terms for advective and dispersive flux can be combined to obtain.

$$J = Q C - b \theta D \frac{\partial C}{\partial x} \quad 6.12$$

As stated before, dispersion occurs by the combined processes of molecular diffusion and hydrodynamic dispersion. These processes are additive, and dispersion coefficient of Eq 6.12 can be expressed as

$$D = D_h + D_r \quad 6.13$$

Where D_h is the coefficient of hydrodynamic dispersion and D_r is the coefficient of molecular diffusion. The value of D_r depends on the small scale structure of the aquifer solid matrix. The value of D_h depends on the large scale properties of the aquifer matrix and on the velocity of groundwater movement. Accordingly, D_h can be expressed as

$$D_h = \alpha V \quad 6.14$$

Where α is the dispersivity of the aquifer matrix and V is groundwater velocity. In turn, the groundwater velocity, V is given by

$$V = \frac{Q}{b\theta} \quad 6.15$$

Extending this to two dimensional flow, the transport equation for the advective - dispersive transport of a dilute dissolved solute in moving groundwater is given as

$$\begin{aligned} & \frac{\partial}{\partial x} \left[b\theta D_{xx} \frac{\partial C}{\partial x} \right] + \frac{\partial}{\partial x} \left[b\theta D_{xy} \frac{\partial C}{\partial y} \right] + \frac{\partial}{\partial y} \left[b\theta D_{yx} \frac{\partial C}{\partial x} \right] \\ & + \frac{\partial}{\partial y} \left[b\theta D_{yy} \frac{\partial C}{\partial y} \right] - \frac{\partial}{\partial x} \left[(Q_x C) \right] - \frac{\partial}{\partial y} \left[(Q_y C) \right] + NC \\ & = b\theta \frac{\partial C}{\partial t} \end{aligned} \quad 6.16$$

Where

C^1 = concentration of nitrate in the leached water, ppm

N = recharge rate, m^3/sec

$$D_{xx} = D_L \frac{V_x \cdot V_x}{V^2} + D_T \frac{V_y \cdot V_y}{V^2} \quad 6.17$$

$$D_{yy} = D_L \frac{V_y \cdot V_y}{V^2} + D_T \frac{V_x \cdot V_x}{V^2} \quad 6.18$$

$$D_{xy} = (D_L - D_T) \frac{V_x V_y}{V^2} \quad 6.19$$

$$\text{and } D_{yx} = D_{xy} \quad 6.20$$

$$D_L = \alpha_L V + D\tau \quad 6.21$$

$$\text{and } D_T = \alpha_T V + D\tau \quad 6.22$$

Where α_L , α_T are the longitudinal and transverse dispersivities of the aquifer matrix.

Groundwater discharge and velocity within an aquifer are related to water-level gradients and transmissivity by the relationships

$$Q_x = -Kb \frac{\partial h}{\partial x} \quad 6.23$$

$$Q_y = -Kb \frac{\partial h}{\partial y} \quad 6.24$$

$$V_x = \frac{Q_x}{\theta b} \quad 6.25$$

$$V_y = \frac{Q_y}{\theta b} \quad 6.26$$

Where Q_x and Q_y are the x and y components of groundwater discharge, V_x and V_y are the x and y components of groundwater velocity, K is hydraulic conductivity, and $\partial h/\partial x$ and $\partial h/\partial y$ are the x and y components of the groundwater hydraulic gradient. The groundwater gradient and thickness can be obtained from values used in or computed from the groundwater model.

To solve the equation 6.16, additional specification of the boundaries for groundwater transport problem is needed. As in the case of the groundwater flow problem, the solution of the transport problem requires definition of the solution domain, aquifer parameters, solute sources and sinks and boundary and initial conditions

a) Solution domain

The solution domain is the space-time domain within which the solute transport equation is to be solved. In general, the transport problem will have the same solution domain as established for the corresponding groundwater problem

b) Aquifer Parameters

Aquifer parameters are the aquifer porosity, dispersivity, thickness, and groundwater velocity distributions over the flow domain. Porosity is usually estimated from analysis of geologic logs from wells. However, very often initial estimates of porosity from field data are modified during the process of calibrating the groundwater transport model. Dispersivity (α) is defined as characteristic mixing length and is a measure of the spreading of the contaminant. Dispersivity values also can be estimated from field tests, but in most cases better values are obtained from the model calibration. The problem in estimating dispersivity from field tests is that dispersivity is a scale - dependent property of an aquifer.

Consequently, results obtained from tracer tests or column experiments cannot be interpreted in terms of larger scale processes occurring in an aquifer. Aquifer thickness is generally estimated from field data. Thickness can be estimated from geologic logs on wells that penetrate the entire thickness of the aquifer.

c) Boundary and Initial Conditions

Like the transient - state groundwater flow equation, the transport equation is a parabolic partial - differential equation. As such, its solution to eq 6.16 can be obtained only if boundary conditions are specified everywhere on the boundary of the flow domain, and initial conditions are specified everywhere within the flow domain.

Concentration boundary condition of a solute transport problem is a mathematical statement of the condition of concentration on the boundary of the flow domain. The specified concentration boundary condition is given by the relationship

$$C = C_b(\Gamma, t) \quad 6.27$$

Where C_b is the specified concentration, and the specified concentration on the boundary can be a function of position and time.

The specified - flux boundary condition is most often encountered in field applications. From the model of groundwater flows, the fluxes of water are known at the boundary of the flow domain. This is the case even if specified-head boundaries are prescribed for the groundwater model. Given the water flux at the boundary, the solute flux can be determined by specifying the solute concentration in the water crossing the boundary. If water moves out of the flow domain, the specified concentration is the solute in the groundwater within the flow domain. If water moves into the flow domain, the specified concentration is the solute concentration in the water moving into the flow domain.

By this approach, the specified-flux boundary is given by the expression.

$$Q_n C_b = J_b (\Gamma, t) \quad 6.28$$

Where Q_n is the water flux normal to the boundary. C_b is the specified solute concentration in groundwater crossing the boundary, and J_b is the solute flux normal to the boundary

Initial conditions are the specification of solute concentrations over the flow domain at the start of the time domain.

d. Sources and Sinks

Sources and sinks are the specification of solute flux into or from the flow domain with the recharge or discharge of water to or from the groundwater system. For groundwater recharge, the solute flux is given by the source term of eq 6.16, NC^1 . Where N is the recharge rate and C^1 is the concentration of nitrate in the leached water.

For ground water discharge, the solute flux is given by the term NC . Where C is Nitrate concentration of water pumped from the aquifer.

The Finite Element Method (FEM) (Appendix E), is the numerical method adopted to solve the groundwater transport equation in the present study.

6.7 **COMPUTER PROGRAM**

A computer program developed by Swain (1978) was adapted with minor modifications to solve the two dimensional transient state problem of solute transport in groundwater (Appendix G). The program utilizes triangular elements and linear trial functions. Sources and sinks are allowed only at nodal points.

This program is a companion to the previously described program for the finite element analysis of groundwater flow. The program for solute transport

utilizes the computed heads from the groundwater flow model for the computation of groundwater discharge, aquifer thickness, and groundwater velocity. Additionally, the solute - transport model utilizes the source - sink strengths from the groundwater flow model for the water-discharge component of the solute source-sink strengths of the solute transport model. Both models make computations on the same finite - element grid and use the same values for aquifer parameters. In this companionship, the groundwater flow model is executed first, and the computed heads and source sink strengths are saved to a file. These quantities are retrieved from that file and the solute - transport model is then executed.

6.7.1 Program Structure

Similar to the groundwater flow model, the solute - transport program has three basic modules : a main driver module, a data input module, and a solution and output module. These modules are shown schematically in fig. 6.14. The main driver program TRANS calls subroutine TDATA, which reads data defining the geometry of the flow domain, initial conditions, aquifer parameters, and sources and sinks. This information is stored in common blocks and control is returned to the main program. The main program in turn calls subroutine TMODEL, which is the solution and output module. The solution and out put module is in turn divided into sub modules that perform limited functions.

The programme modules and submodules that perform these procedures are described in the following sections. In each case, the important variables are identified, the program logic is described, and a source code listing in fortran 77 is provided in appendix G.

a) Main Program TRANS

The purpose of the main program is to call subroutines TDATA and TMODEL, and the module consists essentially of call statements to those subroutines. A source listing of program TRANS is given in appendix G.

b) Subroutine TDATA

The purpose of subroutine TDATA is to input data that describes the solute transport problem to be solved. The input data occurs in two basic groups : definition of the corresponding groundwater flow problem and definition of the groundwater - transport problem. The important variables in both of these groups are described in appendix G. The units of measure and input formats are indicated by comment statements in the source listing. That source listing of subroutine TDATA is given in appendix G.

In the first data - input group, the space time domain of the ground water flow problem is described. These data include the flow time step, number of flow time steps, number of nodes and elements, nodal coordinates, element incidences, hydraulic conductivity, and altitude for base of the aquifer. The same values are used in the transport problem as were used in the corresponding ground water flow problem.

In the second data input group, the solute transport problem is described. This description includes data on the number of solute transport time steps per ground water flow time step, the aquifer porosity, initial concentration, longitudinal and transverse dispersivity, and data on source - sink concentrations, with regard to sources and sink, data are to be provided for the nodes corresponding to the ground water flow problem. This includes the recharge and discharge nodes and the constant-head nodes. The water fluxes at these

nodes are saved from the groundwater flow model at each time step, and values for this quantity are input from a file at each ground water - flow time step of the solute - transport model.

c) Subroutine TMODEL

The purpose of subroutine TMODEL is to march the solution through time. This is accomplished by three basic loops, as is shown schematically in fig. 6 15. The outer most loop is the ground water flow time - step loop, which controls the basic march through time. Within this loop, hydraulic heads and the water source - sink strengths are input from the groundwater flow model and the solute source sink strengths are computed using the source sink concentrations.

Next is a loop over each of the elements by which groundwater velocities, aquifer dispersivities, and global stiffness and mass matrices are computed. Next, the left hand side matrix is upper triangularized. The solute transport time - step loop is then used to compute solute concentrations for each solute-transport time step by back substitution into the upper triangularized left-hand side matrix. A source listing of subroutine TMODEL is given in appendix G.

A compressed storage is used in subroutine TMODEL for the matrices [A], [B] and [L] in a manner similar to that of groundwater flow model. However, for the solute transport model, the matrices are not symmetric, and both the upper and lower half bands must be stored. Nevertheless, the matrices are banded for an efficiently organised problem.

d) Subroutine TSHAPE

The purpose of subroutine TSHAPE is to construct the elemental stiffness and mass matrices $[A^e]$ and $[B^e]$. The coordinates of an element aquifer thickness,

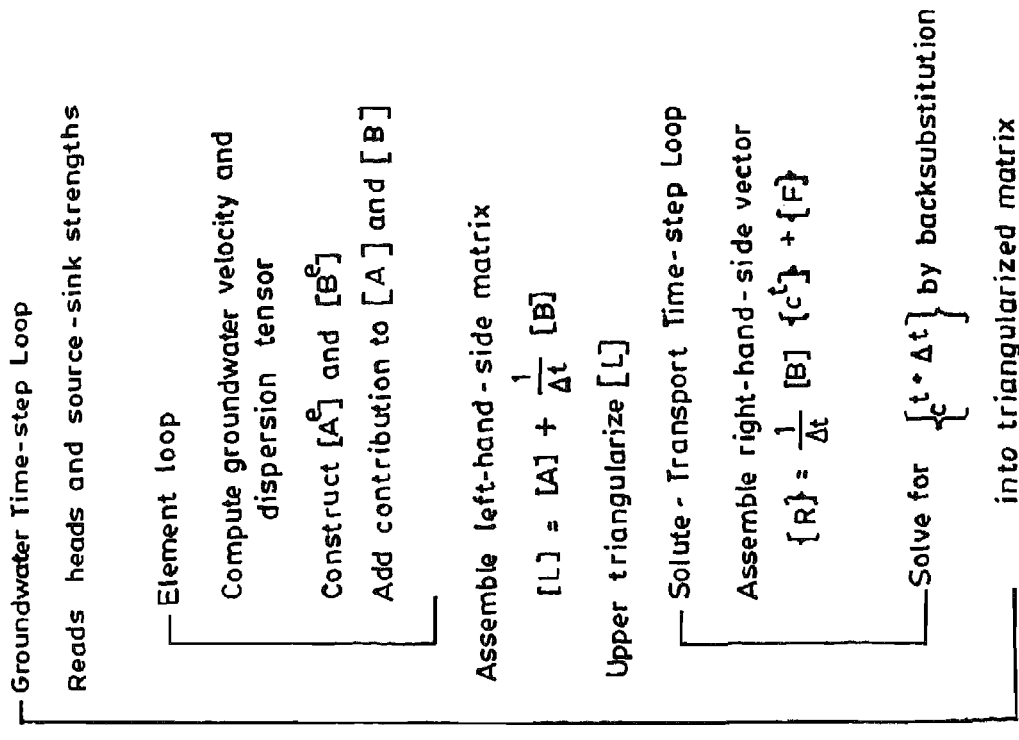


Fig 6.15 Generalized flow diagram for subroutine TMODEL

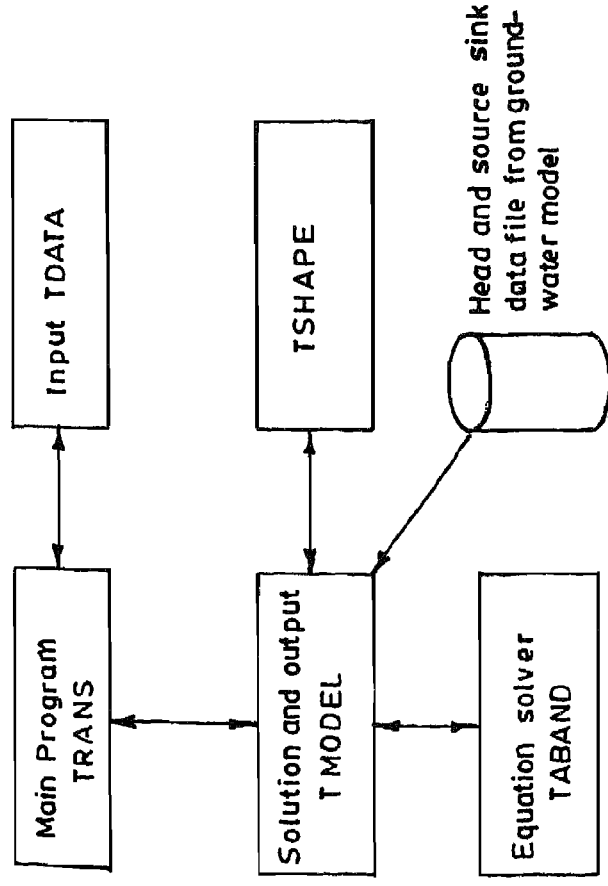


Fig. 6.14 General configuration of finite-element program

hydraulic conductivity, and dispersivities are passed to subroutine TSHAPE from subroutine TMODEL. Subroutine TSHAPE returns $[A^c]$ and $[B^c]$ to subroutine TMODEL. A source listing of subroutine TSHAPE is given in appendix G.

e) Subroutine TBAND

Subroutine TABAND solves the following equation.6.29 in two passes for $\{c^{t+\Delta t}\}$

$$[L] \{c^{t+\Delta t}\} = \{R\} \quad 6.29$$

Where

$$[L] = [A] + \frac{1}{\Delta t} [B] \quad 6.30$$

$$\text{and } \{R\} = \frac{1}{\Delta t} [B] \{C^t\} + \{F\} \quad 6.31$$

First, the matrix $[L]$ is upper triangularized and returned. Second, the upper triangularized form of $[L]$ is passed to subroutine TABAND along with the vector $\{R\}$ and a solution vector is returned in $\{R\}$. In this second pass, a solution is obtained by back substituting $\{R\}$ into the upper triangularized matrix. A source listing of subroutine TABAND is given in appendix G.

The Doolittle method (Swain, 1978) is used to solve the system of equations. The method is based upon the fact that, for an asymmetric matrix, there exists matrices $[l]$ and $[u]$ such that

$$[l] [u] = [L] \quad 6.32$$

Where $[l]$ is a lower triangular matrix and $[u]$ is an upper triangular matrix. As for the Cholesky method (Churchhouse, 1981) an intermediate solution $\{y\}$ can be defined as

$$[I] \{y\} = \{R\} \quad 6.33$$

Because of the triangular structure of $[I]$, equation 6.33 can be readily solved for $\{y\}$ by direct back substitution. However, equations 6.32 and 6.33 can be substituted into equation 6.29 to obtain

$$[I] [u] \{C^{t+\Delta t}\} = [I] \{Y\} \quad 6.34$$

pre multiplication by $[I]^{-1}$ yields

$$[u] \{C^{t+\Delta t}\} = \{Y\} \quad 6.35$$

Once $[I]$ and $[u]$ are known, a solution to equation 6.29 can be obtained. Equation 6.33 is used to obtain $\{Y\}$. Then 6.35 is used to solve for $\{C^{t+\Delta t}\}$. The problem is to obtain the matrices $[I]$ and $[u]$. The procedure by which this is accomplished by the Doolittle method is described in Pinder and Gray (1977).

6.8 APPLICATION OF GROUNDWATER TRANSPORT MODEL TO THE STUDY AREA

6.8.1 Input Data Organization

a) Solution domain

The space - time domain as described in the chapter 6, section 6.4 within which the groundwater problem was solved, is adopted for groundwater transport problem also.

b) Aquifer parameters

Aquifer parameters required by model as input are the aquifer porosity, dispersivity, thickness and groundwater head distribution over the flow domain. The thickness of the aquifer considered for groundwater transport problem is given in the section 6.4.1b. The study area is assumed to have an average aquifer porosity of 0.5 (A.P. State Groundwater board). The same average value is

adopted for the entire study area. The value of dispersivity for the present studies was derived from the literature. The starting range for longitudinal dispersivity (α_L) is 10 ft to 100 ft and transverse dispersivity (α_T) is 30% of α_L (Bredehoeft and Pinder, 1973; Robson, 1974; Konikow and Bredehoeft, 1974). In some of the earlier studies, the reported value of α_L has ranged from 49 m to 990 m (Molz *et al.*, 1983) and 460 m (Cole, 1972). Fried (1975) reported that the value of dispersivity can be higher than 100 m for regional scale. The values of hydraulic heads for each node within the space domain were provided by the solution of the groundwater model and were used as input to the groundwater transport model. These hydraulic heads were used to calculate the Darcy velocity components within each element to solve the ground water transport problem. In this study the dispersivity is obtained by calibrating the model with observed data.

(c) Initial and boundary conditions

(i) *Initial conditions*

The time period considered in this study is the monsoon season of 1995-96. The total period is divided into 5 monthly time steps, each consisting of 30 days. The data of observed nitrate pollutant concentration in the month of May, 1995 (Fig. 6.16) are considered to describe the initial conditions. The observed water table levels in the month of May, 1995 (Fig. 6.7) and computed water table levels for other time steps, during the year 1995, *kharif* season (Appendix F) were used as input for this model.

A finite element grid with 107 triangular elements and 87 nodes (Fig. 6.3) is superposed over the groundwater nitrate concentration contour map for the May, 1995 (Fig. 6.16). Each of the 87 nodes in the flow domain is assigned

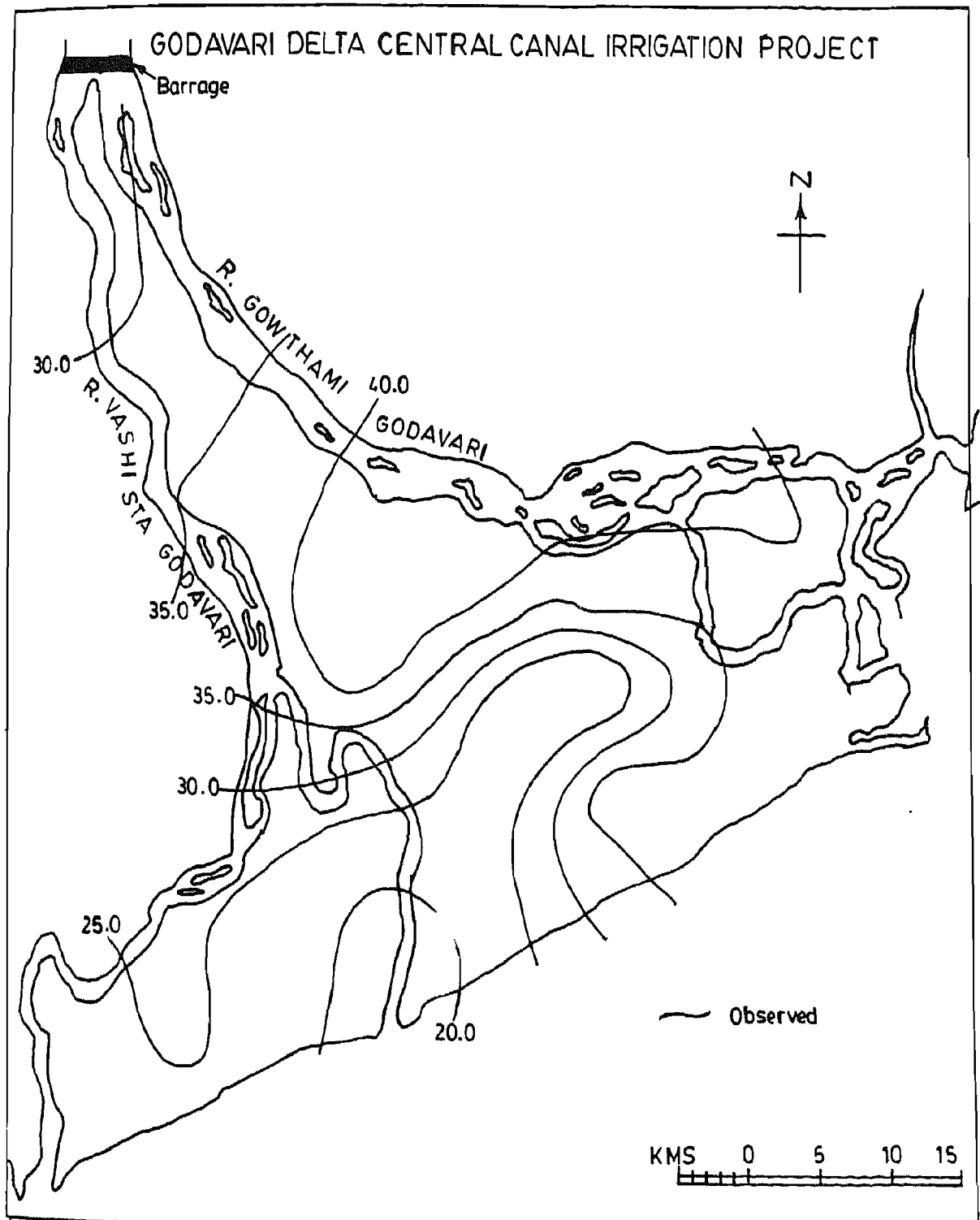


Fig.6.16 Observed nitrate concentration levels in the groundwater, ppm (May 1995)

an initial nitrate concentration obtained by interpolation from the Fig. 6.16. The initial conditions at all nodes are given in the Appendix G.

(ii) *Boundary conditions*

The specified flux boundary condition is incorporated in the model. The fluxes of water are obtained from the specified-head boundaries prescribed for the groundwater model. The hydrological boundaries of the study area are discussed in section 6.4.1c (ii).

(d) Sources and sinks

The nitrate concentrations in the leached water at each node along with recharge rates are derived from the calculated pollutant loads and recharge rates for the basic simulation units (Fig. 5.9, Table 5.15). Nodes falling under each BSU were identified by overlaying of finite element grid (Fig. 6.3, Table 6.1) and BSU map (Fig. 3.7). The detailed procedures for estimation of recharge rates and nitrate loads were given in chapter 4 and chapter 5, respectively

6.8.2 Validation of the Groundwater Transport Model

The model was run with 1995 *kharif* season input data from June to November. Sample file of input data for the year 1995 was given in the Appendix G. In the present study, the values of longitudinal and transverse dispersivities obtained by calibration procedures were 600 m and 200 m respectively. These values are well within the range of values reported in some of the earlier studies (Cole, 1972; Fried, 1975; Molz, 1983). The computed concentration and the corresponding observed values are used to draw the nitrate pollution contour maps at the end of monsoon season 1995. There is a close agreement between the observed and predicted nitrate concentrations Fig. 6.17. For further evaluation of the capability of the model, the observed and simulated water levels for all

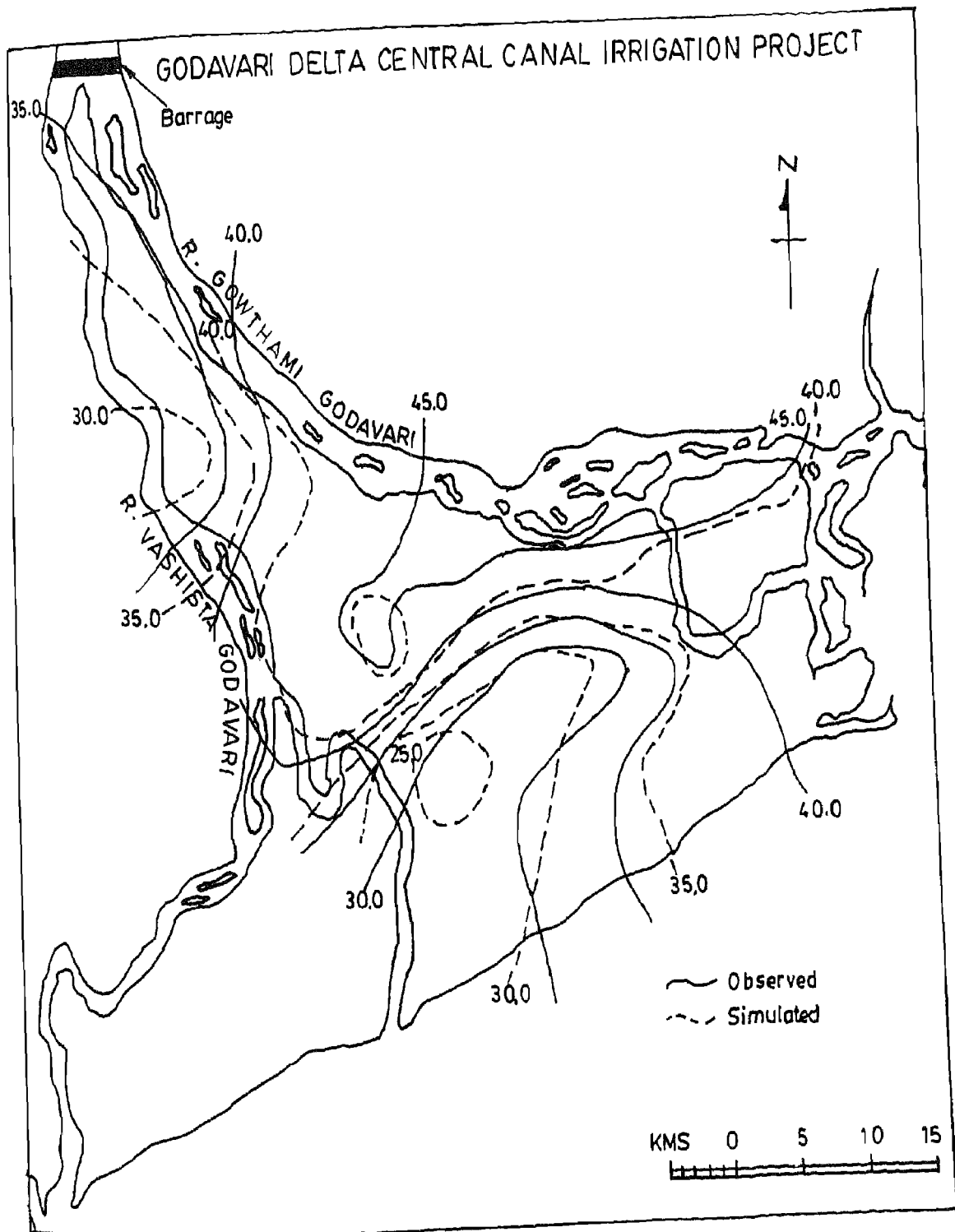


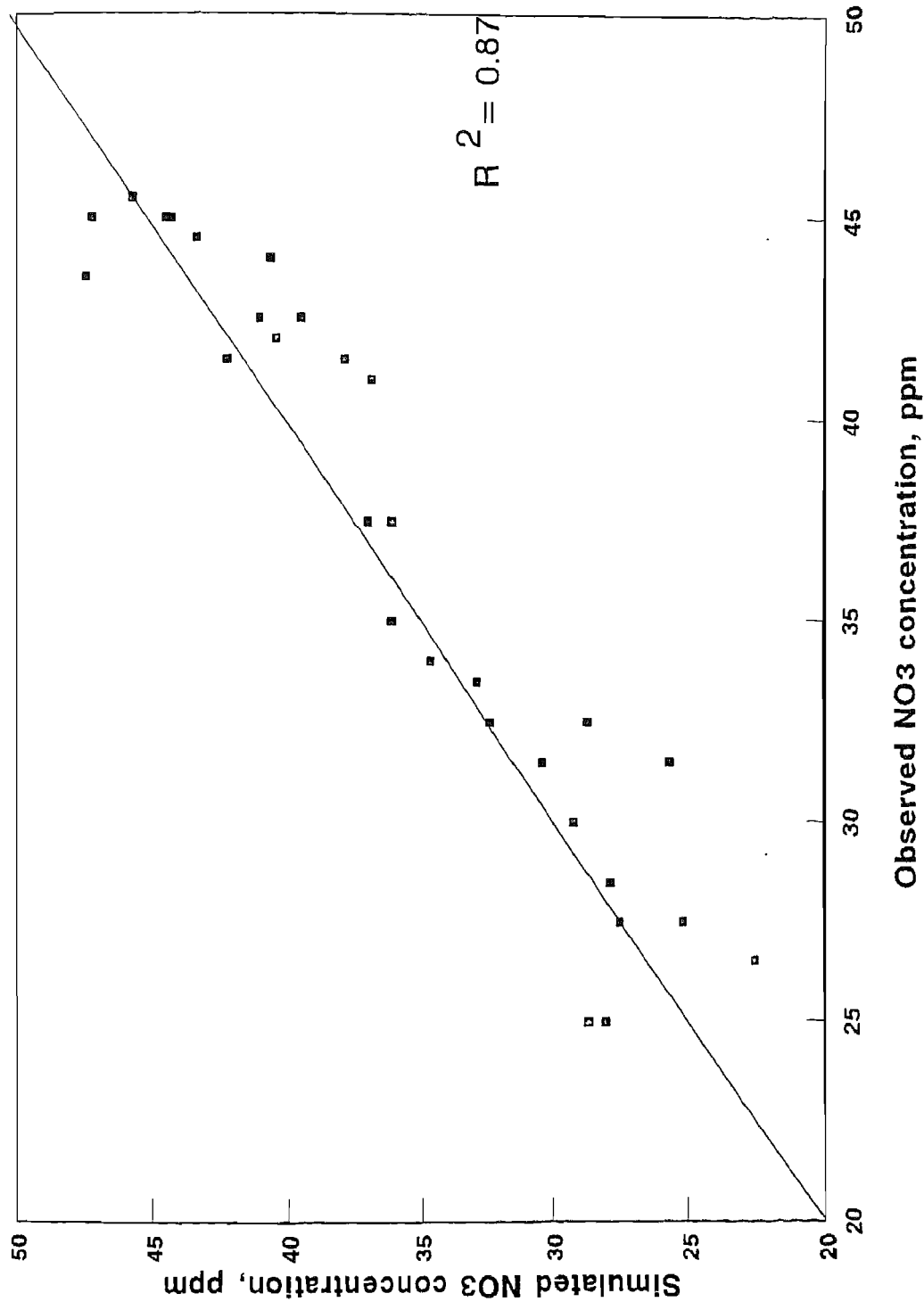
Fig.6.17 Observed and simulated nitrate concentration levels in the groundwater, ppm (Nov,1995)

the internal nodes during the simulation period 1995 are plotted in Fig 6.18 to show comparison between observed and simulated nitrate concentrations. The average difference between the observed and simulated concentrations for most of the the nodes varies between 0 to 5 ppm (Table 6.11). The correlation

Table 6.11 Observed and Simulated nitrate Concentration levels in the groundwater, ppm (Nov, 1995)

Node	Observed NO ₃ , ppm	Simulated NO ₃ , ppm	Difference
16	32.500	28.840	3.66
17	32.500	34.760	-2.26
20	32.500	33.230	-0.73
23	41.500	37.000	4.50
24	43.500	47.470	-3.97
32	42.500	43.360	-0.86
33	44.000	40.700	3.30
34	45.000	45.930	-0.93
35	42.500	39.630	2.87
42	42.500	40.480	2.02
45	32.500	25.700	6.80
46	45.000	47.260	-2.26
47	45.000	44.410	0.59
54	25.000	28.020	-3.02
55	27.500	25.140	2.36
56	26.500	22.440	4.06
57	35.000	36.010	-1.01
58	45.000	44.650	0.35
61	32.500	29.190	3.31
62	27.500	29.200	-1.70
63	27.500	27.770	-0.27
64	42.500	41.120	1.38
69	32.500	33.020	-0.52
70	25.000	28.210	-3.21
71	42.500	42.270	0.23
74	37.500	36.210	1.29
75	32.500	32.470	0.03
76	37.500	37.130	0.37
77	42.500	38.010	4.49
CORRELATION COEFFICIENT (R^2) = 0.87			
MSE = 7.45			
MPE = -0.02			
MAPE = 0.063			

**Fig.6.18 Observed and Simulated Groundwater Nitrate Concentrations
in the study area (November, 1995)**



coefficient (R^2) obtained for simulation during the year 1995 is 0.87, indicating that the model predictions are within the acceptable range. Thus the nitrate pollutant loads obtained using nitrogen balance model can be considered to be representative for the study area. The general agreement between the observed and predicted nitrate concentrations (Fig. 6.17 and 6.18) over the area is satisfactory enough to use the groundwater transport model for future predictions. Sample output file for the year 1995, *khariif* season is given in Appendix G.

6.9 DISCUSSION

Transient, two dimensional solutions for groundwater movement and time rate of movement of nitrate pollutant in aquifer system were obtained by developing suitable groundwater basin simulation model (Section 6.1) and groundwater transport model (Section 6.6) respectively

Simulation of groundwater flow

For the present study, modelling of groundwater flow was accomplished by first developing the partial differential equation of groundwater flow in two dimensions and then using the finite element method for the numerical solution of that equation. Finally, the model is applied to simulate regional groundwater flow in the study area.

In some of the earlier studies, recharge and discharge are often treated as structural parameters of the model to be estimated by a parameter - identification technique, given the specifications of the aquifer parameters (Carrea and Neuman, 1986; Chiew and Mc Mahon, 1991; Boonstra and Bhutta, 1996). Even spatial distribution of recharge was also done by solving inverse problem of aquifer hydrology which essentially treated recharge as an unknown parameter in a numerical aquifer flow model (Carrea and Neuman, 1986). In some studies,

groundwater level fluctuation was considered as an indicator in the spatial distribution of recharge Moench and Kisiel (1970), Besbes *et al.* (1978) and Flug *et al.* (1980). This technique does not provide acceptable results if the relative importance of various potential recharge sources is unknown. The pumpage and recharge were assumed to spread uniformly across the grid for most of the groundwater models, in which temporal and spatial variation of input data was not considered (Sondhi *et al.*, 1989; Rao, 1992; Rao, 1995). For these models annual recharge was estimated based on CGWB norms (lumped value). Sondhi *et al.* (1989) derived recharge distribution coefficients for spatial distribution of the lumped regional recharge. The coefficients are based on the difference between observed and simulated waterlevels at each node. The inverse modelling technique or empirical methods such as of Sondhi *et al.* (1989), Rao and Sarma (1993) for estimating recharge distribution are not suitable for using the model to devise strategies for recharge and pollution management. For such purposes physically based approaches are necessary and the linkage between the physical model and GIS developed in this study provide an efficient means for using the model for management purposes. Though in some of the earlier studies three dimensional groundwater models are used (McDonald and Harbaugh, 1988; Orzol and McGrath, 1992), their use is limited because of large data requirements.

Currently no GIS has the data representation flexibility for space and time, together with the algorithmic capability to be able to build process based models internally (Corwin and Wagenet, 1996). Consequently simulation models and GIS must be coupled. Coupling can range from loose to tight coupling. A loose coupling involves a data transfer from one system to another. The GIS is used to preprocess data or to make maps of input data or model results. A majority of the applications found in the literature represent this approach

because it requires little software modification. In a tight coupling, the data management is integrated into the system. Characteristically, a tight coupling will provide a common user interface for both the GIS and model, and the information sharing between the respective components is transparent. In the present study, groundwater model and GIS were developed separately indicating the level of integration as loose coupling. Input data required by the model are extracted by interfacing GIS and soil water balance model. This level of integration has been demonstrated in several previous studies (Joao and Walsh, 1992; Orzol and McGrath, 1992; Chariat and Delleur, 1993; Roaza *et al.*, 1993).

The performance of model is governed by parameters of aquifer namely K and S, the spatial distribution of recharge and pumping within the study area. It was established in the chapter 6, section 6.5, that the groundwater model of the study area is insensitive to changes in the aquifer parameters K and S over a wide range. So, the discrepancies between the estimated and actual values of recharge as well as pumping rates are responsible for the difference between the observed and the simulated water levels.

Temporal and spatial distribution of recharge rates were obtained for all the BSU's as discussed in chapter 4 and used for the simulation of the groundwater. These recharge rates were allowed at nodal points. Hence it is expected that the estimated recharge rates were reasonably close to actual values. Thus leaving the discrepancies in the pumping rates solely responsible for discrepancies between observed and predicted watertable levels. However, there were difficulties in obtaining the pumping distribution. This was because of unavailability of distribution of wells, timing and duration of pumping. The pumping distribution was derived by following a set of heuristic rules constantly for all the years to adjust the pumping rates after simulating groundwater flow

under uniformly distributed pumping. The pumping distribution coefficients derived using data of 1992-93 was satisfactory as seen from similar kind of agreement between observed and simulated watertable levels for the subsequent years 1993-94, 1994-95 and 1995-96 with the same coefficients (Table 6.4). This approach was used developing relative weightages of pumping rates at different nodes. The satisfactory agreement between observed and simulated watertable levels for these three years indicates that the proposed approach of modifying the pumping distribution is satisfactory. The results of the annual water balance of study area (Table 6.6), further substantiated the validity of procedures adopted in the development of soil water balance model and groundwater model. For the present study the problem of evaluating the water resources of a regional groundwater system was approached from the perspective of large space and time scales by developing regional groundwater basin simulation model.

Simulation of Nitrate transport

Mathematical models of groundwater transport can be used to predict the movement of a pollutant in groundwater, and these models can be differentiated by the absence or occurrence of chemical reactions. For the present study, groundwater transport model was used to simulate the movement of nitrate pollutant which is a conservative constituent. In this case an assumption is made that chemical reactions of the nitrate occur neither with other dissolved constituents nor with the aquifer material. Simulation of nitrate transport is accomplished by first developing the partial differential equation of groundwater transport in two dimensions. In order to account for irregular boundaries, finite element method was used to solve the equation of groundwater transport. For solving groundwater transport problems, input data like dispersivity and nitrate pollutant loads play important role, because of complexity involved in their estimation.

Though the dispersivity values can be estimated from field tests, in most cases better values are obtained from model calibration. The problem in estimating dispersivity from field tests is that dispersivity is a scale dependent property of an aquifer that is, the greater the travel distance in a tracer test used to measure dispersivity, the larger the dispersivity value that is calculated (Fried, 1975; Anderson, 1983). Consequently, results obtained from tracer tests or column experiments cannot be interpreted in terms of larger scale processes occurring in an aquifer. In some of the earlier studies, dispersivities were estimated from concentration data (Strecker and Chu (1986); Keidser *et al.* (1990)). However, no statistical framework was developed for describing the reliability of the parameter estimates. In view of the difficulties mentioned above in making field observations of the dispersivity values, the calibration procedure was used in the present study. The range of dispersivity values used in the calibration procedure were obtained from literature. Similar procedure was adopted in other studies also (Bredehoeft and Pinder, 1973; Robson, 1974; Konikow and Bredehoeft, 1974; Rashid *et al.*, 1988). The values of longitudinal dispersivity and transverse dispersivity values obtained in the present study are 600 m and 200 m respectively. These values were well within the range reported from the literature (Cole, 1972; Fried, 1975; Molz *et al.*, 1983).

In the present study, GIS and groundwater transport model were coupled loosely as discussed above. The groundwater transport model was run independently of the GIS. GIS was coupled to nitrogen balance model and soil water balance model in the estimation of spatially distributed nitrate pollutant loads. In contrast to the present study, Roaza(1993) used GIS for model grid generation only. Hence the intended aim of loose coupling of GIS and solute transport model is to provide spatially distributed data input to the model, which helps in decision making for attaining the desired goal of sustainable agriculture.

In majority of research efforts investigations on the contamination of groundwater were concentrated on detailed studies of agricultural fields of small watersheds only. Generally validation of models have been done by idealized laboratory experiments and a few field experiments at relatively homogeneous sites (Fedler *et al.*, 1989; Gaily *et al.*, 1991; Teresa and Christine 1993; Robert, 1993; Vassilis, 1993). In the present study, an attempt has been made to assess potential groundwater pollution problems over large geographical area. Several investigators in the past have used the method of characteristics to solve the Groundwater transport equation (Robertson, 1974; Konikow and Bredehoeft, 1978; Strecker and Chu, 1986; Keidser *et al.*, 1990; Torben *et al.*, 1996). Though this method is simple in concept, it was difficult to program and is suitable only for specific situations. Some of the mass transport problems considered dispersion mechanism only (Guymon, 1970; Guymon *et al.*, 1970). While some other groundwater transport models were used to simulate movement of point source pollution only (Little *et al.*, 1996; Younger *et al.*, 1993).

In the present study, the groundwater transport model was able to simulate the hydrologic behaviour of the nitrate pollutant in terms of space and time. More specifically, the model was used as a tool to interpret and define the relationships between the changes in nitrate concentration and the hydrologic stresses, such as pumping and recharge. The model is also a useful tool to predict the relationship between nitrate concentration gradients and the various aquifer parameters, such as dispersivity, specific yield, and transmissibility of the study area. Therefore, this model can be used as tool for assessing the impact of alternative fertilizer and irrigation application strategies on groundwater quality. This is described in the following chapter.

7. ASSESSMENT OF IMPACTS OF NITRATE POLLUTION ON GROUNDWATER UNDER DIFFERENT SCENARIOS

The nitrate concentration in the groundwater at the end of May 1995 is within the safe limits of 45 ppm over the entire study area. But with continued fertilizer use this is likely to change. Potential nitrate leaching from rice fields and possible impact of this leaching on deterioration of groundwater quality in the command area depend on a number of factors like, weather, fertilizer application rates, percolation rates and area under the crop. The impacts on groundwater quality will depend on how each of the above factors will vary in future. Of these, weather is the only naturally varying factor. Fertilizer use, percolation rates and area under rice are determined by farmers and guided by public policy. Any assessment of future impacts on groundwater quality is possible only by defining in the context of presumed scenarios. The likely changes in groundwater quality under the following scenarios are evaluated :

- (i) Present (1995) practices of fertilizer and water management are continued for the next four years(i.e.only weather variables change).
- (ii) Fertilizer use increases as indicated by current trends and weather and water use remain unchanged from their 1995 values.
- (iii) More efficient water management practices lead to reduction in percolation rates, while fertilizer use and weather are unchanged from their 1995 values.
- (iv) Increase in canal irrigated area under rice with all other factors remaining same.

For carrying out the evaluation, the starting condition is represented by the simulated nitrate concentrations in the groundwater for May, 1995 under current

production practices . The integrated framework comprising the soil water balance model, nitrogen balance model, groundwater flow model and groundwater transport model is used to predict the likely impacts By evaluating the impacts under the above scenarios in relation to base conditions of 1995 it will be possible to develop appropriate policy guidelines for sustainable water, fertilizer and crop management.

Scenario 1: Current fertilizer and water management trends continue in future.

Simulation of nitrate leaching for many rainfall sequences at a given site enables probability levels to be associated with predicted nitrate movement changes and resultant changes in groundwater quality. The long term average annual rainfall in the study area is 1200 mm. It is proposed to study the response to varied rainfall amounts over a range of -50% to +50% of average annual value. During the period 1992-93 to 1995-96, the variation of annual rainfall is from 747 mm to 1933 mm (Table 6.10). This nearly covers the range of $\pm 50\%$ of the long term average. Accordingly, the future simulations were carried using the daily rainfall data of 1992-93 to 1995-96 on the assumption that the sequence may repeat itself for the next four years. Further, as the canal flows were nearly the same for all the four years, the actual discharges for these four years were assumed to occur for four years of simulation. This assumption leads to using the same rates of recharge corresponding to the period 1992-93 to 1995-96 for future simulations also. The groundwater transport model (Chapter 6, Section 6.6) calibrated with the observed data of 1995-96 was used for performing predictive simulations for the next four years with the corresponding pollutant loadings for each year obtained from nitrogen balance model (Table 7.1).

Table 7.1 Projected nitrate concentrations in the groundwater, ppm

Node	Nitrate concentrations in the groundwater, ppm					
	Observed 1995,may	Simulated 1996,may	after one year	after two years	after three years	after four years
16	33.5	20.93	9.32	2.22	0	0
17	32.5	40.43	39.03	37.60	35.93	34.34
20	30.0	39.44	37.90	35.82	32.33	29.33
23	37.5	41.48	39.13	37.74	36.13	33.65
24	37.5	51.81	47.57	45.05	42.46	38.30
32	37.5	51.41	50.44	49.60	47.71	45.46
33	40.0	48.23	47.30	46.49	44.68	42.51
34	40.0	56.94	59.86	63.05	67.25	70.47
35	40.0	36.72	23.17	9.05	0	0
42	35.0	51.77	54.30	55.43	55.63	55.07
45	32.5	15.94	3.46	0	0	0
46	40.0	59.96	63.19	65.38	67.81	69.76
47	40.0	55.40	58.65	62.30	66.74	70.61
54	22.5	33.71	34.60	35.81	37.29	38.91
55	22.5	30.29	31.10	32.18	33.51	34.96
56	25.0	27.12	27.89	28.89	30.21	31.43
57	32.5	42.91	42.66	42.60	42.57	42.52
58	40.0	53.98	54.48	55.46	56.65	57.70
61	27.5	32.00	27.33	22.49	17.17	10.79
62	22.5	37.22	41.33	46.02	51.42	56.64
63	25.0	33.91	35.03	36.19	37.50	38.73
64	37.5	49.44	49.62	49.69	50.08	50.09
69	30.0	39.05	38.27	37.41	36.45	35.27
70	25.0	33.96	34.48	35.20	35.98	36.62
71	37.5	53.13	57.07	61.05	64.87	69.24
74	32.5	44.44	45.97	47.56	49.26	50.98
75	30.0	39.84	41.23	42.67	44.21	45.78
76	32.5	38.40	30.32	20.8	10.29	0
77	37.5	39.39	29.57	20.26	11.01	0
Average	32.9	41.35	39.8	38.74	38.10	38.88

The various steps involved in carrying out the computations are given below:

- (i) The simulated groundwater levels and nitrate concentrations (Fig. 6.15) for May 1996 define the initial conditions for the future projections
- (ii) Daily nitrate loadings to groundwater for each BSU were estimated for the rainfall and canal supplies data of 1992-93, 1993-94, 1994-95 and 1995-96 using the soil water balance model and nitrogen balance model .
- (iii) The groundwater flow and transport models are run for the weather data of four years (1992-96) with the initial conditions defined by (i), and input data of recharge rates calculated earlier (Table 4.11 to 4.14) and pollutant loads obtained from (ii).

The projected changes in the nitrate loadings into the groundwater and associated changes in nitrate concentration of groundwater are given in Table 7.1 (Fig. 7.1). An examination of these results leads to the following observations:

- (i) The average concentration of NO_3 in the groundwater for the entire study area decreased marginally each year and is within the permissible limit of 45 ppm.
- (ii) The nitrate concentrations in groundwater in May were above the permissible limit of 45 ppm at 10-12 internal nodes in all the years of simulation including the base year of 1996.
- (iii) Fourteen nodes in the central region of the command area showed continuous increase in NO_3 concentration over the four years.
- (iv) In some parts of study area, nitrate concentration levels are even beyond 50 ppm;

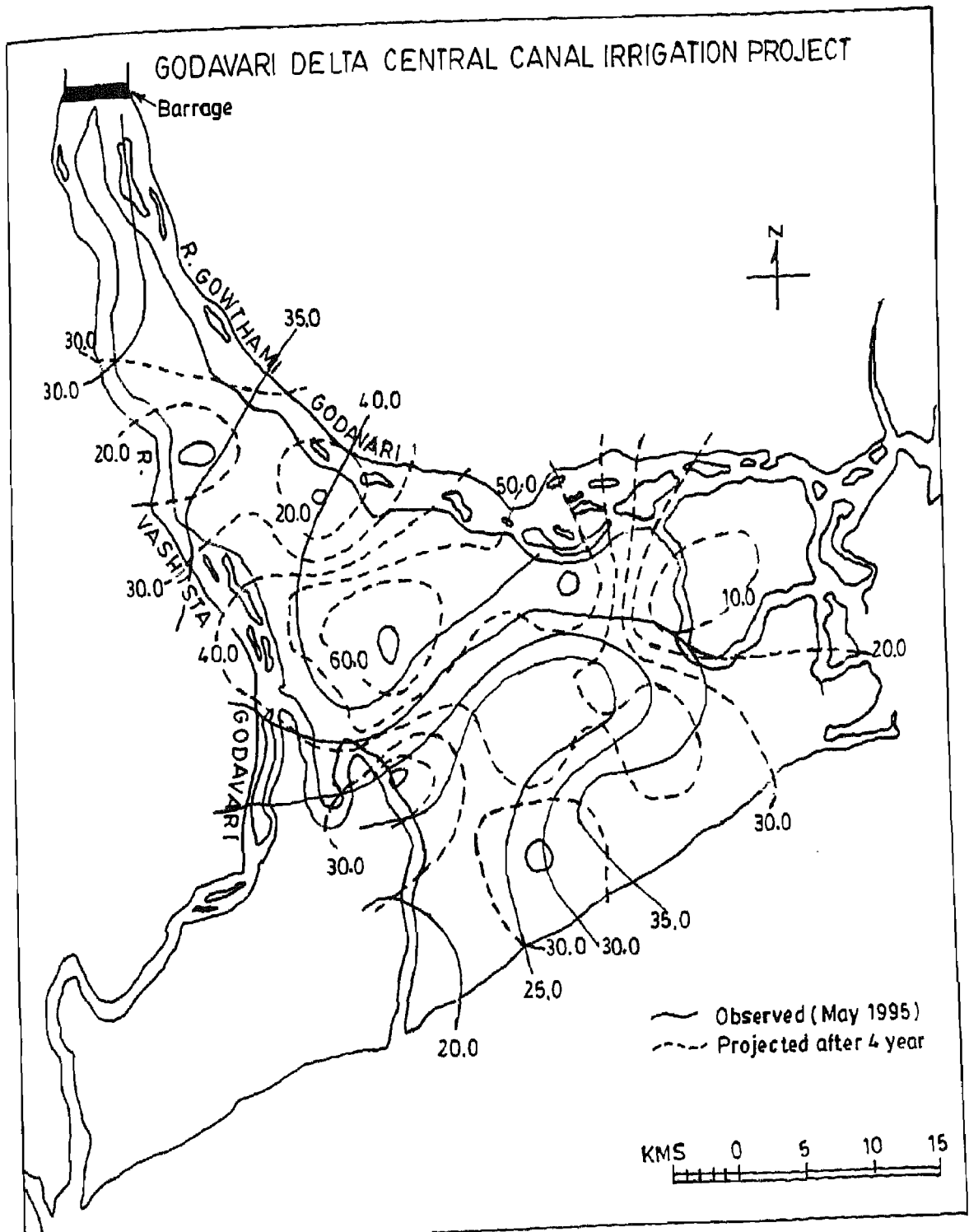


Fig.7.1 Projected nitrate concentration levels in the groundwater, ppm

- (v) In other nodes, the NO_3 concentration either decreased or increased with each year. In some nodes the values were less than those observed in May 1995; and
- (vi) Significantly higher portion (Fig. 7.1) of the central region of the command area will be above the threshold limit of 45 ppm after 4 years compared to May 1996.

Scenario 2 : Increased use of urea

Since urea is highly prone to leaching losses, the amount of fertilizer applied will markedly influence the pollutant loadings to the groundwater and associated groundwater quality. The impact of increased fertilizer rates on pollutant loadings from each BSU is assessed by running the nitrogen balance model for the rainfall and water supply conditions of 1994-95 (Table 7.2). The corresponding changes in the groundwater quality for these pollutant loadings are assessed by running the groundwater transport model (Fig. 7.2). Results of simulated nitrate concentrations in the groundwater when the conventional fertilizer use is doubled are given in Table 7.3. From these results, the following observations are made:

- (i) The average NO_3 concentration in groundwater increased beyond the threshold limit of 45 ppm in May 1996 by about 5 ppm:
- (ii) Nitrate concentration increased at all the nodes in the study area compared to conventional practices. The increase is more in the central region of the command area. and
- (iii) Nitrate concentration levels in the groundwater increased beyond 45 ppm at 14 nodes in the central region of the study area compared to when conventional practices are followed (Table 7.3);

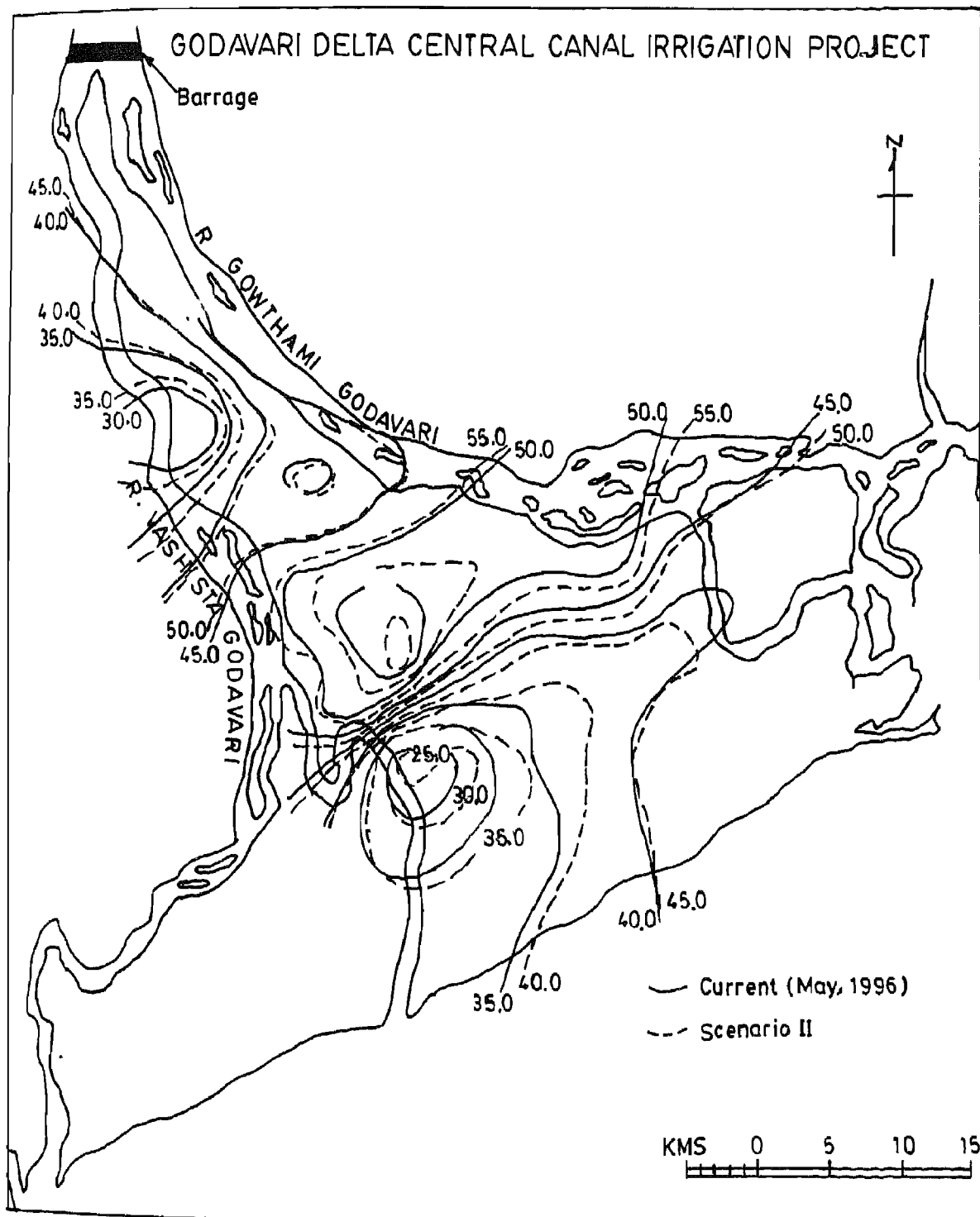


Fig.7.2 Comparison of simulated nitrate concentration levels obtained for the conditions of current practices and scenario II (doubled fertilizer use), ppm

Table 7.2 Annual nitrate loadings to groundwater for all basic simulation units, ppm

BSU	Nitrate loadings into groundwater, ppm			
	Conventional practices	Fertilizer use doubled	Percolation losses reduced by 50%	Area under paddy doubled
1	523.00	1046.00	1073.00	1046.00
2	529.30	1058.58	1002.66	1058.58
3	473.41	946.83	1026.02	946.53
4	538.89	1077.79	1050.90	1077.79
5	468.01	926.03	1016.01	936.03
6	533.14	1066.29	1047.11	1066.29
7	526.21	1052.43	1002.30	1052.43
8	468.01	936.03	1016.01	936.03
9	484.15	968.28	1052.81	968.28
10	533.14	1066.29	1047.11	1066.29
11	555.88	1111.77	1094.47	1111.77
12	484.15	968.28	1052.81	968.28
13	526.21	1052.43	1002.30	1052.43
14	469.16	938.30	1012.24	938.30
15	469.16	938.30	1012.24	938.30
16	471.27	942.50	1008.12	942.53
17	555.88	1111.77	1094.47	1111.77
18	539.03	1078.06	1049.50	1078.06
19	532.69	1065.39	1005.79	1065.39
20	555.88	1111.77	1094.47	1111.77
21	539.03	1078.06	1049.50	1078.06
22	471.27	942.53	1008.12	942.53
23	532.66	1065.33	1040.98	1065.33
24	533.04	1066.07	1035.40	1066.07
25	471.27	942.53	1008.12	942.53
26	539.03	1078.06	1049.50	1078.06
27	981.88	1963.75	1663.37	1963.75
28	970.88	1941.77	1671.01	1941.77
29	976.11	1952.22	1663.59	1952.22
30	532.69	1065.39	1005.79	1065.39
31	970.88	1941.77	1671.01	1941.77
32	970.88	1941.77	1671.01	1941.77
33	976.11	1952.22	1663.59	1952.22
34	976.11	1952.22	1663.59	1952.22
35	979.14	1958.29	1671.58	1958.29
36	979.14	1958.29	1671.58	1958.29
37	979.14	1958.29	1671.58	1958.29
38	981.88	1963.75	1663.37	1963.75

Table 7.3 Simulated nitrate concentration under different management practices, ppm (May 1996)

Node	Nitrate concentration in groundwater, ppm			
	Conventional practices	Fertilizer use doubled	Percolation losses reduced by 50%	Area under paddy doubled
16	20.93	23.5	18.89	23.50
17	40.43	45.42	34.13	45.42
20	39.44	44.35	34.36	44.35
23	41.48	46.85	35.72	46.85
24	51.81	58.51	44.72	58.51
32	51.41	57.93	44.20	57.93
33	48.23	54.35	41.49	54.35
34	56.94	65.30	48.48	65.30
35	36.72	41.34	33.51	41.34
42	51.77	58.15	43.14	58.15
45	15.94	17.87	15.07	17.87
46	59.96	67.00	50.09	67.00
47	55.40	62.61	46.85	62.61
54	33.71	38.07	28.22	38.07
55	30.29	34.23	25.37	34.23
56	27.12	30.65	22.70	30.65
57	42.91	49.73	37.75	49.73
58	53.78	60.70	46.94	60.70
61	32.00	36.53	27.43	36.53
62	37.22	35.61	26.53	35.61
63	33.91	40.67	31.02	40.67
64	49.44	55.70	41.59	55.70
69	39.50	43.62	32.82	43.62
70	33.13	39.17	31.23	39.17
71	53.13	59.65	44.02	59.65
74	44.44	49.93	37.09	49.93
75	39.84	44.76	33.25	44.76
77	39.39	44.28	35.03	44.28
Average	41.35	46.54	35.37	46.54

Scenario 3 : Reduction of percolation losses by improved water management

Percolation losses in the area ranges from 9 to 14 mm and the average is about 10 mm/day (Table 4.8). There is considerable scope to reduce these by improved water management. Since nitrate moves along with the percolating water, changes in percolation rates will lead to changes in nitrate pollutant loadings to groundwater. The percolation rate depends on the rainfall and irrigation practices. However, among these factors, the time and quantity of rainfall cannot be controlled. The only management practice which can be adopted to reduce nitrate loadings to the groundwater is by reducing percolation amounts. Hence in the present study, nitrate loadings for each BSU (Table 7.2) are estimated using the nitrogen balance model for the condition of 1995-96 after reducing the percolation losses by 50%. The groundwater transport model is run for the same year with input derived from the output of the nitrogen balance model. The results of groundwater nitrate concentrations at different nodes are given (Table 7.3). From a comparison of the base level simulated nitrate concentration levels for May 1996 and simulated nitrate concentration levels for the above scenario (Fig. 7.3), the following observations are made:

- (i) The average NO_3 concentration in groundwater reduced by about 6 ppm;
- (ii) All the nodes in the study area (Table 7.3) showed reduction in the nitrate concentration; and
- (iii) The number of nodes with nitrate concentration levels above permissible limit reduced considerably from 14 (conventional practices) to 4 (Table 7.3).

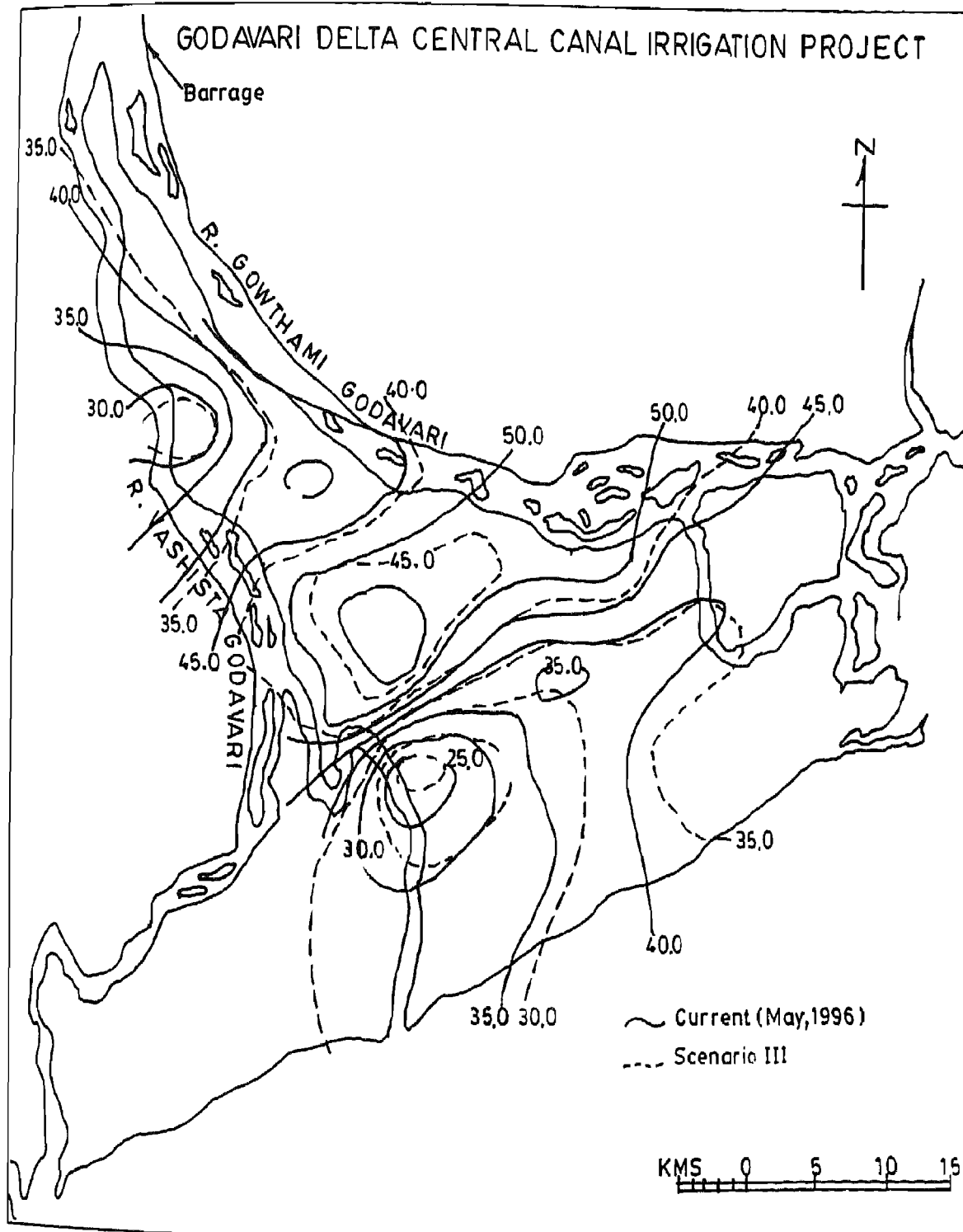


Fig.7.3 Comparison of simulated nitrate concentration levels obtained for the conditions of current practices and scenario III (reduced percolation losses), ppm

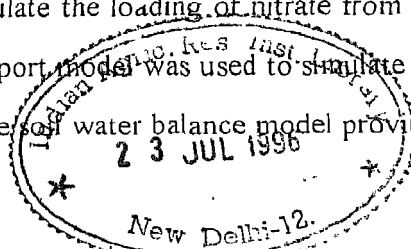
Scenario 4 : Increased area under paddy

The impact of rice area on pollutant loads from each BSU was studied by multiplying the pollutant loads per ha obtained for the condition of 1995-96 with the new area under the crop (Table 7.2). This is then given as input to the groundwater transport model to assess impacts on the groundwater nitrate concentration (Table 7.3, Fig 7.4). The simulation results obtained for the increase of rice area (Scenario IV) are similar to that of results obtained under scenario II.

7.1 DISCUSSION

Information on nitrate dynamics under a range of management practices for a given combination of climate, crop, soil and irrigation are necessary to devise practices to conserve and effectively use fertilizer N in rice based cropping systems, without adverse impacts on groundwater quality. In general, the estimation of nitrate loadings into the groundwater and nitrate movement within the aquifer system under varied weather conditions require long term demonstration projects and expensive on site measurements and monitoring. However, on a practical basis, constraints on resources and time generally make it impossible to monitor a large number of combinations of practices over a sufficiently long time period. The analytical framework developed in this study based on simulation models and GIS could be used effectively to provide guidelines for developing strategies for alternative agricultural management scenarios.

The approach used involved integration of the soil water balance model, the nitrogen balance model, groundwater model and groundwater transport model. The nitrogen balance model was used to calculate the loading of nitrate from the soil root zone, where as the groundwater transport model was used to simulate the movement of nitrate in the aquifer system. The soil water balance model provided



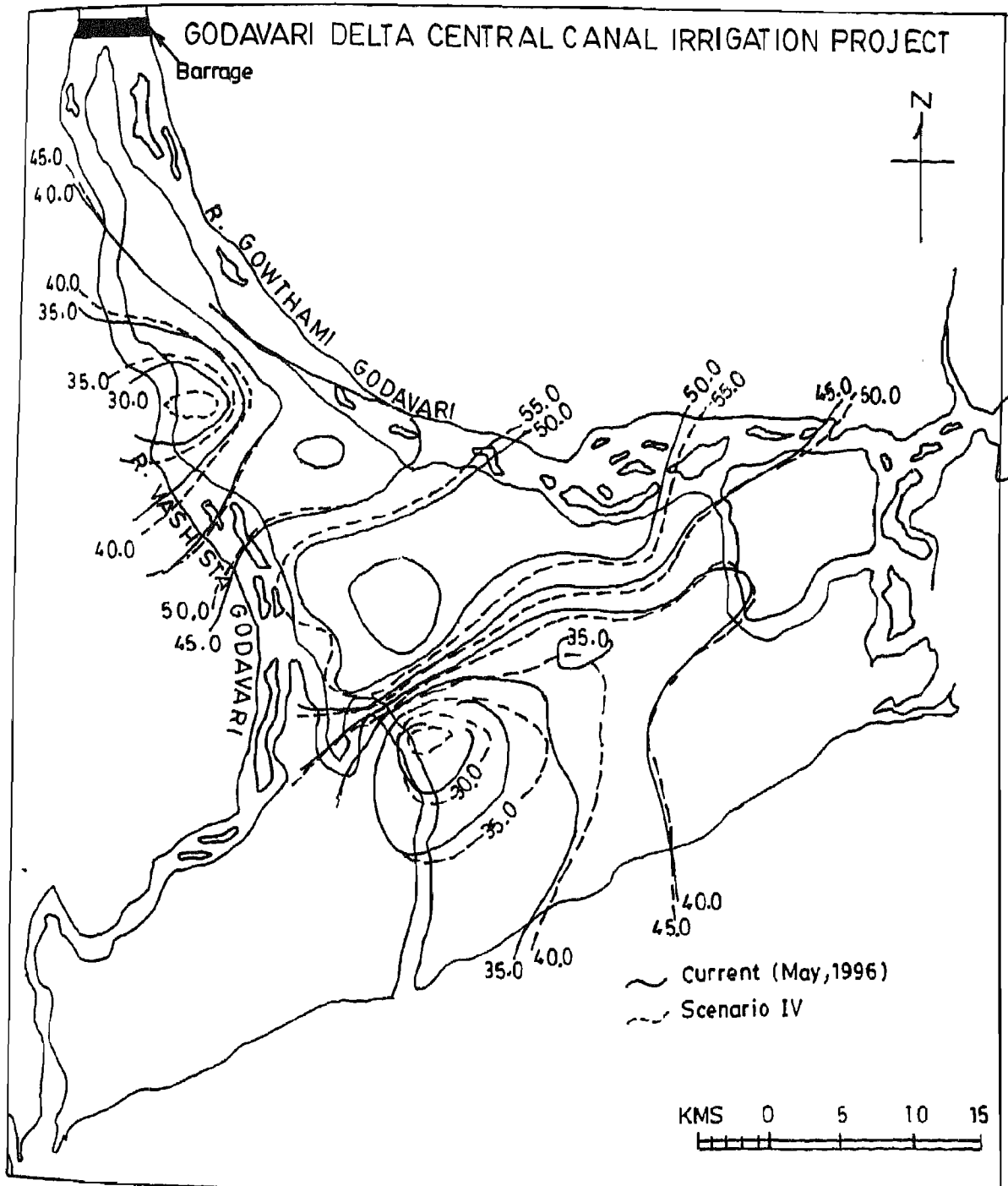


Fig.7.4 Comparison of simulated nitrate concentration levels obtained for the conditions of current practices and scenario IV (increased paddy area), ppm

the input for the nitrogen balance model while the groundwater model provided inputs for the groundwater transport model. The predicted nitrate loadings to groundwater and its movement within the aquifer system incorporated soil characteristics, weather, irrigation, fertilizer management and crop management practices.

For assessing the impacts on groundwater quality from the point of view of long term sustainability of water resources, the following scenarios were considered:

- (i) Present practices of fertilizer and water management are continued in future years
- (ii) Fertilizer use increases as indicated by current trends
- (iii) Change in water management practices leads to change in percolation rates
- (iv) Irrigated area under rice increases(doubles)

If the current agricultural practices are continued for another four years(Table 7.1), the concentration of nitrate in the aquifer increase continuously and is beyond 45 ppm in the central region of the command area. The region is particularly vulnerable for adverse impacts on groundwater quality. The region close to the boundaries are relatively safer. The build up of nitrate concentration is related to the outflow from the aquifer. Nitrate concentration levels in the groundwater not only depends on nitrate loadings but also on other factors like water table level, boundary conditions, pumping distribution and aquifer parameters.

Increase in N fertilization rates increases the amount of potentially leachable nitrates in the soil (Table 7.2). With doubling the fertilizer use from its current level (1995-96), the potentially leachable nitrates also doubled. This led to increase in nitrate concentrations in the groundwater beyond 45 ppm for most of the nodes. Increase in nitrate concentration in the groundwater associated with increasing fertilizer use were also reported by Schepers *et al.*, 1986; Kanwar *et al.*, 1988.

In many cases, nitrate leaching losses can be substantially reduced by controlling the amount and uniformity of irrigation applications to minimize deep percolation (Aulakh and Singh, 1997). It is seen from the Table 7.2, that the concentrations of nitrate loading to the groundwater considerably increased with the reduction of percolation losses by 50 per cent. Although, the concentration of nitrate loadings was doubled, the total pollutant loading into the groundwater was considerably reduced with the reduction of percolation losses, which eventually reduced the nitrate concentrations in the groundwater below 45 ppm at 24 nodes (Table 7.3).

Reduction of percolation losses from the paddy fields can be achieved by following efficient irrigation scheduling procedures. It has been shown through field experiments that contrary to conventional practice, rice fields do not require and indeed should not be continuously flooded to 10-20 cm depth. Rice plants grow generally well in shallow ponded water on the field if the soil maintains at least a saturated condition between water applications (Prihar and Sandhu, 1987; Rao and Rees, 1992). So translating such scientific recommendations into implementable irrigation schedules will definitely help in the mitigation of non-point source pollution impacts on the groundwater and also save water. Increase in the rice area could also have a potentially negative impact on groundwater quality (Table 7.3).

Just and Antle (1990) developed a conceptual framework to understand the potential impacts of agricultural practices on groundwater quality in regions containing substantial underground aquifers. However, this framework was not validated with the reliable field specific data. Economic analysis of water quality issues and policies were conducted at a field or farm scale (Johnson, 1991; Bryant *et al.*, 1992; Mapp, 1994). In all these studies, impact assessment was made for aerobic conditions. In the present study, simulations were carried out to estimate the probable impact of several water and nitrogen management practices for anaerobic conditions. Though,

changes in groundwater quality simulated under different scenarios could not be verified by measured data, they do appear conceptually sound. Although, the simulation runs are oriented to a particular location, it is believed that the net results of various process interactions, as indicated by the simulations, would generally be expected to be similar in other areas having similar conditions. Further, the results offer example of an approach for quantifying the effects of management on the groundwater quality rather than generalizing about them.

In some of the earlier studies, several policies like taxing or restricting nitrogen use on certain soils or restricting or taxing nitrogen use in certain production systems have been suggested as a means of reducing nitrate contamination of ground and surface water (Mapp, 1994). Policies which reduce expected nitrate losses, such as a broad restriction on total nitrogen, might not reduce the probability that a high rainfall or irrigation event will cause nitrate contamination by percolation. The simulations carried out in the study area indicated that improved water management offers the best means to reduce impacts on groundwater quality by controlling percolation losses (Table 7.3). Sensitivity analysis of the nitrogen balance model indicated that the slight increase or decrease in the nitrification rate constant will have a considerable effect on nitrate pollution loads (Table 5.11). Thus use of nitrification inhibitors is another possible option for reducing nitrate pollution loads (Rajkumar and Sekhon, 1981). Although the joint management of water and N fertilization appears to offer a potential for minimizing groundwater contamination, emphasis should be placed on the improvement of irrigation practices to minimize the leaching of nitrate.

8. SUMMARY AND CONCLUSIONS

SUMMARY

Groundwater forms more than 90% of the total fresh water available and it has become an important source of water for meeting the demands of ever growing population. Pollution from agricultural, industrial and domestic wastes is increasingly inhibiting the use of groundwater. The growing concern over health hazards resulting from contaminants in drinking water has brought the degradation of the quality of groundwater to public attention. The quality of groundwater is a primary environmental concern not only for health reasons, but also for its effect on crop production. Excessive use of fertilizers and improper water management are the main reasons for pollution and degradation of groundwater in the irrigated areas. In particular, nitrogen fertilizers are considered to be carcinogenic and detrimental to healthy crop growth.

Assessing the environmental impacts of non point source pollutants at a global, regional and localized scale is a key component in achieving sustainability of agriculture as well as preserving the environment. Field data of Godavari Delta Central Canal Irrigation Project in Andhra Pradesh were used as a case study to develop the procedures. Assessment of groundwater pollution from agricultural sources involves the estimation of non point source pollutant loading into the aquifer and its movement in the aquifer system. The pollutant loading occurs along with the recharge water. Recharge represents the primary contaminant transport mechanism into the aquifer. It describes the fraction of water available at the surface that infiltrates into the soil and percolates through the vadose zone into the groundwater.

Seepage from the water distribution system (canals, branch canals and distributaries) and percolation losses from fields are the main sources of groundwater recharge in irrigation project areas. Seepage losses depend on the canal geometry, discharge and the seepage rate coefficient which is a function of the material of the canal section, whereas percolation losses depend on rainfall,

soils, crops and frequency and depth of irrigation. All of these vary spatially and temporally. But often, simple empirical methods are used in most practical situations to estimate recharge. For example, recharge from rainfall is estimated as 20-30% of rainfall. Such lumped estimates are not acceptable when rainfall, soils, irrigation and crops are spatially variable. Any realistic estimate of groundwater recharge should thus be based on the actual physical conditions. In the present study, physically based models were developed for the estimation of seepage and percolation losses in irrigation project command area. For estimation of seepage losses, the simple canal flow model based on uniform flow in a canal was developed. A root zone soil water balance model was also developed for estimation of recharge to groundwater from rainfall and percolation losses flow from irrigated areas. The soil water balance model incorporated several features to facilitate estimation of percolation losses from multiple cropped area. Specifically, daily percolation losses from :

- i) rice fields which require flooded conditions (*Kharif* and *Rabi* seasons)
- ii) other cropped areas (pulses, sugarcane and coconut plantations)
- iii) rice fallow lands, and
- iv) uncultivated lands

were estimated for different set of soil, weather and water supply conditions.

In case of water balance studies for paddy, runoff was estimated as rainfall in excess of that stored within the bunds of the field, and deep percolation was calculated using Darcy's law. The amount of irrigation applied to paddy crop was obtained from canal discharge values after accounting for seepage losses from main canal, branches and distributaries. For other crops, the two layer daily soil water balance model incorporates the runoff estimation which uses the soil moisture accounting procedure by Sharpley and Williams (1990). For uncultivated areas, evapotranspiration was replaced by soil evaporation, which is estimated by a two stage evaporation model (Richie, 1972). In case of rice fallow lands, soil water balance model for paddy crop was combined with two stage evaporation model (Ritchie, 1972).

In order to incorporate spatial and temporal distribution of the relevant variables, newer technologies like GIS was used to identify spatially homogeneous units over which models can run with limited data of some important soil and crop parameters and weather variables. The basis is that the command area was divided into a set of basic simulation units (BSU's) that are homogeneous with respect to the conditions that influence the soil water balance by using the capabilities of GIS. The soil map, raingauge thiessen polygon map, command area map and the *mandal* map were digitized to obtain the respective coverages using ARC/INFO (Ver 3.4.2). By performing overlay operations sequentially with all the four coverages, a fifth coverage was obtained. The very small polygons of this coverage were edited to merge with the adjacent large polygons. Each polygon of this coverages is homogeneous with respect to the soil parameters, the daily rainfall and water supply data input to the soil water balance model. The polygons of newly derived coverage are designated as basic simulation units (BSU's). The daily soil water balance model was run for each BSU to obtain the daily percolation losses from various fields. The development of the interface between the GIS and models facilitated efficient use of both GIS and models. The GIS was used to generate files that can be read by the FORTRAN programme. Once the models were run, the output was brought into GIS to generate thematic maps. The percolation losses and seepage losses were added to obtain the total annual recharge and display on the GIS.

Quantifying the nitrate losses is important for devising measures to control them and ensure sustainability of soil and groundwater resources. This requires quantifying the different nitrogen transformation processes occurring in rice fields. Hence to estimate nitrate loading into the groundwater, nitrogen balance was carried out in the root zone by developing a generalized model which considered different nitrogen transformation processes like urea hydrolysis, mineralization, volatilization, nitrification, denitrification, immobilization and uptake. Many models consider nitrification, denitrification, mineralization and immobilization but a few do not consider one or more of these processes. All these processes are influenced by weather, soil properties, irrigation and other factors. Further, the concentration of nitrate in the leached water depends on the percolation rate.

Thus, nitrate loadings to ground water will also depend on the percolation losses from rice fields. The nitrate loads will vary spatially and temporally over the project area. Nitrate losses were determined for a given set of conditions by coupling a daily soil water balance model that estimates percolation losses with a daily nitrogen balance model that accounts for nitrogen transformations in the rice fields. The seasonal nitrate leaching losses were displayed on the GIS

Once the leached nitrate reaches the water table, its retention or dispersal in the aquifer is governed by the flow conditions in the aquifer. To model the movement of the nitrate in the aquifer, it is necessary to simulate the groundwater flow conditions. A sequential solution of the groundwater flow and transport problems is therefore necessary. A two dimensional finite element model for the groundwater basin of the study area was developed for simulating the groundwater flow conditions with the appropriate modification in the model developed by Swain (1978). The model was successfully validated using the historic well inventory data. Temporal and spatial distribution of recharge rates were obtained for all the BSU's as discussed above and used for the simulation of the groundwater levels. These recharge rates were allowed at nodal points. However, there were difficulties in obtaining the pumping distribution. This was because of unavailability of distribution of wells, timing and duration of pumping. This pumping distribution was derived by following a set of heuristic rules. The results of the annual water balance of study area further substantiated the validity of procedures adopted in the development of soil water balance model and groundwater model.

For the present study, 2-D finite element groundwater transport model was used to simulate the movement of nitrate pollutant which is a conservative constituent. In this case an assumption is made that chemical reactions of the nitrate occur neither with other dissolved constituents nor with the aquifer material. For solving groundwater transport problems, input data like dispersivity and nitrate pollution loads play important role, because of complexity involved in their estimation. Though the dispersivity values can be estimated from field tests in most cases, these values are obtained from model calibration in the present

study. Nitrate pollutant loads were obtained from a coupled soil water balance-nitrogen balance model.

The analytical frame work developed in this study involves simulation models and GIS were used effectively to ascertain whether non point source pollution levels change as a consequence of alternative management strategies and whether such changes can be evaluated using a GIS based modelling framework.

CONCLUSIONS

(1) A generalized integrated framework has been developed for the assessment of non point source pollution of groundwater in irrigation project areas with the objective of ensuring sustainability of soil and groundwater resources. Even though the procedures were developed using the specific data of Central Godavari Delta Irrigation Project, they are sufficiently general to be extended to other areas.

(2) The integrated framework consists of databases, Basic Simulation Units (BSU's) derived for the command area using GIS, simulation models (Canal flow model, soil water balance model, nitrogen balance model, groundwater flow model and groundwater transport model) and interfaces between the models and GIS. The models are interlinked such that the output of one model serves as input to other model. The capabilities of GIS for derivation of BSU's and for selecting the input files required to run the models were demonstrated.

(3) The soil water balance model was used to assess the percolation losses from fields which is an important component of aquifer recharge. The model developed in this study, incorporates several features to facilitate estimation of percolation losses from multiple cropped areas including rice, and from uncropped areas. This ensures that the model can be applied to different cropping systems that are practised round the year in any area.

(4) It was shown that it is possible to take advantage of the capabilities of soil water balance and canal flow models and GIS to assess the spatial distribution of recharge in irrigation projects by taking account of the spatial variations in agrohydrologic processes.

- (5) The spatial distribution of recharge derived from the GIS was validated by a finite element groundwater flow model. A heuristic basis was developed for estimating the spatial distribution of pumping in the area. The model predicted the observed groundwater level adequately for the study area.
- (6) The nitrogen balance model developed in the present study for rice is simple, comprehensive and includes all the important nitrogen transformation processes that occur in both soil and flood water zones. All transformation processes are treated as first order rate reactions. A heuristic procedure was developed for the selection of rate constants under different soil and environmental conditions. A significant feature of the model and parameter selection process is that they are sufficiently general to be used across a variety of environments. This was demonstrated by validating the model at several locations.
- (7) The finite element groundwater transport model developed in this study was able to simulate the hydrologic behaviour of the nitrate pollutant derived from the N-balance model in terms of space and time.
- (8) A scenario based approach was developed for strategic planning based on the assessment of future non-point source pollution levels resulting from alternative management strategies. It was shown that the current levels of nitrate pollution in the study area are not alarming. The water quality over most of the study area is likely to deteriorate if current practices, trend on fertilizer use and increasing rice area are continued.
- (9) Although, the joint management of water and nitrogen application is often suggested for minimizing groundwater contamination, greater emphasis should be placed on the improvement of irrigation practices to minimize the leaching of nitrate and groundwater pollution in the study area.
- (10) The frame work developed in this study uses loose integration between models and GIS. This is both time and cost effective as model developed could be carried out independently of the GIS.

REFERENCES

- Addiscott, T.M. 1977. A simple computer model for leaching in structured soils. *J. of Soil Sci.* **28** : 554-563.
- Addiscott, T.M. and Wagenet, R.J. 1985. Concepts of solute leaching in soils: A review of modelling approaches. *J. of Soil Sci.* **36** : 411-424.
- Ahmed, N. 1974. Groundwater resources of Pakistan. Ripon Printing Press, Lahore, 295 pp.
- Allison, G.B., Gee, G.W. and Tyler, S.W. 1994. Vadose zone techniques for estimating groundwater recharge in arid and semi arid regions. *Soil Sci. Soc. Am. J.* **58** : 6-14.
- Anderson, M.P. 1979. Using models to simulate the movement of contaminants through groundwater flow systems. *Crit. Rev. Environ. Control* **9**(2) : 97-156.
- Anderson, M.P. 1983. Movement of contaminants in groundwater-transport. (In) Groundwater contamination : Product of a Technological Society, National Academy of Science.
- Anila Kumar, K. and John Kutty 1990. Effect of continuous flooding and intermittent irrigation on the soil available N, yield and N uptake by rice. *Oryza*. **27** : 489-90.
- Anila Kumar, K., Jose Mathew and Sivakumar, C. 1994. Relative efficiency of modified urea fertilizers in transplanted rice on an acid lateritic soil. *Oryza*. **31** : 242-44.
- Ardakani, M.S., Rehbock, J.T. and McLaren, A.D. 1973. Oxidation of nitrite in a soil column. *Soil Sci. Soc. Am. Proc.* **37** : 53-56.
- Armstrong, W. 1964. Oxygen diffusion from the roots of some British bog plants. *Nature* **204**(4960) : 801-802.
- Arora, V.K. and Gajri, P.R. 1996. Performance of simplified water balance models under maize in a semiarid subtropical environment. *Agricultural Water Management*. **31** (1-2) : 51-64.
- Asami, T. 1971. Immobilization and mineralization of nitrogenous compounds in paddy soils. 5. Distribution of immobilized N in various organic fractions. *J. Sci. Soil. Manure* **42** : 103-108.
- Aulakh, M.S. and Singh, B. 1997. Nitrogen losses and fertilizer N use efficiency in irrigated porous soils. *Nutrient Cycling in Agroecosystems*, **47** : 197-212.
- Awasthe, R.K. and Mishra, B. 1987. Yield and nitrogen uptake by rice in relation to nitrogen release from modified urea materials in a submerged soil. *J. Indian Soc. Soil Sci.* **35** : 52-57.
- Bajpai, S., Srivastava, O.P. and Pathak, A.N. 1984. Effect of organic matter on urea hydrolysis in soil. *Indian Soc. Soil. Sci. Bull. No. 13* : 155-159.
- Balwinder Singh and Bajwa, M.S. 1987. Ammonia volatilization from salt affected soils fertilized with urea under submerged conditions. *J. Indian Soc. Soil Sci.* **35** : 358-364.
- Barber, S.A. 1962. A diffusion and mass flow concept of soil nutrient availability. *Soil Sci.*, **92** : 39-49.

- Barber, S.A. and Olsen, R.A. 1968. Fertilizer use by corn (In) L.B. Nelson (ed.) changing patterns in fertilizer use. *Soil Sci. Soc. Am.* Madison. Wis. p 163-168
- Bear, Jacob. 1979. *Hydraulics of groundwater*, McGraw Hill, New York.
- Beri, V., Brar, S.S. Sekhon, G.S. and Ghuman, B.S. 1978. Extent of urea leaching in soils and its biochemical control. *J. Indian Soc. Soil. Sci.* **26** : 116-124.
- Besbes, M., Delhomme, J.P. and DeMarsily, G. 1978. Estimating recharge from ephemeral streams in arid regions: A case study at Kariokan, Tunisia. *Water Resour. Res.* **14**(2) : 281-290.
- Bhagat, R.M., Kanwar, B.B., Verma, T.S. and Minhas, R.S. 1988. Nitrogen economy in lowland rice culture. *Oryza*. **25** : 255-60.
- Biswas, A.K. 1992. Transformation of fertilizer nitrogen in a rice wheat cropping sequence with special reference to the forms and availability of residual N. Ph.D. thesis. Division of Soil Science. Indian Agricultural Research Institute, New Delhi.
- Boisvert, J.B., Dyer, J.A. and Brewin, D. 1992 a. The versatile soil moisture budget (VB) reference manual version 4, Res. Branch Agriculture Canada, Ottawa, Ontario, Canada.
- Boniol, D., Munch, D. and Williams, M. 1993. Mapping recharge to the floridan aquifer using a geographic information system. In : Proc. 13th annual ESRI user conf. (Vol. 3), Palm Springs, CA. 24-28. May, 1993. Environmental systems Res. Inst. Redlands, C.A.
- Boonstra, J. and Bhutta, M.N. 1996 Groundwater recharge in irrigated recharge agriculture : The theory and practice of inverse modelling. *J. of Hydrology*(Amsterdam) **174**(3/4) : 357-374.
- Boonstra, J. and De Ridder, N.A. 1981. Numerical modelling of groundwater basin. ILRI Pub. No. 29. Wageningen. The Netherlands, 226 pp.
- Borg, G.C., Jansson, P.E. and Linden, B. 1990. Simulated and measured nitrogen conditions in a manured and fertilized soil. *Plant and Soil*, **121** : 251-267.
- Borg, H. and Grimes, D.W. 1986. Depth development of roots with time : An empirical description. *Trans. of ASCE*, **29**(1) : 194-197.
- Bos, M.G. and Nugteren, J. 1978. On irrigation efficiencies. Int. Inst. for land reclamation and improvement. Wageningen, The Netherlands. pp 138.
- Brandon, D.M. and Wells, B.R. 1986. Improving nitrogen fertilization in mechanized rice culture. *Fertilizer Research* **9** : 161-170.
- Bredehoeft, J.D. and Pinder, G.F. 1970. Digital analysis of areal flow in multiaquifer groundwater system : A quasi three dimensional model. *Water Resour. Res.* **6** (3) : 883-888.
- Bredehoeft, J.D. and Pinder, G.F. 1973. Mass transport in flowing groundwater. *Water Resour. Res.* **9**(1).
- Broadbent, F.E. 1978. Transformations of soil nitrogen. p. 543-559. In . *Soils and Rice*, IRRI, Los Banos, Philippines.
- Broadbent, F.E. and Tusneem, M.E. 1971. Losses of nitrogen from some flooded soils in tracer experiments. *Soil Sci. Soc. Am. Proc.* **35** : 922-926.
- Broadbent, F.E., Hill, G.N. and Tyler, K.B. 1958. Transformations and movement of urea in soils. *Soil Sci. Soc. Am. Proc.*, **22** : 303-307

- Brown, K.W., Turner, F.T., Thomas, J.C., Deuel, L.E. and Keener, M.E. 1978. Water balance of flooded rice fields. *Agricultural water management*. 1:277-291.
- Bryant, K.J., Masud, S.M., Lacewell, R.D. and Keeling, J.W. 1992. Profit, cost and soil erosion implications of dryland crop production systems : Texas high plains *J Prod. Agr.* 5 : 307-312
- Bulusu, K.R. and Panda, S.P. 1990. Nitrates - A serious threat to groundwater pollution *BHU-JAL News, Quarterly Journal of Central Groundwater Board*. 5(2) 39
- Bunyakina, R.F. 1976. Fractional composition of nitrogen and nitrogenous fertilizers in the leached chernozem of the Kuban region (based on pot experiment with N-15). *Soviet Soil Sci.* 8 : 438-442.
- Burns, I.G. 1975. An equation to predict the leaching of surface applied nitrate. *J. Agric Sci. Camb.* 85 : 443-454.
- Burrough, P.A. 1986. Principles of geographical information systems for land resources assessment. Clarendon Press. Oxford. U.K.
- Caberera, M.L. and Kissel, D.E. 1984. Rate of urea hydrolysis in soil as affected by urea concentration. *76th Annual meeting of Am. Soc. Agron.* p. 268
- Cao Zhi-Hong, De Datta, S.K. and Fillery, I.R.P. 1984. Effect of placement methods on flood water properties and recovery of applied nitrogen (¹⁵N-labelled urea) in wetland rice. *Soil Sci. Soc. Am. J.* 48 : 197-203.
- Carrea, J. and Neuman, S.P. 1986. Estimation of aquifer parameters under transient and steady state conditions. I. Maximum likelihood method incorporating prior information *Water Resour. Res.* 22(2) : 201-211.
- CGWB(Central Ground Water Board). 1984. Report of Groundwater Estimation Committee, Ministry of Irrigation, Govt of India, New Delhi.
- CGWB 1993. Groundwater resources and development prospects in East Godavari district, Andhra Pradesh. Ministry of water Resources. Government of India, New Delhi.
- Chakravorthi, S.P., Chalam, A.B. and Mohanty, S.K. 1989. Comparative efficiency of prilled urea and urea supergranule for wetland Rice. *J. Indian Soc. Soil Sci.*, 37 : 177-179.
- Chandra, H. and Abrol, I.P. 1972. Effect of three nitrogenous fertilizers on the solution composition of saline sodic soil. *Commun. Soil. Sci. Pl. Anal.* 3 : 51-56.
- Chariat, S. and Delleur, J.W. 1993. Integrating a physically based hydrological model with GRASS. p. 143-150. In *Application of geographic information systems in hydrology and water resources management*. K. Kovar and H.P. Nachtnebel (ed.). IAHS Publ. 211. IAHS, The Netherlands
- Charlu, T.G.K. and Dutt, D.K. 1982. Groundwater development in India. Rural electrification Corporation, *New Tech. Series*, No. 1 228 p.
- Chiew, F.H.S. and Mc Mahon, T.A. 1991. Groundwater recharge from rainfall and irrigation in the camaspe river basin (Victoria). *Australian Journal of Soil Research* 29(5) 651-670.
- Chin, W., and Kroontje, W. 1963. Urea hydrolysis and subsequent loss of ammonia *Soil Sci. Soc. Am. Proc.* 27 : 316-319
- Chow, V.T. 1959. Open Channel Hydraulics McGraw Hill, New York, 680 pp.

- Churchhouse, R.F. 1981. (ed.) Handbook of Applicable Mathematics Volume III, Numerical methods, John Wiley, New York.
- Cole, J.A. 1972. Some interpretations of dispersion measurements in aquifers *In : Ground water pollution in Europe* (Eds.) J.A. Cole, pp 86-95; Water Research Association, Reading, England.
- Connolly, M.G., O'Toole, P. and Morgan, M.A. 1980 Urease activities and comparative transformations of urea and ammonium nitrate in some Irish soils under laboratory and green house conditions *J. Life Sci. Royal Dublin Soc.* 1 : 157-165.
- Corwin, D.L. and Wagenet, R.J. 1996. Applications of GIS to the modelling of nonpoint source pollutants in the vadose zone : A conference overview. *J. Environ. Qual* 25 : 403-411
- Craswell, E.T. and Vlek, P.L.G. 1979. Fate of fertilizer nitrogen applied to wetland rice p 195-192. *In : Nitrogen and Rice.* IRRI, Los Banos, Philippines.
- Craswell, E.T. and Vlek, P.L.G. 1982. Nitrogen management for submerged soils. *Trans 12th Int. Congress. Soil Sci. Symposium Paper II*, New Delhi 8-16, Feb 158-181
- Craswell, E.T. De Datta, S.K. Weeraratne, C.S. and Vlek, P.L.G. 1985. Fate and efficiency of nitrogen fertilizer applied to wetland rice. *The philippines Fertilizer Research* 6 : 49-63.
- Daftardar, S.Y. 1973. Urea and ammonium nitrate as fertilizers for lowland rice studies with N-15 tagged materials on nitrogen transformations, losses and utilization Ph D Thesis, IARI, New Delhi.
- Dagan, G. and Bresler, E. 1979. Solute dispersion in unsaturated heterogeneous soil at field scale. I. theory., *Soil Sci. Soc. Am. J.* 43 : 461-466.
- Das, S. and Singh, T.A. 1994. Nitrogen use efficiency by rice and flood water parameters as affected by fertilizer placement techniques. *J Indian Soc. Soil Sci.*, 42 : 46-50
- Datta, N.P., Banerjee, N.K. and Prasad, Rao, D.M.V. 1971. A new technique for study on N-balance sheet and an evaluation of nitro-phosphate using ¹⁵N under submerged conditions of growing paddy. *Proc. Int. Symp. Soil. Fertil. Evaln.* 1 : 631-638
- Davidson, J.M. Graetz, D.A. Rao, P.S.C. and Selim, H.M. 1978. Simulation of nitrogen movement, transformations and uptake in plant rootzone. EPA-600-3-78-029 Environmental research laboratory. U.S. Environmental Protection agency, Athens, GA.
- De Datta, S.K. 1981. Principles and Practices of Rice Production. John Wiley and Sons, New York, 618 pp.
- De Datta, S.K. 1986. Improving nitrogen fertilizer efficiency in lowland rice in tropical Asia. *Fertilizer Research* 9 : 171-186.
- De Datta, S.K. 1987. Nitrogen transformation processes in relation to improved cultural practices for lowland rice. *Plant and Soil.* 100 : 47-69.
- De Datta, S.K., Fillery, I.R.P., Obcemea, W.N. and Evangelista, R.C. 1987a Flood water properties, nitrogen utilization and nitrogen-15 balance in a calcareous lowland rice soil. *Soil. Sci. Soc. Am. J.* 51 : 1355-1362.
- De Datta, S.K., Magnaye, C.P. and Moomaw, J.C. 1968. Efficiency of fertilizer nitrogen (¹⁵N-labelled) for flooded rice. *Trans. 9th Int. Congr. Soil Sci.* 4 : 67-76

- De Datta, S.K., Obcemea, W.N., Chen, R.Y., Calabio, J.C. and Evangelista, R.C. 1987b Effect of water depth on nitrogen use efficiency and nitrogen-15 balance in lowland rice. *Agron J.* **79** : 210-216.
- De Laune, R.D. and Patrick, Jr., W.H. 1970. Urea conversion to ammonium in waterlogged soils. *Soil Sci. Soc. Am. Proc.* **34** : 603-607.
- De Smedt, F. and Wierenga, P.J. 1978 Approximate analytical solution for solute flow during infiltration. *Soil. Sci. Soc. Am. J.* **42** : 407-412.
- Deacon, N.H.G. 1984. Seepage and Durability of irrigation canal linings. Hydraulics Research, Wallingford, Oxfordshire.
- Dhyani, B.P. and Mishra, B. 1993. The fate of fertilizer nitrogen in a flooded rice field. *J Indian Soc. Soil. Sci.* **41**(4) : 770-771.
- Die, Y. and Yamasaki, S. 1979. Effect of water and crop management on nitrogen supplying capacity of paddy soil. In : *Nitrogen and Rice*, pp 451-463 Los Banos, Philippines, IRRI.
- Doorenbos, J. and Kassam, A.H. 1979. Yield response to water. FAO. *Irrigation and drainage paper No. 33*, FAO, Rome, Italy.
- Doorenbos, J. and Pruitt, W.O. 1977. Crop water requirements. FAO. *Irrigation and drainage paper No. 24*, FAO, Rome, Italy.
- Doraiswamy, P. 1992. Development of an Integrated Expert Decision Support System for Irrigation Scheduling. Ph.D. Thesis, Division of Agricultural Engineering, Indian Agricultural Research Institute, New Delhi, India.
- Dubey, S.K. and Bisen, C.R. 1989. Nitrogen uptake by rice as influenced by different levels, sources and methods of nitrogen application. *Oryza.* **26** : 37-42.
- Edmunds, W.M. Bath, A.H. and Miles, D.L. 1982. Hydrochemical evolution of the east midlands triassic sandstone aquifer, England. *Geochemica et cos mochimica Acta.* **46** : 2069-2081.
- Ergatoudis, I., Irous, B.M. and Zienkiew, O.C. 1968. Curved isoparametric quadrilateral elements for finite element analysis, *Int. J. Solids Structures*, Vol. 4, pp. 54-42 FAO (1974)
- Fayer, M.J., Gee, G.W., Rockhold, M.L., Freshley, M.D. and Walters, T.B 1996. Estimating recharge rates for a groundwater model using a GIS.
- Feddes, R.A., Kabat, P. Van Bakel, P.J.T. Bronswijk, J.J.B. and Halbertsma, J. 1988. Modelling soil water dynamics in the unsaturated zone-state of the art. *J. of Hydrology*, **100** : 69-111.
- Fedler, C.B. Rainwater, K.A., Yueying, D., Dvoracek, M.J. and Ramsey, R.H. 1989. Field study of tracer movement in a shallow alluvial aquifer. *American Society of Agricultural Engineers* **32**(3) : 1989.
- Ferguson, J.A. 1970. Effect of flooding depth on rice yield and water balance. *Arkansas Farm Res.* **19** : 4.
- Fillery, I.R.P. and De Datta, S.K. 1986. Ammonia volatilization from nitrogen sources applied to rice fields. I. Methodology, ammonia fluxes and nitrogen-15 loss. *Soil. Sci. Soc. Am.J.* **50** : 80-86.
- Fillery, I.R.P., Simpson, J.R. and De Datta, S.K. 1984. Influence of field environment and fertilizer management of ammonia loss from flooded rice. *Soil Sci. Soc. Am.J.* **48** : 914-920.

- Flug, M., Abi-Ghanem, G.V. and Duckstein, L. 1980. An event based model of recharge from an ephemeral stream. *Water Resour. Res.* 16(4) : 685-690.
- Fread, D.L. 1978. National Weather Service Operational Dynamic Wave Model. National Weather Service, Silver springs, MD, USA.
- Frenay, J.R., Denmead, O.T., Watanabe, I. and Craswell, E.T. 1981. Ammonia and nitrous oxide losses following applications of ammonium sulfate to flooded rice. *Aust. J. Agric. Res.* 32 : 37-45.
- Fried, J.J., 1975. Groundwater pollution. American Elsevier Publishing Co. Inc., New York, NY.
- Gailey, R.M., Gorelick, S.M. and Gowe, A.S. 1991. Coupled process parameter estimation and prediction uncertainty using hydraulic head and concentration data, *Adv. Water Resources* 14(5) : 301-314.
- Gates, J.S. and Kisiel, C.C. 1974. Worth of additional data to a digital computer model of a groundwater basin. *Water Resour. Res.* 10(5) : 1031-1038.
- Gee, G.W., Wierenga, P.J., Andraski, B.J., Young, M.H., Fayer, M.J. and Rockhold, M.L. 1993. Variations in water balance and recharge potential at three western desert sites. *Soil Sci. Soc. Am. J.* 58 : 63-72.
- Geethadevi, T., Srinivas, N., Swamygowda, S.N., Rabindra, B. and Kenchaiah. 1991. Nitrogen loss studies in wetland rice using modified urea materials. *Oryza*. 28 : 485-87
- Geo Trans, Inc., 1990. SWICHA: A three dimensional finite element code for analyzing seawater intrusion in coastal aquifers, Version 5.0. Geo Trans, Inc.
- Ghildyal, B.P. and satyanarayana, T. 1965. Effect of compaction on physical properties of four soils of India. *J. Indian Soc soil sci.* 13 : 149-155
- Goodchild, M.F., Parks, B.O. and Steyart, L.T. 1993. (Eds.) In : *Environmental modelling with GIS*. Oxford university press.
- Gormly, J.R. and Spalding, R.F. 1979. Sources and concentrations of nitrate nitrogen in groundwater of the central plote region. Nebraska. *Groundwater*, 17 : 291-301.
- Goswami, N.N. and Sahrawat, K.L. 1982. Nutrient transformation in soils. Macronutrients. p. 123-145. In : Rev. of Soil Res. in India, Part I. *Indian Soc. Soil Sci.*, New Delhi, India.
- Greenwood, D.J., Wood, J.T. and Cleaver, T.J. 1974. A dynamic model for the effects of soil and weather conditions on nitrogen response. *J. Agric. Sci.* 82 : 455-467.
- Gritzman, H. and Margaritz, M. 1986. Investigation of water movement in the unsaturated zone under an irrigated area using environmental tritium *Water Resour. Res.* 22 : 635-642.
- Gupta, S.C. 1992. Udaipur Kshetra ke bhujaal main nitrate ka badhata star. *BHU-JAL news*. Quarterly journal of the central groundwater board. 7(1) : 17-19.
- Gupta, S.C. and Kapoor, V.K. 1983. Fundamentals of mathematical statistics Eighth Edition, Sultan Chand and Sons, New Delhi.
- Guymon, G.L. 1970. A finite element solution of the one dimensional diffusion - convection equation. *Water Resour. Res.* 6 : 204-210

- Guymon, G.L., Scott, V.H., and Herrmann, L.R. 1970. A general numerical solution of the two dimensional diffusion - convection equation by the finite element method. *Water Resour. Res.* 6 : 1611-1617.
- Haan, C.T., Nofziger, D.L. and Gregory, M. 1993. An agricultural Chemical evaluation and management system. *J. Agric. Engg. Res.* 56 : 301-312
- Hajilal, M.S. 1993. Real Time Management of a storage based canal Irrigation System Ph.D. Thesis, Division of Agricultural Engineering, Indian Agricultural Research institute, New Delhi, India.
- Hajilal, M.S., Rao, N.H. and Sarma, P.B.S. 1997. Real time management in storage based irrigation systems. Central Board of Irrigation and Power. Publication No. 256 New Delhi. pp. 370.
- Hajilal, M.S., Rao, N.H. and Sarma, P.B.S. 1998. Planning intraseasonal water requirements in irrigation projects (In Press). *Agricultural Water Management*.
- Halberg, G.R. 1989. Nitrate in groundwater in the united states. In. R.F. Follett (ed.). Nitrogen management and groundwater protection. Elsevier, Amsterdam.
- Harris, J., Gupta, S., Woodside, G. and Ziemba, N. 1993. Integrated use of a GIS and a 3-dimensional finite element model : San Gabriel basin groundwater flow analysis In : Goodchild, M.F., Parks, B.O. and Steyaert, L.T. (Eds.) Environmental modelling with GIS. pp. 168-72, Oxford University Press, New York.
- Hill, A.R. 1982. Nitrate distribution in the groundwater of the Alliston region of Ontario. Canada. *Groundwater*. 20 : 697-702
- Howard, K.W.F. and Lloyd, J.W. 1979. The sensitivity of parameters in the penman evaporation equations and direct recharge balance. *J. Hydrology*, 41 : 329-344.
- Hubbard, R.K., Gascho, G.J. Hook, J.E. and Knisel, W.G. 1986. Nitrate movement into shallow groundwater through a coastal plain sand. *Trans. of the ASAE* 29(6) : 1564-1571
- Humenik, F.J., Smolen, M.D. and Dressing, S.A. 1987. Pollution from nonpoint sources : Where we are and where we should go, *Environ. Sci. Technol.* 21(8) : 737-742.
- Hutson, J.L. and Wagenet, R.J. 1991. Simulating nitrogen dynamics in soils using a deterministic model. *Soil use and management*. 7 (2) : 74-78.
- Hydraulics Research Station, 1975. Canal linings and canal seepage. Hydraulics Research, Wallingford, Oxfordshire, England.
- IRRI (International Rice Research Institute). 1987. Annual Report for 1986. IRRI, Los Banos, Philippines.
- Jansson, P., and Anderson, R. 1988. Simulation of runoff and nitrate leaching from an agricultural district in Sweden. *J. Hydrology*, 99 : 33-47.
- Jansson, S.L. and Persson, J. 1982. Mineralization and immobilization of soil nitrogen. In : *Nitrogen in agricultural soils* (F.J. Stevenson, ed.). *Agronomy* 22 : 229-252.
- Jayakumar, M., Saseendran, S.A. and Hemaprabha, M. 1988. Crop coefficient for coconut (*Cocos Nutifera* L.) : A lysimetric study. *Agricultural and forest meteorology*, 43. pp. 235-240.
- Jayaweera, G.R. and Mikkelsen. 1990. Ammonia volatilization from flooded soil systems. A computer model I. Theoretical aspects. *Soil. Sci. Soc. Am. J.* 54 : 1447-1455.

- Jemison, J.M., J.D. Jabro and Richard, H.F. 1994. Evaluation of LEACHM ; II. Simulation of nitrate leaching from nitrogen-fertilized and manured corn. *Agron. J.* **86** : 852-859.
- Jena, D. and Misra, C. (1990). The fate of ^{15}N tagged urea leached with infiltrating water under rice and bare soil situation. *Oryza*, **27** : 40-47
- Joao, E.M. and Walsh, S.J. 1992. GIS implications for hydrologic modelling : Simulation of nonpoint pollution generated as a consequence of watershed development scenarios. *Comput Environ. Urban Syst* **16** : 43-63.
- Johnson, S.L., Adams. R.M. and Perry, G.M. 1991. The in farm costs of reducing groundwater pollution. *Amer. J. Agri. Econ.* **73**(Nov): 1063-73
- Johnsson, H., Bergstrom, L., Jansson, P. and Paustian, K. 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agric. Ecosystem Environ.*, **18** : 333-356.
- Joliffe, I.B. 1984. Computation of Dynamic waves in channel networks. *Journal of Hydraulic Engineering Division*, ASCE, **110** (10) : 1358-1369
- Joseph, K. Menon, P.K.G. and Anila Kumar, K. 1993. Studies on the losses of applied nitrogen in the lowland rice fields as influenced by different nitrogen sources *Oryza* **30** : 51-53.
- Joshi, N.R., Shukla, S.P. and Adkine, B.D. 1986. The Jayakwadi Irrigation System. In : Marathwada Agricultural University, Agricultural Development of Jayakwadi and Purna command areas, MAU, Parbhani, Maharashtra.
- Jury, W.A. 1982. Simulation of solute transport using a transfer function model, *Water Resour. Res.*, **18** : 363-368.
- Just, R.E. and Antle, J.M. 1990. Interactions between agricultural and environmental policies : A conceptual frame work. *Amer. Econ. Rev.* **80** :197-202.
- Kai, H. and Wada, A.K. 1979. Chemical and biological immobilization of nitrogen in paddy soils. In : Nitrogen and Rice. p. 157-174. International Rice Research Institute, Los Banose, Philippines
- Kampen, J., 1970. Water losses and balance studies in lowland rice irrigation. Unpublished Ph.D. Thesis. Cornell University, pp 416.
- Kanwar, R.S., Baker, J.L. and Laflin, J.M. 1985. Nitrate movement through the soil profile in relationship to tillage system and fertilizer application method. *Trans of ASAE* **28**(6) : 1802-1807.
- Kanwar, R.S. Baker, T.L. and Baker, D.G. 1988. Tillage and split N-fertilizer effects on subsurface drainage water quality and crop yields. *Trans. of ASAE.* **31**(2) : 453-460.
- Karanjac, J.M., Altunkayank and Oval, G. 1977. Mathematical model of uluova plain, Turkey- a training and management tool. *Groundwater* **15**(5) : 348-357.
- Keeney, D. and Sahrawat, K.L. 1986. Nitrogen transformations in flooded soils *Fertilizer Research* **9** : 15-38.
- Keidser, A.D., Rosbjerg, K.H. and Bitsch, K. 1990. A joint kriging and zonation approach to inverse groundwater modelling. IAHS Publ. pp. 95 171-183.
- Keith, S.J. 1981. Stream channel recharge in the Tucson basin and its implications for groundwater management. M.S. Thesis., University of Arizona, Tucson, Arizona.

- Khumbate, N.N. and Biswas, B.C. 1992. Weekly potential evapotranspiration over India. Division of Agricultural meteorology. Meteorological monograph, Agrimet/No. 14/1992. Indian meteorological Department, Pune-5, 1992
- Khind, C.S. and Datta, N.P. 1985. Priming effect as affected by method and time of application of N-labelled Ammonium sulphate in lowland rice. *J. Indian Soc. Soil Sci.*, **33** : 685-87.
- Kisiel, C.C., Supkow, D. and Tetley, W. 1972. Role of digital computer models of aquifers in water resources planning. Case study in Tucson, Arizona, Int. Symp. on the planning of water resources, Mexico City, 22 pp
- Klempt, W.B., Knowles, T.R., Elder, G.R. and Sich, T.W. 1979. Groundwater resources and model applications for the Edwards (Balcones Fault Zone) aquifers in the San Antonio Region Report 239, Texas, Dept. of water Resources, Austin, Texas, 88 pp. Kowal, and Krabe 1972.
- Knisel, W.G. 1980. CREAMS . A field-scale Model for Chemicals, Runoff and erosion from Agricultural Management Systems. U.S. Department of Agriculture, *Conservation Research Report No. 26*, 640 pp.
- Konikow, L.F. and Bredehoeft, J.D. 1974. Modelling flow and chemical quality changes in an irrigated stream aquifer system *Water resour. Res.* 10(3).
- Konikow, L.K. and Bredehoeft, J.D. 1978. Computer model of two dimensional solute transport and dispersion in groundwater. In: *Techniques of water resources investigations*, book 7. Chap. C2, 90pp. U.S. Geol. Surv. Reston. Va., 1978
- Koshino, M. 1975. Incoming and outgoing of fertilizer nutrients in cropped lands in HESC organizing committee, Science Council of Japan. Proc. of the Int Congress on the human environ. (HESC), Tokyo, Japan, p. 206-214.
- Koyama, T. 1975. Practice of determining potential nitrogen supplying capacities of paddy soils and rice yields (in Japanese) *J. Sci. Soil Manure.*, **46** : 260-269
- Krabbenhoft, D.P. and Babinarz, C.L. 1992. The role of groundwater transport in aquatic mercury cycling. *Water Resour. Res.* **28**(12) : 3119-3128.
- Krantz, B.A., Ohlrogge, A.J. and Scarseth, G.D. 1943. Movement of nitrogen in soils. *Soil Sci. Soc. Am. Proc.*, **8** : 189-195.
- Krishnappa, A.M. and J.E. Shinde. 1980. The turnover of ¹⁵N labelled straw and FYM in a rice-rice rotation under flooded conditions at two locations. *J. Indian Soc. Soil Sci.* **28** : 474-479.
- Liao, C.F.H. and Bartholomew, W.V. 1974. Relation between nitrate absorption and water transpiration by corn. *Soil Sci. Soc. Am. Proc.* **38** : 472-477
- Little, R., Muller, E. and Mackay, R. 1996. Modelling of contaminant nitrogen in a chalk aquifer. *J. Hydrology*, (Amsterdam) **175** (1/4) : 473-509.
- Loague, K., Green, R.E., Giambelluca, T.W., Liang, T.C. and Yost, R.S. 1990. Impact of uncertainty in soil, climatic and chemical information on a pesticide leaching assessment. *J. Contam. Hydrol.* **5** : 171-194.
- Lunkad, S.K. 1994. Rising nitrate levels in groundwater and increasing N-fertilizer consumption. *BHU-JAL News*. March, 4-10.
- Mahajan, K.K. and Tripathi, B.R. 1992. Effect of increasing levels of different urea based fertilizers on yield and nitrogen nutrition of rice in an Allisoi. *Oryza*, **29** : 101-106

- Mahapatra, P., Panda, D. and Mohanty, S.K. 1991. Flood water chemistry and ammonia volatilisation in transplanted wetland rice soil. *oryza*. **28** : 185-191.
- Mahmood, K. and Yevjevich, V. (eds.) 1975. Unsteady flow in open channels. Water Resources Publications, Fort Collins, Colorado.
- Maidment, D.R. 1993. GIS and hydrologic modelling. In . *Environmental modelling with GIS* (eds.) Goodchild, M.F. Parks, B.O. and Steyert, L.T. Oxford University Press, New York. 147-167.
- Mandal, D.K. and Kar, S. 1991. Soil loss of Nitrogen under rice. *J. Indian Soc. Soil Sci.*, **39** : 764-66.
- Mandal, D.K. and Kar, S. 1995. Water and nitrogen use by rice-wheat on Ultic Haplustalf. *J. Indian Soc. Soil Sci.*, **43** (1) : 9-13
- Mandavia, A.B. and Acharya, K.D. 1995. Canal hydraulics and hydraulic simulation by mathematical model, Proc. International Conference on water and energy 2001, New Delhi, India, 9-12, Oct. 1995, Central Board of irrigation and Power Vol. II, 552-568 pp.
- Mangaraja, S. and Mishra, C. 1978. Effect of temperature on denitrification. *J. Indian Soc. Soil Sci.* **26** : 401-402
- Mapp, H.P., Bernardo, G.J., Geleta, and Watkins, K.B. 1994. Economic and environmental impacts of limiting nitrogen use to protect water quality. A stochastic regional analysis. *Amer. J. Agr. Econ.* **76** : 889-903.
- McDonald, M.G. and Harbaugh, A.W. 1988. A modular three dimensional finite difference groundwater flow module. U.S. Geological survey techniques of water resource investigations box 6, 586 pp.
- McInnes, K.J., Ferguson, R.B., Kissel, D.E. and Kanemasu, E.T. 1986. Field measurement of ammonia loss from surface application of urea solution to bare soil. *Agron. J.* **78** : 192-196.
- Mehran, M. and Tanji, K.K. 1974. Computer modelling of nitrogen transformations in soils. *J. Environ. Quality* **3**(4) : 391-396.
- Mehta, B.C., Singh, R.V., Srivastava, S.K. and Das, S. 1990. Impact of fertilizer use on groundwater quality in parts of ganjam district, Orissa. *BHU-JAL News*. Quarterly journal of central groundwater board **7**(4) : 24-28.
- Mengel, K., Schon, H.G., Keerthisinghe, G. and De Datta, S.K. 1986. Ammonium dynamics of puddled soils in relation to growth and yield of lowland rice. *Fertilizer Research* **9** : 117-130.
- Ministry of Agriculture. 1972. Handbook of Hydrology. Government of India, New Delhi
- Mishra, B., Sharma, R.D. and Murthy, J.R. 1990. Effect of neem cake and shellac coating of urea and greenmanure on Ammonia volatilisation and nitrogen use efficiency for rice. *J. Indian Soc. Soil Sci.*, **38** : 224-28.
- Mishra, B.K. and Misra, B. 1991. Kinetics of nitrification and nitrate reduction during leaching of ammonium nitrate through a limited ultisol profile. *J. Indian Soc. Soil Sci.*, **39** : 221-228.
- Mishra, G.C. and Seth, S.M. 1988. Recharge from a river of large width to a shallow watertable aquifer. *Groundwater*, **26** (4) : 439-444.

- Misra, C. and Mishra, B.K. 1977. *Soil Sci Soc. Am. J.* 41 : 496.
- Mitsui, S. 1954. Inorganic nutrition fertilization and soil amelioration for lowland rice. Yokendo Ltd. Tokyo. 107 p.
- Mitsui, S. 1973. Urea - its characteristics and efficient use as a fertilizer in Japan. c.f. Urea - its potentialities, JUC, New Delhi.
- Mizutani, M., Kalita, P.K. and Shinde, D. 1989. Effect of different rice varieties and mid term drainage practice on water requirement in dry season paddy - Observational studies on water requirement of lowland rice in Thailand. *J Irrig. Eng. Rural Plann.* 17 : 6-20
- Moench, A.F. and Kisiel, C.C. 1970. Application of the convolution relation to estimating recharge from an ephemeral stream. *Water Resour. Res.* 6(4) : 1087-1094.
- Mohapatra, N.P., Tosh, B.N., Panda, D. and Mohanty, S.K. 1983. Effect of urea-based fertilizers on nitrogen transformation, yield and uptake of nitrogen by rice under flooded conditions. *Oryza*, 20 : 119-124.
- Molz, F.J. Guven, O. and Melville, J.G. 1983. An examination of scale dependent dispersion coefficients. *Groundwater* 21(6) : 715-725.
- Murayama, N. 1979. The importance of nitrogen for rice production. In : *Nitrogen and Rice*. p. 5-24. International rice Research Institutue, Los Banos, Philippines.
- Murayama, T., 1989. Paddy field irrigation. *J. Irrig. Eng. Rural Plann.* 16 : 16-22.
- Murthy, V.V.N. and Koga, K. 1992. Soil and Water Engineering for Paddy Field Management. Edited Book. Asian Institute of Technology, Bangkok, Thailand. pp 448.
- Naphade, J. D. and Ghildyal, B.P. 1971. Effect of puddling on physical properties of rice soil. *Indian J. of Agr. Sci.* 41 : 1065-1067
- Narasimhan, T.N. and Witherspoon, P.A. 1982. Overview of the finite element method in groundwater hydrology. Finite elements in water resources. *Proc. of the 4th International Conference*, Hannover, Germany.
- Narasimhan, T.N. and Witherspoon, P.A. 1982. Overview of the finite element method for subsurface hydrology using a Explicit Implicit scheme. *Water Resour. Res.*, 14 : 5, 863-877.
- National Institute of Hydrology(NIH). 1992. Seasonal groundwater balance study in central Godavari delta Andhra Pradesh. Part I & II. CS-117 and TR-166. Deltaic regional centre, Kakinada, Andhra Pradesh.
- Nye, P.H. 1977. The rate limiting step in plant nutrient absorption from soil. *Soil Sci.*, 123 : 292-297.
- Oden, J.T. 1972. Finite elemnets of non linear continua. Mc Graw Hill, New York, pp. 125-137.
- Odhiambo, L.O. and Murthy, V.V.N. 1996. Modeling water balance components in relation to field layout in lowland paddy fields. I : Model application *Agricultural water management* 30 : 185-199
- Odhiambo, L.O. and Murthy, V.V.N. 1996. Modeling water balance components in relation to field layout in lowland paddy fields. II : Model application. *Agricultural water management* 30 : 201-216.
- Olsen, S.R. and Kemper, W.D. 1968. Movement of nutrients to plant roots *Advances in Agronomy*, 30 : 91-151.

- Orzol, L.L. and McGrath, T.S. 1992. Modifications of the U.S. Geological survey, Modular three dimensional finite difference groundwater flow module. U.S. Geological survey open-file Report, 92-50, 202 pp.
- Overrein, L.N. and P.G. Moe., 1967. Factors affecting urea hydrolysis and ammonia volatilization in soil. *Soil Sci. Soc. Amer. Proc* **31** : 57-61.
- Pal, S. and P.K. Chonkar. 1981. Urease activity in relation to soil characteristics. *Pedobiologia* **21** : 152-158.
- Panda, M. 1993. Relative efficiency of some urea formulations for rice in coastal soils of Orissa. *Oryza* **30** : 38-40.
- Pande, H.K. 1975. Water management practices and rice cultivation in India. Symposium on water management in rice field. Tropical agriculture research centre, Ministry of agriculture and forestry. Japan Technical Report. p13, Aug.26-29.
- Pande, R.R. and Adak, N.R. 1971. Leaching losses of nitrogen in submerged rice cultivation. *Exp. Agric.* **7** : 329-336.
- Pathak, H. and Sarkar, M C 1995. Nitrogen mineralization in manure amended soils in relation to soil water regime. *J Indian Soc. Soil. Sci.*, **43** (2) 267-269
- Patnaik, S. 1965. ¹⁵N tracer studies on the utilization of fertilizer nitrogen by rice in relation to time of application. *Proc. Indian Acad. Sci. Sect B* **61** : 31-39.
- Patrick, W.H. Jr. and S. Gotoh. 1974 The role of oxygen in nitrogen loss from flooded soils. *Soil Science* **118** : 78-81
- Paulson, K.N. and L.T. Kurtz. 1969. Locus of urease activity in soil. *Soil Sci Soc Am Proc.* **33** : 897-901.
- Pereira, L.S. 1989. Modernization of irrigation systems : a case of research oriented to improve management. *Irrigation and Drainage systems.* **2** (1) : 63-67
- Pereira, L.S. Van den Broek, B.J., Kabat, P. and Allen, R.G. (eds). 1995 Crop water simulation models in practice. 15th congress of the international commission on irrigation and drainage (ICID) at the Hague, The Netherlands in 1993. pp 339.
- Philip, J.R. 1957. The theory of Infiltration : IV : Sorptivity and algebraic infiltration equations. *Soil Science*, **84** : 257-284.
- Pinder, G. F. 1974. Finite element simulation in surface and subsurface hydrology. Academic Press, New York.
- Pinder, G.F. and Gray, W.G. 1977. Finite element simulation in surface and sub-surface hydrology. Academic press, New York, 295 pp.
- Porwal, A.K. and Rao, N.H. 1988. Simulation of field soil water balance. *Journal of Indian Water resources Society* **8**(4) : 35-41.
- PPR. 1980. Regional soil and water management pilot project report. Jagityal, SRSP-CADA, Karimnagar, Andhra Pradesh.
- Prasad, B. and Singh, K.N. 1992. Cumulative volatilization loss of ammonia from rice field under integrated nutrient management. *J. Indian Soc. Soil Sci.*, **40** : 209-210.
- Prasad, R., Rajale, G.B. and Lakhdive, B.A. 1971. Nitrification retarders and slow release nitrogen fertilizers. *Adv. Agron.* **23** : 337-383.

- Praveen Kumar, Aggrawal, R K. and Sharma, B.M. 1990. Effect of method of application of urea, time and depth of water application on movement of urea in an arid sandy soil. *J. Indian Soc. Soil. Sci.* **38** : 398-403.
- Prickett, T.A. 1976. Advances in Groundwater flow modelling. In : Saleem, Z.A., *Advances in Groundwater Hydrology*. American water well Association, Minnesota, U.S.A. pp 102-112.
- Prickett, T.A. and Lonquist, C.G. 1971. Selected Digital computer techniques for groundwater resource evaluation. Bull. No. 55, Illinois State water Surv. Urbana, pp 62.
- Prihar, S.S., and Sandhu, B.S. 1987. Irrigation of field crops; Principles and practices. Publishers, publications and information division, ICAR.
- Purakayastha, T.J., Katyal, J.C. and Goswami, N.N. 1995. Ammonia volatilization as affected by methods of fertilization. *J. Indian Soc. Soil Sci.*, **43** (2) ; 173-177.
- Purohit, R.C. and Gosain, A.K. 1990. Simulation of soil water balance in an arid region In: Menenti, M. (ed.) *Remote sensing in evaluation and management of irrigation. Proceedings International Symposium*, Mendoza, Argentina.
- Rachhpal Singh and Kirk, G.J.D. 1993. A model for predicting the fate of nitrogen fertilizer in lowland rice fields. II Predicted dynamics of inorganic carbon, nitrogen and acidity in the soil and floodwater. *J. of Soil Sci.* **4** : 285-297.
- Rajkumar and Sekhon G.S. 1981. Nitrification inhibitors for low land rice. *Fertilizer News*, **26** : 13.
- Ramaiah, N.V., Satyam, Y. Ramamurthy, V., Reddy, S.N., Raju, M.S. and Singh, B.G. 1986. Effect of nitrogenous fertilizers and nitrification inhibitors on dry matter production and nitrogen uptake in wetland rice. *Oryza*, **23** : 37-41.
- Rantz, S.E. and Eakin T.E. 1971. A summary of methods for the collection and analysis of basic hydrologic data for arid regions. U.S. Geol. Surv. Open File Rep. Water Resources, Div., 125 pp.
- Rao, C.X. and Maurer, E.P. 1996. A simplified model for predicting daily transmission losses in a stream channel. *Water Resources Bulletin*, **32** (6) : 1139-1146.
- Rao, D.L.N. 1987. Slow release urea fertilizers - effect on flood water chemistry, ammonia volatilization and rice growth in an alkali soil. *Fertilizer Research*, **13** : 209-221.
- Rao, K.V. 1995. Decision support system for conjunctive use in irrigation projects. Ph.D. thesis. Division of Agricultural Engineering. Indian Agricultural Research Institute, New Delhi.
- Rao, N.H. 1985. Operational Management of Irrigation systems for single and multiple crops. Ph.D. Thesis, Department of Civil Engineering, Indian Institute of Technology, New Delhi, India.
- Rao, N.H. 1987. Field Test of a simple soil water Balance Model for Irrigated Area. *J. Hydrology*, **91** : 179-186
- Rao, N.H. 1990. Seepage losses from Canal irrigation schemes. Influence of surface and sub surface conditions and implications for conjunctive use. *Water Resource Development*, **6** (1) : 55-62.
- Rao, N.H. 1991. Irrigation scheduling with limited water supplies. *Central board of irrigation and power publication No.218*, pp.108.
- Rao, N.H. 1993. Aquifer recharge by seepage losses from canals *Sadhana*, Vol. **18**, Part 6, pp 999-1008.

- Rao, N.H. and Rees, D.H. 1992. Irrigation scheduling of rice with a crop growth simulation model. *Agricultural Systems*, **39** : 115-132.
- Rao, N.H. and Sarma, P.B.S. 1982. Recharge to finite aquifers from strip basins. *J. of Hydrology* (Netherlands). Vol. **66** : 245-252.
- Rao, N.H. and Sarma, P.B.S. 1984. Recharge to finite aquifers with mixed boundaries. *J. of Hydrology*, Vol., **74** : 43-51.
- Rao, N.H. and Sarma, P.B.S. 1988. Water resources utilization in irrigation project areas in India. *Water Resources Development*, **4** (1) : 198-207.
- Rao, N.H., Sarma, P.B.S. and Chander, S. 1990. Optimal multicrop allocation of seasonal and intraseasonal irrigation water. *Water Resources Research*, **26** (4) : 551-559.
- Rao, P.S.C., Jessup, R.E. and Reddy, K.R. 1984. Simulation of nitrogen dynamics in flooded soils. *Soil Science*, **138** (1) : 54-62.
- Rao, V.V. 1992. Studies on water management in irrigation canal command areas - A case study. Ph.D thesis. Division of Agricultural Engineering. Indian Agricultural Research Institute, New Delhi.
- Rao, V.V. and Sarma, P.B.S. 1993. Regional groundwater modelling using finite element method. A Case study. Proceedings, Session III, International conference on hydrology and water resources, Kluwer Publications, Netherlands.
- Rashid, A.L., Hasan, Y., and Remy, D. 1988. Numerical modelling of solute transport patterns in the Dammam aquifer. *Water Resources Bulletin*, **24** (1) : 77-85.
- Reddy, G.R.S. and Patrick W.H. Jr. 1986. Denitrification losses in flooded rice soils. *Fertilizer Research* **9** : 99-116.
- Reddy, K.R. and W.H. Patrick Jr. 1986a. Denitrification losses in flooded rice fields. *Fertilizer Research* **9** : 99-116.
- Reddy, K.R. Patrick, W.H. and Phillips, R.E. 1978. The role of nitrate diffusion in determining the order and rate of denitrification in flooded soil. I. Experimental results. *Soil Sci. Soc. Am. J.* **42** : 268-272.
- Reddy, V.R.M. and Mishra, B. 1983. Effect of altered soil urease activity and temperature on ammonia volatilization from surface applied urea. *J. Indian Soc. Soil Sci.* **31** : 143-45.
- Reddy, V.R.M. Mishra, B. and Sharma, R.D. 1986. Ammonia volatilization from three mollisols following surface application of urea under laboratory conditions. *J. Indian Soc. Soil Sci.* **34** : 43-46.
- Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* **8** (5) : 1204-1213.
- Roaza, H., Roaza, R.M., and Jeffry, R.W. 1993. Integrating Geographic Information systems in groundwater applications using numerical modelling techniques. *Water Resources Bulletin* **29** (6) : 981-988.
- Robert, A.M., David, E.D. and Robert, L.S. 1993. Optimal groundwater management 2. Application of simulated annealing to a field scale contamination site. *Water Resour. Res.* **29** (4) : 847-860.
- Robertson, J.B. 1974. Digital modeling of radioactive and chemical waste transport in the snake river plain aquifer at the national reactor testing station, Idaho. USGS Open-file Report. IDO - 22054, 41 pp.

- Robson, S.G. 1974. Feasibility of digital water quality modeling illustrated by application at Barstow, California, U.S. Geological survey water resources investigations 46-73
- Rogowski, A.S. 1996 GIS modelling of recharge on a watershed. *J Environmental Quality* 25 : 463-474
- Rolston, D.E. 1990. Modelling of denitrification. Approaches, success and problems. In : *Proc. Int. Workshop on denitrification, soil, rhizosphere and aquifer* Glessen FRG March 17-19, 1989.
- Rolston, D.E. and Marino, M.A. 1976. Simultaneous transport of nitrate and gaseous denitrification products in soil. *Soil Sci. Soc. Am. J.* 40 (6) : 860-865
- Rose, C.W., Chichester, F.W., Williams, J.R. and Ritchie, J.T. 1982. Application of an approximate analytic method of computing solute profiles with dispersion in soils. *J. Environ. Qual.*, 11 : 151-155.
- Rushton, K.R. 1975. Aquifer analysis of Lincolnshire Limestone using mathematical models. *Journal Inst. Water Eng. (London)*, 29 : 373-389
- Rushton, K.R. 1988. Numerical and conceptual models for recharge estimation in arid and semi-arid zones. L. Simmers (ed), *Estimation of Natural Groundwater Recharge*, 223-238.
- Rushton, K.R. and S.C. Redhaw, 1979. Seepage and groundwater flow. John Wiley & Sons, New York, 339 pp.
- Rushton, K.R. and Ward, C. 1979. The estimation of groundwater recharge. *J. Hydrology*, 41 : 345-361.
- Sahrawat, K.L. 1979a. Nitrogen losses in rice soils. *Fertilizer News* 24 : 38-48
- Sahrawat, K.L. 1980. Nitrogen mineralization in acid sulphate soils. *Plant soil*, 57 : 143-146
- Sahrawat, K.L. 1980. Urease activity in tropical rice soils and floodwater. *Soil biology & Biochemistry*, 12 : 195-196.
- Sahrawat, K.L. 1983. Nitrogen availability indices for submerged rice soils. *Adv. Agron.*, 36 : 415-451.
- Sahrawat, K.L. and Burford, J.R. 1982. Modification of the alkaline permanganate method for assessing the availability of soil nitrogen in upland soils. *Soil Science*, 133 : 53-57.
- Saleh, A.R., Bengtson, R.L. and Fouss, J.L. 1994. Performance of the DRAINMOD-CREAMS model with an incorporated nutrient submodel. *Trans. of ASAE*, 37 (4) : 1109-1114
- Sanchez, P.A. 1973. Puddling tropical rice soils. 2. Effects of water losses. *Soil Science*, 11 : 303-308.
- Sankhayan, S.D. and Shukla, U.C. 1976. Rate of urea hydrolysis and ammonia volatilization in soil. *Soil Sci. Soc. Am. Proc.*, 31 : 57-61
- Sannigrahi, A.K. and Mandal, L.N. 1987. Mineralization of slow release nitrogenous fertilizers in soils. *J. Indian Soc. Soil Sci.*, 35 : 10-18.
- Santra, G.H., Das, D.K. and Mandal, L.N. 1994. Losses of nitrogen through leaching from flooded rice soils. *J. Indian Soc. Soil Sci.*, 42 (3) : 452-454
- Saregumba, J.L., Pritchelt, W.L. and Smith, W.H. 1978. Transformation of urea in a lean fine sand under four soil moisture regimes. *Proc. Soil. Crop Sci. Soc. Florida*, 37 : 146-150.

- Sarma, P.B.S., Ashwani kumar, P., Tiwari, P.N. and sharma, S.K 1986. Chapters 8,9,10 and 11 on water resources and irrigation management. Resource analysis for integrated development, Sultanpur district, U.P. pp.220-327. Ed. P.B.S. Sarma (ICAR publication).
- Sarma, P.B.S. and Immaraj, A. 1990. Estimation of aquifer parameters through identification problem. *Hydrology Journal of Indian Association of Hydrology* 13 (1) : 13-24
- Sarma, P.B.S. and Mani .A.1992 . A simple soil water balance model. *Hydrology Journal* Vol 3 & 4:pp.13-20.
- Sarma, P.B.S., Rao, N.H. and Rao, K.V.P. 1980. Calculation of water balance in crop root zone by computer. *J. Hydrology*, 45 (1-2) : 123-131
- Savant, N.K. and De Datta, S.K. 1980. Movement and distribution of ammonium-N following deep placement of urea in a wetland rice soils. *Soil Sci. Soc. Am. J.* 44 : 559-565
- Savant, N.K. and De Datta, S.K. 1982. Nitrogen transformation in wetland rice soils. *Adv. Agron.* 35 : 241-302.
- Savant, N.K. and De Datta, S.K. and Craswell E.T. 1982. Distribution patterns of ammonium nitrogen and ^{15}N uptake by rice after deep placement of USG in wetland rice. *Soil Sci. Soc. Am. J.* 46 : 567-573.
- Savant, N.K. James, A.F. and Mc Clellan, G.H. 1985. Effect of soil submergence on urea hydrolysis. *Soil Science*, 140 : 81-88.
- Schaffraner, R.W., Baltzer, R.A. and Goldberg, D.E. 1981. A model for simulation of flow in singular and interconnected channels. (In) *Techniques of water resources investigations of the United States Geological Survey*, Book 7, U.S. Geological Survey, Washington, D.C.
- Schaller, J. 1992. GIS application in environmental planning and assessment. *Computer Environment Urban systems*, 16 : 337-353.
- Schepers, J.S., Franks, K.D. and Bourgs, 1986. Effect of yield goal and residual soil nitrogen consideration on fertilizer BMPs for irrigated maize in Nebraska. *J. Fert. Issues*
- Segerlind, L.J. 1976. Applied finite element analysis. John Wiley and sons, Inc. New York.
- Sen, H.S. and Bandyopadhyay, B.K. 1986. Effect of placement, Urease inhibitors and acidic amendments on ammonia volatilization from wetland rice field fertilized with urea. *J. Indian Soc. Soil. Sci.* 34 : 514-519.
- Seyfried, M.S. and Rao, P.S.C. 1988. Kinetics of nitrogen mineralization in costa Rican Soils. Model Evaluation and pretreatment effects. *Plant and Soil*, 106 : 159-169.
- Shaffer, M.J. and Dutt, G.R. 1973. Nitrification in soil water systems - A computerized activated complex model. *Proceedings of the first world congress on water Resources*, Chicago, Illinois, September, 24-28, 4 : 284-294.
- Sharma, B.D. and Gupta, I.C. 1989. Effect of rate and source of nitrogen moisture content of soil on ammonia volatilization from sandy soils. *J. Indian Soc. Soil. Sci.* 37 : 665-669.
- Sharma, P.K. and De Datta, S.K. 1985. Puddling influence on soil, rice development, and yield. *Soil Sci. Soc. Am. J.* 49 : 1451-1457.
- Sharpley, A.N. and Williams, J.R. (Eds.). 1990. EPIC - Erosion Productivity Impact calculator : (1) : Model Documentation, pp 235. (2) User's manual. pp 127. U.S.D.A. Technical Bulletin No. 1768.

- Shimura, H., 1987 Requirements for modernization of paddy field irrigation-based on Japanese experience. *J. Irrig. Eng. Rural Plann.*, **12** : 1-3
- Shukla, R.K. and Sharma, R.S. 1994 Uptake and recovery of nitrogen in transplanted rice under different sources and levels of nitrogen. *Oryza*, **31** : 43-46
- Simpson, J.R., Freney, J.R., Wetselaarr, R., Muirhead, W.A., Leuning, R. and Denmead, O.T. 1984. Transformation and losses of urea nitrogen after application to flooded rice. *Aust. J. Agric. Res.* **35** : 189-200
- Simpson, J.R., Freney, J.R., Muirhead W.A. and Leuning, R. 1985 Effects of phenyl phosphorodiamidate and dicyanidamide on N loss from flooded rice. *Soil Sci. Soc. Am. J.* **49** : 1426-1431.
- Singandhupe, R.B. and Rajput, R.K. 1990. Nitrogen uptake by rice as influenced by irrigation regime and nitrogen in sodic soil. *J. Indian Soc. Soil Sci.* **38** : 297-303
- Singh, G.R. and Singh, T.A. 1989. Relative efficiency of urea and urea supergranules in rice. *J. Indian Soc. Soil. Sci.* **37** : 725-731.
- Singh, J.P., Dahiya, D.J. and Vinod Kumar. 1995 Effect of water depth and initial soil water content on the volatilization losses of ammonia. *J. Indian Soc. Soil Sci.* **43** (2) : 177-182.
- Singh, K.N. and Prasad, B. 1991. Cumulative volatilisation loss of ammonia from calcareous wetland rice fields. *Oryza*, **28** : 477-479.
- Singh, K.N. and Prasad, B. 1992. Volatilization loss of ammonia as influenced by integrated nutrient management in calcareous soils. *J. Indian Soc. Soil Sci.* **40** : 82-86
- Smith, J.D. 1979. Stream hydraulic package - Computer program description. Resource Management Associates, Lafayette, California
- Smith, M. 1992. CROPWAT-A computer programme for irrigation planning and management. *irrigation and drainage Paper 46, Food and Agriculture Organization, Rome*
- Smith, S.J., Ahuja, L.R. and Ross, J.D. 1984. Leaching of a soluble chemical under field crop conditions. *Soil Sci. Soc. Am. J.* **48** : 252-258
- Sondhi, S.K., Rao, N.H. and Sarma, P.B.S. 1989. Assessment of groundwater potential for conjunctive water use in a large irrigation project in India. *J. of Hydrology*, **107**, pp 283-295.
- Sophocleous, M. and Pary, C.A. 1985. Experimental studies in natural groundwater recharge dynamics. The analysis of observed recharge events. *J. Hydrology*, **81** : 297-332.
- Spalding, R.F. and Exner, M.E. 1993. Occurrences of nitrate in groundwater A review. *J. Environ. Qual.* **22** : 392-402.
- Spalding, R.F., Exner, M.O., Lindau, C.W. and Eaton, D.W. 1982. Investigation of sources of groundwater nitrate contamination in the burbank Wallula area of Washington. *U.S.A. J. Hydrology*, **58** : 307-324.
- Sreedevi, B. and Thangamuthu, G.S. 1991. Studies on NPK Uptake by rice under integrated nitrogen management. *Oryza*, **28** : 255-56.
- Sreenivasulu, P., Jagmohan Das, G. and Choudary, K.V.L.N.P. 1984. Finite Element Analysis of inhomogeneous aquifers. *Proc. of the National workshop on water resources development management*, Warangal, Andhra Pradesh

- Stanford, G. and Smith, S.J. 1972. Nitrogen mineralization potentials of soils. *Soil Sci Soc. Am. Proc.* **36** : 465-472
- Stephens, D.B. and Knowlton, R. 1986. Soil water movement and recharge through sand at a semi arid site in New Mexico. *Water Resour. Res.* **22** : 881-889.
- Stockle, C.C., Martin, S.A. and Campbell, G.S. 1994. Crop syst. a cropping systems simulation model: Water/nitrogen budgets and crop yield. *Agricultural systems* **46** : 335-359
- Stockle, C.O. and Campbell, G.S. 1989. Simulation of crop response to water and nitrogen : An example using spring wheat. *Trans of the ASAE*. **32** : 60-68
- Stoertz, M.W., and Bradbury, K.R. 1989. Mapping recharge areas using a groundwater flow model - A case study. *Groundwater*. **27(2)** : 220-228
- Strecker, E.W., and Chu, W. 1986. Parameter identification of a groundwater contaminant transport model. *Groundwater*, **24** (1) : 56-62.
- Strelkoff, T. 1969. One dimensional equations of open-channel flow. *Journal of Hydraulic Engineering Division, ASCE*, **95** (3) : 861-876.
- Sudhakara, K. and Prasad, R. 1986. Ammonia volatilization losses from prilled urea, urea supergranules (USG) and coated USG in rice fields. *Plant and Soil*. **94** : 293-295
- Suresh, S., Velu, V. and Ramaswami, P.P. 1994. Dynamics of nitrogen forms in the leachate in relation to yield and nitrogen uptake by Rice. *J Indian Soc. Soil Sci.* **42** : 398-401.
- Suresh, S., Velu, V. and Ramaswami, P.P. 1994. Leaching loss of nitrogen from different nitrogen sources in wetland rice soil. *Oryza*, **31** : 213-18
- Swain, L.A. 1978. Predicted water-level and water quality effects of artificial recharge in the upper coachella Valley, California, Using a Finite Element Digital Model U.S. Geol. Survey Water Resources investigation, 77-129.
- SWRRB. 1990 A Basin scale simulation model for soil and water resources management. by Arnold, J.G. Williams, J.R., Nicks, A.D. and Sammons, N.B. Texas A & M University, Texas, USA.
- Tabatabai, M.A. and Al-khafafi, A.A. 1980. Comparison of nitrogen and sulfur mineralization in soils. *Soil Sci. Soc. Am. J.* **44** : 1000-1006.
- Tabbal, D.F., R.M. Lainpayan and Bhuiyan, S.I. 1992. Water-efficient irrigation technique for rice. In (ed V.V. Murthy and Koga, K.) . *Soil and Water Engineering for paddy field management*. Asian Institute of Technology, Bangkok, Thailand. pp 146-159
- Tahir, Ali and Singh, T.A. 1994. Nitrogen use efficiency and ammonia volatilization potential in flooded rice as affected by modified urea materials. *J Indian Soc. Soil Sci.* **42** : 536-539.
- Taylor, R.G. and Howard, K.W.F. 1996. Groundwater recharge in the victoria Nile basin of east Africa. Support for the soil moisture balance approach using stable isotope tracers and flow modelling. *J. of Hydrology (Amsterdam)* **180** (1/4) : 31-53
- Teresa, B.C. and Christine, A.S. 1993. Optimal control for groundwater remediation by differential dynamic programming with quasi-newton approximations. *Water Resour. Res.* **29** (4) : 823-831.
- Thangaraj, T. and Muthuswami, S. 1990. (In) Fruits - Tropical and subtropical (eds.) Bose, T.K. and Mitra, S.K. 1990. Nayaprakash Publishers, Calcutta, India. pp. 336-385.
- Thompson, N., Barrie, I.A. and Ayles, M. 1981. The meteorological office rainfall and evaporation calculation system : MORECS (July 1981) Hydrological memorandum 45, Met Office, Braknel, UK.
- Thorat, S.T. and Patil, B.P. 1987. Nitrogen uptake by early rice cultivars as influenced by nitrogen fertilization and plant density. *Oryza*. **24** : 262-64

- Tim, U.S. and Jolly, R. 1994. Evaluating agricultural nonpoint source pollution using integrated geographic information systems and hydrologic/water quality model. *J Environ Qual.* **23** : 25-35.
- Tomar, J.S., Kirby P.C. and Mackenzie, A.F. 1985. Field evaluation the effects of a urease inhibitors and crop residues on urea hydrolysis. *Canadian J Soil Sci.* **65** (4) : 777-787.
- Torben, O.S., Peter, E., and Rosbjerg, D. 1996. Contaminant transport at a waste residue deposit 1. Inverse flow and non-reactive transport modelling. *Water Resour. Res.* **32** (4) : 925-938.
- Trescott, P.C. and Larson, S.P. 1977. Comparison of iterative methods for solving two-dimensional groundwater flow equations. *Water Resour. Res.* **13** (1) : 125-136.
- Tyson, H.R. and Webber, E.M. 1964. Groundwater management for the Nation's future-computer simulation of groundwater basins. *Journal of Hydraulics Division* ASCE **90** (HY4), 59-77.
- U.S. Bureau of Reclamation, 1967. Design standards No. 3 Canals and Related Structures Denver, Colorado, pp 1-2.
- U.S. Bureau of Reclamation, 1977. Groundwater manual U.S. Department of Interior Washington.
- USDA, 1972. National Engineering Handbook, Section 4. Hydrology, United States Department of Agriculture. Soil Conservation service, USA.
- Varade, S.B. and Ghildyal, B.P. 1967b. Mechanical impedance and growth of paddy in artificially compacted lateritic sandy loam soil. *J. of Indian Soc Soil Sci.* **15**(3) : 157-162.
- Vassilis, Z.A. 1993. Simulation of water and nitrogen dynamics in soils during waste water applications by using a finite element model. *Water Resources Management*, **7** : 237-251.
- Verma, A., Kanwar, R.S. and Tim, U.S. 1995. Modification of Drainage Model by using the nitrogen component from the GLEAMS Model. *Trans. of ASAE*. **38** (3) : 717-724.
- Verstraeten, L.M.J. 1978. Interaction between urease activity and soil characteristics. *Agrochimica* **22** : 455-464.
- Vlek, P.L.G. and Craswell, E.T. 1979. Effect of nitrogen sources and management on ammonia volatilization losses from flooded rice system. *Soil Sci. Soc. Am. J.* **43** : 352-356.
- Vlek, P.L.G. and Craswell, E.T. 1981. Ammonia volatilization from flooded soils. *Fertilizer Research*, **2** : 247-259.
- Vlek, P.L.G. and Stumpe, J.M. 1978. Effect of solution chemistry and environmental condition on ammonia volatilization losses from aqueous systems. *Soil Sci. Soc. Am. J.* **42** : 416-421.
- Voinova - Raikova, Z. 1977. Biological immobilization of fertilizer N in the soil. In Soil Biology Section of the Soc. for Soil Sci. of the Hungarian Assoc. of Agric. Sciences held at Keszthely Univ. of Agric. in Sept. 1975.
- Vyas, S.K. and Sarma, P.B.S. 1992. An Analytical model for estimation of flows at various locations in a canal command Area. *Journal of Irrigation and Power*. **48** (1) : 125-137.
- Wagner, B.J. 1992. Simultaneous parameter estimation and contamination source characterization for coupled groundwater flow and contaminant transport modelling. *J Hydrology*, **135** : 275-303.
- Wagner, B.J. and Gorelick, S.M. 1987. Optimal groundwater management under parameter uncertainty. *Water Resour. Res.*, **23** (7) : 1162-1174.
- Wagenet, R.J. and Rao, B.K. 1983. Description of nitrogen movement in the presence of spatially variable soil hydraulic properties. *Agricultural water management*, **6** : 227-242.
- Walker, W.R. and Skogerboe, G.V. 1987. Surface Irrigation, Theory and Practice, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

- Watanabe, T. 1992. Water Budget in paddy fields (In) V.V.N. Murthy and K. Koga (eds.), *Soil and Water engineering for paddy field management*, 1-11 Asian Institute of Technology, Bangkok, Thailand.
- Watts, D.G. and Hanks, R.J. 1978. A soil water nitrogen model for irrigated corn on sandy soils. *Soil Sci. Soc. Am. J.* **42** : 492-499.
- Wesseling, J.G. and Van Den Brock, B.J. 1988. Prediction of irrigation scheduling with the numerical model SWATRE, *Agricultural water management*, **14** : 299-306.
- Wickham, T.H. and Singh, V.P. 1978. Water movement through wet soils. In *Soils and Rice*. Intern. Rice Research Institute, Los Banos, Philippines, pp 37 - 357.
- Wickham, T.H. and Singh, V.P. 1978. Water movement through wet soils. In *Soils and Rice*. Intern. Rice Research institute, Los Banos, Philippines, pp 37-357.
- Wiklander, L. 1977. Leaching of plant nutrients in soils. IV contents in drainage water and groundwater. *Acta. Agric. Scand*, **27** : 175-189.
- Wilson, J.P., Inskeep, W.P., Rubright, P.R., Cooksey, D., Jacobsen, J.S. and Snyder, R.D. 1993. Coupling geographic information systems and models for weed control and groundwater protection. *Weed Technol*, **7** : 255-264.
- Wilson, J.P., Inskeep, W.P., Wraith, J.M. and Snyder, R.D. 1996. GIS based solute transport modelling applications - Scale effects of soil and climatic data input. *J Environ Qual* **25** : 445-453.
- Xevi, E., Gilley, J. and Feyen, J. 1996. Comparative study of two crop yield simulation models. *Agricultural Water management*, **30(2)** 155-177.
- Yoshida, S. 1981. Fundamentals of rice crop science. International Rice Research Institute, Los Banos, Philippines, 269 pp.
- Yoshida, T. and Padre, B.E. 1975. Effect of organic matter application and water regime on the transformation of fertilizer nitrogen in a Philippine soil. *Soil Sci Plant Nutr*, **21** : 281-292.
- Young, R.A., Onstad, C.A., Bosch, D.D. and Anderson, W.P. 1987. Agricultural Nonpoint source pollution Model (AGNPS) : A watershed analysis tool. US Department of Agriculture Research Service. Conservation Research Report 35. Washington. USDA - ARS.
- Younger, P.L., Mackay, R. and Connorton, B. 1993. Streambed sediment as a barrier to groundwater pollution - Insights from field work and modelling in the river Thames basin. *J. Inst. Water Environ. Mang.* **7** : 577-585.
- Yukuma, K., 1989. Historical development of rice cultivation and its water management. *J Irrig. Eng. Rural Plann.* **16** : 60-70.
- Zienkiewicz, O.C. 1971. The finite element method in engineering science. Mc Graw-Hill, London, page 93.
- Zienkiewicz, O.C., Mayer, P. and Choung, Y.K. 1966. Solutions of anisotropic seepage by finite elements. *J. Engg. Mech. ASCE*. Vol. 92. EMI.

APPENDIX - A

Particulars of pumping test data for the study area

Location : Surasani yanam, Uppalaguptam Mandal

1.	Date of test	12-03-1992
2	Geology	Coastal alluvium
3	Particulars of pump used	22.5 HP
4.	Method of discharge	Volumetric
5	Duration of pumping	240 minutes
6	Discharge	1385 lpm
7	Transmissibility	3580.88 m ² /day
8	Specific capacity	511 lpm/mdd

Location : Mandapeta, 16°51'37"

1	Date of test	23-06-1977 to 06-07-1977
2	Geology	Coastal alluvium
3	Particulars of pump used	Submersible (20 HP)
4	Transmissibility	3826 m ² /day
8	Specific capacity	500 lpm-mdd

(Source : NH TR-166, 1991-92)

SAMPLE INPUT DATA OF CANAL DISCHARGES FOR CANAL FLOW MODEL (1994-1996)

GANNAVARAM CANAL:

INPUT DATA FILE : GCFLOW

1994 1995

27.1,39

21.6,95

464.0	464.0	464.0	487.0	464.0	466.0	466.0	372.0	350.0	350.0
350.0	292.0	265.0	265.0	282.0	282.0	282.0	282.0	303.0	303.0
400.0	413.0	441.0	516.0	596.0	619.0	697.0	697.0	1021.0	696.0
742.0	742.0	774.0	742.0	696.0	821.0	732.0	835.0	657.0	696.0
735.0	833.0	772.0	701.0	732.0	823.0	788.0	788.0	788.0	741.0
774.0	826.0	774.0	774.0	611.0	434.0	433.0	454.0	456.0	619.0
588.0	619.0	556.0	556.0	530.0	619.0	603.0	613.0	722.0	603.0
603.0	657.0	742.0	784.0	700.0	700.0	700.0	613.0	700.0	657.0
744.0	700.0	700.0	614.0	700.0	700.0	824.0	824.0	824.0	601.0
804.0	722.0	671.0	794.0	722.0	722.0	613.0	556.0	557.0	650.0
595.0	595.0	569.0	567.0	575.0	567.0	603.0	670.0	660.0	637.0
653.0	690.0	690.0	619.0	619.0	811.0	735.0	735.0	931.0	849.0
857.0	821.0	813.0	865.0	649.0	567.0	567.0	716.0	310.0	350.0
262.0	88.0	108.0	92.0	75.0	170.0	217.0	237.0	0.0	321.0
439.0	324.0	343.0	343.0	343.0	343.0	343.0	343.0	361.0	361.0
361.0	361.0	361.0	361.0	294.0	232.0	192.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	216.0	206.0	196.0	241.0
284.0	784.0	340.0	340.0	340.0	397.0	397.0	428.0	433.0	423.0

503.0	503.0	516.0	433.0	412.0	603.0	603.0	650.0	650.0	650.0
650.0	824.0	830.0	697.0	697.0	697.0	792.0	845.0	849.0	893.0
886.0	774.0	886.0	886.0	890.0	865.0	832.0	835.0	835.0	835.0
835.0	835.0	788.0	788.0	788.0	788.0	728.0	783.0	783.0	783.0
783.0	700.0	700.0	650.0	650.0	650.0	650.0	619.0	619.0	619.0
619.0	588.0	464.0	464.0	464.0	464.0	464.0	464.0	490.0	517.0
657.0	618.0	657.0	700.0	700.0	744.0	788.0	790.0	877.0	750.0
826.0	826.0	774.0	826.0	758.0	758.0	0.0	772.0	772.0	832.0
832.0	832.0	702.0	702.0	774.0	874.0	826.0	826.0	848.0	826.0
826.0	851.0	795.0	851.0	851.0	851.0	851.0	794.0	0.0	738.0
774.0	774.0	774.0	880.0	816.0	816.0	826.0	826.0	826.0	826.0
735.0	0.0	0.0	0.0	789.0	789.0	789.0	789.0	696.0	696.0
735.0	696.0	516.0	576.0	545.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1995	1996								
18.1.47									
20.6.96									
461.0	470.0	547.0	553.0	518.0	660.0	578.0	508.0	727.0	726.0
692.0	675.0	675.0	686.0	688.0	665.0	608.0	784.0	745.0	727.0
748.0	720.0	623.0	664.0	692.0	715.0	733.0	654.0	759.0	474.0
692.0	798.0	800.0	850.0	856.0	856.0	846.0	775.0	852.0	803.0
656.0	659.0	659.0	584.0	557.0	446.0	294.0	258.0	507.0	260.0
254.0	263.0	594.0	688.0	747.0	740.0	705.0	647.0	714.0	734.0
714.0	685.0	712.0	572.0	761.0	779.0	961.0	754.0	657.0	657.0
754.0	658.0	669.0	732.0	775.0	761.0	761.0	775.0	789.0	754.0
818.0	818.0	801.0	839.0	834.0	818.0	551.0	669.0	732.0	536.0
692.0	714.0	749.0	759.0	763.0	692.0	646.0	623.0	652.0	789.0
774.0	754.0	668.0	663.0	669.0	624.0	553.0	624.0	554.0	742.0
697.0	684.0	687.0	719.0	715.0	747.0	719.0	706.0	868.0	719.0
719.0	719.0	740.0	725.0	706.0	692.0	706.0	0.0	569.0	569.0
0.0	0.0	218.0	146.0	220.0	240.0	297.0	206.0	315.0	0.0
0.0	0.0	0.0	617.0	530.0	114.0	140.0	150.0	148.0	312.0
260.0	355.0	385.0	453.0	457.0	464.0	247.0	317.0	427.0	434.0
454.0	0.0	457.0	0.0	544.0	300.0	310.0	315.0	464.0	0.0
0.0	472.0	664.0	705.0	450.0	0.0	668.0	682.0	742.0	691.0
701.0	719.0	615.0	614.0	592.0	603.0	603.0	614.0	585.0	759.0
761.0	761.0	763.0	779.0	779.0	754.0	782.0	678.0	602.0	316.0
276.0	294.0	706.0	711.0	711.0	669.0	639.0	728.0	728.0	759.0
759.0	739.0	0.0	539.0	491.0	392.0	390.0	435.0	606.0	606.0
606.0	606.0	620.0	568.0	438.0	402.0	402.0	402.0	700.0	704.0
683.0	683.0	683.0	683.0	683.0	683.0	683.0	536.0	570.0	613.0
613.0	613.0	613.0	619.0	619.0	519.0	693.0	702.0	704.0	648.0
644.0	657.0	657.0	657.0	645.0	651.0	651.0	631.0	631.0	631.0
712.0	704.0	704.0	712.0	712.0	712.0	712.0	712.0	704.0	704.0
704.0	704.0	704.0	785.0	785.0	747.0	751.0	751.0	604.0	704.0
704.0	704.0	704.0	704.0	735.0	735.0	750.0	603.0	516.0	512.0
512.0	522.0	516.0	513.0	526.0	513.0	513.0	513.0	513.0	513.0
522.0	522.0	522.0	513.0	513.0	513.0	512.0	522.0	516.0	516.0
516.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	199.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0				

AMALAPURAM CANAL

1994	1995								
27.1,38									
21,6,95									
541.0	541.0	541.0	541.0	568.0	568.0	433.0	412.0	412.0	412.0
354.0	333.0	333.0	346.0	346.0	346.0	346.0	364.0	364.0	454.0
475.0	545.0	624.0	624.0	738.0	819.0	882.0	701.0	851.0	907.0
851.0	907.0	851.0	722.0	913.0	819.0	929.0	696.0	774.0	774.0
811.0	865.0	784.0	825.0	862.0	974.0	974.0	974.0	916.0	889.0
774.0	649.0	649.0	547.0	475.0	474.0	495.0	474.0	553.0	509.0
593.0	541.0	541.0	541.0	619.0	508.0	542.0	645.0	568.0	593.0
562.0	593.0	743.0	835.0	835.0	835.0	741.0	835.0	835.0	882.0
835.0	835.0	788.0	835.0	835.0	835.0	835.0	835.0	568.0	835.0
824.0	774.0	788.0	742.0	742.0	700.0	686.0	411.0	567.0	576.0
516.0	557.0	0.0	619.0	567.0	703.0	670.0	737.0	737.0	735.0
737.0	612.0	713.0	713.0	737.0	812.0	812.0	1028.0	953.0	983.0
838.0	865.0	784.0	737.0	737.0	593.0	541.0	412.0	258.0	147.0
162.0	184.0	147.0	123.0	237.0	283.0	322.0	332.0	296.0	361.0
412.0	412.0	412.0	412.0	412.0	412.0	412.0	412.0	412.0	433.0
433.0	433.0	433.0	258.0	218.0	219.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	268.0	323.0
323.0	374.0	374.0	374.0	510.0	567.0	650.0	619.0	642.0	692.0
611.0	568.0	567.0	619.0	648.0	811.0	925.0	925.0	925.0	925.0
902.0	927.0	902.0	902.0	902.0	902.0	920.0	886.0	949.0	949.0
826.0	788.0	788.0	784.0	784.0	833.0	836.0	833.0	722.0	722.0
722.0	722.0	794.0	774.0	774.0	774.0	735.0	735.0	735.0	735.0
735.0	735.0	725.0	735.0	735.0	735.0	833.0	774.0	774.0	774.0
788.0	740.0	788.0	788.0	788.0	788.0	876.0	877.0	863.0	920.0
813.0	920.0	866.0	813.0	788.0	833.0	833.0	877.0	758.0	835.0
929.0	826.0	789.0	835.0	835.0	835.0	809.0	809.0	784.0	784.0
877.0	908.0	908.0	794.0	794.0	826.0	784.0	818.0	826.0	826.0
826.0	826.0	826.0	826.0	826.0	826.0	794.0	794.0	794.0	826.0
826.0	826.0	774.0	848.0	848.0	789.0	789.0	789.0	789.0	744.0
744.0	744.0	744.0	722.0	759.0	650.0	681.0	593.0	593.0	619.0
593.0	567.0	561.0	593.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	130.0					
1995	1996								
18,1,48									
22,6,94									
461.0	509.0	590.0	534.0	469.0	955.0	465.0	764.0	818.0	830.0
789.0	872.0	878.0	868.0	715.0	942.0	691.0	817.0	862.0	785.0
837.0	937.0	745.0	801.0	930.0	840.0	872.0	905.0	949.0	508.0
500.0	784.0	849.0	857.0	935.0	896.0	973.0	981.0	896.0	958.0
960.0	714.0	701.0	715.0	395.0	437.0	456.0	363.0	312.0	300.0
309.0	294.0	309.0	325.0	634.0	621.0	678.0	740.0	647.0	696.0
724.0	791.0	668.0	801.0	617.0	775.0	842.0	953.0	888.0	743.0
789.0	782.0	755.0	744.0	850.0	807.0	820.0	840.0	861.0	856.0
815.0	846.0	846.0	872.0	890.0	913.0	896.0	619.0	723.0	807.0
743.0	734.0	743.0	749.0	692.0	813.0	901.0	780.0	642.0	714.0
921.0	834.0	892.0	647.0	763.0	781.0	691.0	594.0	725.0	436.0
595.0	820.0	680.0	743.0	789.0	780.0	793.0	792.0	868.0	808.0
731.0	731.0	905.0	784.0	775.0	780.0	817.0	826.0	656.0	656.0
656.0	0.0	0.0	259.0	165.0	245.0	278.0	247.0	395.0	243.0
0.0	0.0	0.0	0.0	62.0	63.0	42.0	51.0	47.0	45.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	130.0					
1995	1996								
18,1,48									
22,6,94									
456.0	535.0	571.0	706.0	663.0	863.0	663.0	1085.0	997.0	936.0
893.0	983.0	887.0	938.0	753.0	903.0	759.0	912.0	913.0	992.0
1028.0	1028.0	938.0	908.0	911.0	998.0	998.0	908.0	850.0	684.0
893.0	1006.0	1005.0	1049.0	1054.0	1078.0	1063.0	1060.0	1056.0	1050.0
853.0	851.0	849.0	478.0	460.0	495.0	243.0	167.0	486.0	425.0
154.0	163.0	420.0	663.0	821.0	819.0	793.0	704.0	826.0	840.0
896.0	741.0	826.0	671.0	848.0	911.0	950.0	935.0	605.0	605.0
653.0	689.0	644.0	771.0	898.0	978.0	928.0	953.0	983.0	983.0
955.0	758.0	743.0	948.0	929.0	929.0	676.0	784.0	808.0	576.0
771.0	823.0	839.0	886.0	886.0	890.0	822.0	706.0	781.0	978.0
911.0	933.0	799.0	709.0	717.0	691.0	726.0	520.0	391.0	497.0
505.0	720.0	675.0	797.0	782.0	821.0	811.0	716.0	716.0	712.0
712.0	666.0	807.0	831.0	836.0	819.0	819.0	717.0	717.0	717.0
0.0	0.0	191.0	135.0	157.0	146.0	164.0	308.0	217.0	0.0
0.0	0.0	0.0	612.0	418.0	306.0	345.0	34.0	34.0	391.0
288.0	413.0	439.0	519.0	504.0	513.0	306.0	484.0	496.0	538.0
623.0	623.0	603.0	603.0	716.0	811.0	823.0	751.0	792.0	719.0
748.0	719.0	748.0	903.0	905.0	905.0	821.0	803.0	863.0	1041.0
1065.0	1042.0	577.0	948.0	816.0	978.0	933.0	933.0	959.0	1010.0
1010.0	1010.0	1018.0	1020.0	1020.0	1026.0	1096.0	913.0	913.0	846.0
846.0	797.0	686.0	686.0	686.0	686.0	589.0	391.0	611.0	611.0
611.0	627.0	727.0	727.0	758.0	758.0	742.0	742.0	742.0	742.0
660.0	660.0	660.0	660.0	536.0	536.0	536.0	492.0	492.0	492.0
508.0	513.0	513.0	513.0	513.0	646.0	599.0	609.0	699.0	812.0
812.0	829.0	829.0	829.0	829.0	829.0	829.0	829.0	877.0	720.0
720.0	720.0	703.0	703.0	615.0	615.0	670.0	670.0	713.0	713.0
799.0	798.0	702.0	702.0	702.0	702.0	756.0	728.0	825.0	749.0
749.0	794.0	794.0	695.0	695.0	695.0	695.0	700.0	700.0	700.0
700.0	700.0	700.0	605.0	605.0	605.0	519.0	519.0	509.0	504.0
519.0	519.0	519.0	519.0	519.0	525.0	292.0	292.0	186.0	194.0
172.0	195.0	195.0	195.0	195.0	195.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	510.0	780.0	456.0	480.0	480.0	480.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0				

MAIN CANAL

1994	1995								
25,1,39									
21,6,96									
1762.2	1824.3	1572.9	1847.3	1760.2	1638.0	1379.7	1199.4	1177.4	1177.4
1093.3	982.1	955.1	1000.1	1017.2	1017.2	1017.2	1051.2	1072.3	1302.6
1452.8	1608.0	1809.2	1994.5	2226.7	2561.1	2629.2	2752.8	2849.4	2659.2
2642.2	2766.3	2728.3	2270.8	2598.1	2641.2	2747.3	2288.8	2188.7	2268.8
2384.9	2553.1	2362.9	2380.9	2249.8	2311.8	2300.8	2324.8	2218.7	2241.7
2452.0	2202.7	2004.5	1743.2	1385.7	1220.5	1253.5	1450.8	1590.0	1739.2
1792.2	1744.2	1681.1	1681.1	1797.2	1738.2	1691.1	1966.4	1901.3	1807.2
1744.2	1851.3	2193.7	2449.0	2364.9	2368.9	2003.5	2277.8	2309.8	2368.9
2408.9	2364.9	2209.7	2278.8	2364.9	2364.9	2489.0	2489.0	2113.6	2265.8
2458.0	2303.8	2349.9	2302.8	2354.9	2072.5	1896.3	1474.8	1618.0	1902.4

1753.2	1765.2	1210.5	1860.3	1834.3	1985.4	1822.3	1775.2	1781.2	1815.2
1845.3	1976.4	2079.6	2118.6	2356.9	2624.2	2548.1	2742.3	3204.7	2893.4
2662.2	2622.2	2454.0	2511.0	2181.7	1799.2	1718.1	1462.8	837.9	633.5
615.5	492.3	439.1	545.4	542.4	683.6	803.8	833.9	537.3	1071.3
1318.6	1298.6	1317.6	1317.6	1317.6	1317.6	1317.6	1351.7	1335.6	1390.7
1390.7	1390.7	1390.7	1001.1	700.6	566.4	217.6	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	241.7	231.6	715.7	1115.3
1158.4	1672.1	1251.5	1227.5	1337.6	1427.8	1560.9	1534.9	1563.9	1922.4
1887.3	1746.2	1936.4	1987.5	2085.6	2440.0	2461.0	2376.9	2332.8	2332.8
2553.1	2797.3	2873.4	2535.1	2600.1	2535.1	2648.2	2800.3	2779.3	2913.4
2646.2	2563.1	2675.2	2720.3	2678.2	2691.2	2523.0	2425.9	2199.7	2199.7
2199.7	2312.8	2429.9	2497.0	2270.8	2367.9	2179.7	2234.7	2234.7	2234.7
2272.8	2240.7	2282.8	2242.7	2242.7	2242.7	2336.8	2191.7	2109.6	2004.5
2082.6	2048.5	1979.4	2024.5	1979.4	1979.4	2009.5	2273.8	2288.8	2372.9
2016.5	2474.0	2554.1	2537.1	2512.0	2513.0	2640.2	2474.0	2515.0	2520.0
2691.2	2588.1	2499.0	2727.3	2659.2	2659.2	1734.1	2546.1	2465.0	2471.0
2508.0	2666.2	2536.1	2431.9	2504.0	2701.2	2611.1	2634.2	2610.1	2588.1
2588.1	2613.1	2291.8	2321.8	2422.9	2338.8	2306.8	2249.8	1600.0	2444.0
2480.0	2466.0	2402.9	2760.3	2700.2	2630.2	2619.1	2619.1	2551.1	2426.9
2335.8	1600.0	1600.0	1477.8	2304.8	2138.6	2169.7	2026.5	1933.4	1991.5
1972.4	1874.3	1658.1	1813.2	571.4	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	285.8					
1995	1996								
14,1,50									
21,6,96									
1405.7	1541.9	1736.1	1821.3	1678.1	2507.0	1734.1	2385.9	2571.1	2521.0
2402.9	2559.1	2469.0	2521.0	2184.7	2539.1	2086.6	2542.1	2549.1	2533.1
2642.2	2714.2	2334.8	2405.9	2562.1	2582.1	2632.2	2496.0	2587.1	1694.1
2113.6	2617.1	2683.2	2785.3	2874.4	2859.4	2911.4	2845.4	2833.4	2840.4
2498.0	2252.8	2237.7	1805.2	1439.8	1405.7	1020.2	814.8	1332.6	1012.2
743.7	746.7	1350.6	1704.1	2230.7	2208.7	2204.7	2119.6	2215.7	2298.8
2362.9	2245.7	2234.7	2072.5	2254.8	2494.0	2782.3	2671.2	2178.7	2033.5
2224.7	2157.6	2096.6	2275.8	2552.1	2575.1	2538.1	2597.1	2662.2	2622.2
2617.1	2451.0	2418.9	2688.2	2682.2	2689.2	2151.6	2100.6	2291.8	1947.4
2234.7	2299.8	2359.9	2422.9	2369.9	2423.9	2397.9	2137.6	2103.6	2510.0
2635.2	2550.1	2387.9	2047.5	2177.7	2124.6	1998.5	1766.2	1698.1	1703.1
1825.3	2252.8	2070.5	2287.8	2314.8	2376.9	2351.9	2242.7	2481.0	2267.8
2190.7	2144.6	2481.0	2368.9	2345.9	2319.8	2370.9	1570.9	1970.4	1970.4
682.6	0.0	435.1	566.4	568.4	657.6	765.8	787.8	954.1	268.7
0.0	0.0	0.0	1256.5	1037.2	509.3	553.4	260.7	254.7	774.8
930.0	1089.3	1018.2	1417.7	1462.8	1517.9	1097.3	1132.3	1371.7	1495.8
1601.0	1119.3	1556.9	1117.3	1775.2	1740.2	1873.3	1836.3	2027.5	1158.4
1418.7	1862.3	2083.6	2359.9	2192.7	1759.2	2343.9	2284.8	2380.9	2615.1
2635.2	2646.2	2076.6	2496.0	2281.8	2482.0	2448.0	2464.0	2439.0	2711.2
2678.2	2716.2	2706.2	2743.3	2724.3	2705.2	2820.4	2533.1	2517.0	2099.6
2059.5	1991.5	2292.8	2297.8	2287.8	2245.7	2118.6	2009.5	2099.6	1988.5
2149.6	2145.6	1505.9	2045.5	2028.5	1929.4	1952.4	1997.5	2124.6	2124.6
2042.5	2065.5	2175.7	2123.6	1869.3	1833.3	1721.1	1677.1	1975.4	1979.4
1974.4	1979.4	2075.6	2068.5	2068.5	2201.7	2154.6	2027.5	2151.6	2307.8
2307.8	2325.8	2325.8	2344.9	2344.9	2244.7	2418.9	2427.9	2478.0	2264.8
2259.8	2205.7	2188.7	2188.7	2098.6	2104.6	2191.7	2206.7	2249.8	2249.8
2401.9	2392.9	2435.0	2425.9	2314.8	2314.8	2368.9	2340.9	2429.9	2352.9
2389.9	2403.9	2403.9	2356.9	2356.9	2318.8	2322.8	2327.8	2180.7	2234.7
2234.7	2234.7	2234.7	2139.6	2170.7	2170.7	2099.6	1952.4	1775.2	1766.2

1781.2	1791.2	1785.2	1782.2	1795.2	1788.2	1554.9	1389.7	1122.3	1130.3
1087.3	1032.2	1009.2	1016.2	734.7	734.7	538.3	548.4	542.4	542.4
542.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	175.5	175.5
225.6	225.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	536.3	806.8	482.2	506.3	656.6	855.9
223.6	225.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0				

DAILY RAINFALL DATA FOR ALL THE RAIN GAUGE STATIONS LOCATED IN THE STUDY AREA FOR THE YEAR 1995

RAINGAUGE STATION: SAKHINETIPALLI

1995

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.90	0.00
0.00	0.00	26.00	0.00	0.00	0.00	0.00	5.10	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00	9.60	22.90	48.30	157.50	30.30
5.10	0.00	29.00	22.90	83.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00	0.00	0.00	38.10	0.00	0.00
0.00	0.00	0.00	25.90	5.00	0.00	0.00	0.00	58.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31.40	71.70	0.00	0.00	0.00	80.30	47.10	10.40	0.00	14.50
3.80	3.60	13.90	20.00	13.70	87.00	0.00	0.00	1.80	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.90	12.20
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.60
0.00	0.00	3.80	0.00	34.00	20.30	0.00	4.50	10.20	38.20
23.00	43.20	12.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	63.50	7.60	0.00	0.00	3.50	32.60
61.20	89.90	129.50	2.50	10.20	0.00	15.20	45.90	115.30	12.70
6.50	0.00	0.00	38.30	25.60	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00					

RAINGAUGE STATION: MONDEPULANKA

1995

[illegible]

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00	0.00	14.00	18.50	170.00	21.00
14.00	0.00	30.20	13.20	4.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.20	0.00	0.00
0.00	0.00	29.40	5.50	0.00	0.00	0.00	0.00	24.50	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19.00	0.00	8.00	7.00	0.00	27.00	43.00	0.00	0.00	14.00
4.00	4.00	6.00	5.00	6.00	12.00	0.00	0.00	0.00	0.00
0.00	24.00	0.00	1.10	1.00	10.00	0.00	0.10	45.00	45.00
0.00	0.00	0.00	0.00	17.30	0.00	0.00	0.00	0.00	22.10
0.00	21.00	10.00	0.00	0.00	0.00	0.20	10.20	54.00	0.30
2.50	3.52	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	34.00	16.00	0.00	0.00	0.00	0.00
4.30	132.00	35.00	11.00	7.00	0.00	8.00	4.00	117.00	0.00
0.00	0.00	0.00	22.00	0.00	7.00	36.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00					

RAINGAUGE STATION MUKKAMALA

1995

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.40	0.00
0.00	0.00	4.00	0.00	0.00	0.00	0.00	5.80	0.00	0.00
0.00	0.00	0.00	0.00	0.00	4.40	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00	1.00	7.00	39.00	95.00	66.00
25.00	0.00	37.30	10.20	7.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00	0.00	0.00
0.00	10.00	15.30	6.00	0.00	0.00	0.00	2.30	16.30	2.00
1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	60.00	0.00	8.00	19.90	18.00	47.10	30.00	2.20	30.00
2.20	3.50	3.20	6.10	17.00	10.00	2.00	0.00	0.00	0.00
0.00	0.00	0.00	1.00	1.00	10.00	0.00	0.70	45.00	45.00
0.00	0.00	0.00	0.00	17.80	0.00	0.00	0.00	0.00	22.10

0.00	21.80	10.00	0.00	0.00	0.00	1.20	10.20	50.00	0.30
2.00	30.20	21.00	2.40	0.00	0.00	1.00	0.00	0.00	0.00
0.00	0.00	67.00	4.70	8.00	0.00	1.00	0.00	0.00	9.00
11.00	0.00	0.00	14.20	2.00	0.00	0.00	0.00	0.00	4.20
0.00	11.00	0.00	15.00	8.00	0.00	0.00	7.00	4.00	20.00
24.00	134.00	115.00	6.00	2.20	0.00	0.00	7.00	70.00	1.80
7.80	0.00	7.00	0.00	0.00	1.80	1.20	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00					

RAINGAUGE STATION: GOPALAPURAM

1995

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	5.08	0.00	0.00	0.00	0.00	8.89	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	2.54	7.62	24.13	117.50	61.25	8.00
0.00	0.00	47.50	22.50	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00
11.25	10.00	0.00	0.00	0.00	0.00	21.25	21.25	0.00	7.50
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.75	0.00	11.25	0.00	15.50	17.00	82.50	46.25	16.00	3.50
0.00	7.00	9.00	0.00	15.00	8.25	0.00	0.00	0.00	0.00
0.00	10.50	0.00	1.25	11.25	3.75	0.00	21.25	45.50	0.00
0.00	0.00	4.50	6.00	0.00	0.00	0.00	0.00	6.75	0.00
0.00	22.75	0.00	0.00	0.00	3.50	0.00	18.75	2.50	2.50
24.50	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	8.00	10.00	2.50	0.00	15.00	0.00	0.00	0.00	12.50
0.00	0.00	6.75	75.00	0.00	0.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	0.00	0.00	0.00	0.00	11.50	16.50	37.50
0.00	166.00	10.00	8.75	0.00	0.00	26.25	59.25	10.50	13.00
0.00	2.25	20.00	29.00	0.00	6.25	0.00	0.00	0.00	0.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.00	0.00	0.00	0.00	0.00					

APPENDIX - B

SOURCE LISTING FOR SIMPLE CANAL FLOW MODEL

```
C*****
C   PIRRIG1.FOR
C**  PROGRAMME TO FIND OUT SEEPAGE LOSSES IN WATER DISTRIBUTION
C     SYSTEM AND IRRIGATION DEPTHS IN RICE FIELDS FOR DIFFERENT
C     IRRIGATION SCHEDULING PERIODS.
C     PROGRAMME IS ALSO USED FOR DEVELOPMENT OF RATING CURVES
C     FOR ESTIMATION OF SEEPAGE LOSSES
C*****
C*   INPUT DATA FILES
C*   GCFLOW - GANNAVARAM CANAL FLOW DATA
C*   ACFLOW - AMALAPURAM CANAL FLOW DATA
C*   BCFLOW - BANK CANAL FLOW DATA
C*   MCFLOW - MAIN CANAL FLOW DATA
C*   DSL=DAILY SEEPAGE LOSS
C*   MONTHS.OUT MONTHLY SEEPAGE LOSSES
C*   PIRRK.OUT PADDY IRRIGATION FOR KHARIF SEASON
C*   PIRRR.OUT PADDY IRRIGATION FOR RABI SEASON
C*   Q(I)      DAILY CANAL FLOW, CUSEC
C*   AREAK     PADDY AREA UNDER CANAL COMMAND AREA DURING KHARIF SEASON
C*             HACTARES
C*   AREAR     PADDY AREA UNDER CANAL COMMAND AREA DURING RABI SEASON
C*             HACTARES
C*   ISD       IRRIGATION SCHEDULING DURATION,DAYS
C*   NTK       DAY NUMBER CORRESPONDING TO PADDY TRANSPLANTING DATE
C*             DURING KHARIF SEASON
C*   NTR       DAY NUMBER CORRESPONDING TO PADDY TRANSPLANTING DATE
C*             DURING RABI SEASON
C*   NIR       NUMBER OF IRRIGATIONS DURING KHARIF SEASON
C*   NTK       NUMBER OF IRRIGATIONS DURING RABI SEASON
C*   ICOD      IRRIGATION CUTOFF DURATION BEFORE HARVESTING,DAYS
C*   NCK       CROP DURATION FOR KHARIF PADDY,DAYS
C*   NCR       CROP DURATION FOR RABI PADDY,DAYS
C*   NASK      AGE OF PADDY SEEDLING,KHARIF SEASON,DAYS
C*   NASR      AGE OF PADDY SEEDLING,RABI SEASON,DAYS
C*   CSR       CANAL SEEPAGE RATE ham/day/10**6 sq.m of wetted area
C*   WAREA     WETTED AREA,sq.m
C*   B1,B2     CANAL BED WIDTH,m
C*   S1,S2     CANAL BED SLOPE
C*   RL        CANAL REACH LENGTH,m
C*   Z         SECTION FACTOR
C*   CN        MANNING COEFFICIENT
C*   NDK       TRANSPLANTING DATE, KHARIF SEASON
C*   NMK       MONTH NUMBER CORRESPONDING TO WATER YEAR FROM JUNE
C*             (KHARIF SEASON)
C*   MNK       MONTH NUMBER CORRESPONDING TO NORMAL YEAR FROM
C*             JANUARY FOR KHARIF SEASON
C*   NY1       YEAR
C*   NDR       TRANSPLANTING DATE,RABI SEASON
C*   NMR       MONTH NUMBER CORRESPONDING TO WATER YEAR FROM JUNE
C*             (RABI SEASON)
C*   MNR       MONTH NUMBER CORRESPONDING TO NORMAL YEAR FROM
C*             JANUARY
C*             FOR RABI SEASON
C*   DSL       DAILY SEEPAGE LOSS,CUMEC
C*   SLD       DAILY SEEPAGE LOSS FROM DISTRIBUTARIES
```

```

C*   SEEP           DAILY SEEPAGE LOSS, M**3/DAY
C*   TSEEP1,TSEEP2, AVERAGE MONTHLY SEEPAGE LOSS, CUMEC
C    KFD   DURATION OF FALLOW LAND AFTER KHARIF PADDY
C    RFD   DURATION OF FALLOW LAND AFTER RABI PADDY

```

```

C*****

```

```

    DIMENSION STATION(20),Q(400),DSL(400),SEEP(400)
    DIMENSION PIRRK(150),PIRRR(150),PIRRI(150),SEEPM(12)
    DIMENSION PIRK(150),PIRR(150),QIRK(150),QIR(150)
    DIMENSION PERSL(400),QFLOW(400),sld(400)
    integer rfd
    WRITE(*,*)'GANNAVARAM CANAL ID=1'
    WRITE(*,*)'AMALAPURAM CANAL ID=2'
    WRITE(*,*)'BANK CANAL      ID=3'
    WRITE(*,*)'MAINCANAL      ID=4'

```

```

C
C*****OPENING THE FILES ACCORDING TO CANAL ID
C

```

```

    ID=1
    DO 1500 ID=1,4
    GO TO(61,62,63,64)ID
61  OPEN(5,FILE='GCFLOW',STATUS='OLD')
    OPEN(8,FILE='MSEEPG2')
    OPEN(9,FILE='PIRKG2')
    OPEN(10,FILE='PIRRG2')
    OPEN(11,FILE='RATEDSCG')
    OPEN(12,FILE='CURVEG')
    GO TO 255
62  OPEN(5,FILE='ACFLOW',STATUS='OLD')
    OPEN(8,FILE='MSEEPA2')
    OPEN(9,FILE='PIRKA2')
    OPEN(10,FILE='PIRRA2')
    OPEN(11,FILE='RATEDSCA')
    OPEN(12,FILE='CURVEA')
    GO TO 255
63  OPEN(5,FILE='BCFLOW',STATUS='OLD')
    OPEN(8,FILE='MSEEPB2')
    OPEN(9,FILE='PIRKB2')
    OPEN(10,FILE='PIRRB2')
    OPEN(11,FILE='RATEDSCB')
    OPEN(12,FILE='CURVEB')
    GO TO 255
64  OPEN(5,FILE='MCFLOW',STATUS='OLD')
    OPEN(8,FILE='MSEEPM2')
    OPEN(9,FILE='PIRKM2')
    OPEN(10,FILE='PIRRM2')
    OPEN(11,FILE='RATEDSCM')
    OPEN(12,FILE='CURVEM')
    GO TO 255

```

```

C
C    READING INPUT DATA (CANAL DIMENSIONS)
C

```

```

255  READ(5,8) STATION
    WRITE(*,8)STATION
8    FORMAT(2X,20A4)
    IF(ID .EQ. 3)GOTO 125
    IF(ID .EQ. 4)GOTO 126
    WRITE(*,*)'ID=',ID
    READ(5,11)B1,B2,B3,B4,B5
    WRITE(*,11)B1,B2,B3,B4,B5
11   FORMAT(4X,F6.3,1X,F6.3,1X,F6.3,1X,F6.3,1X,F6.3)

```

```

      READ(5,12)S1,S2,S3,S4,S5
      WRITE(*,12)S1,S2,S3,S4,S5
12    FORMAT(4X,E9.3,2X,E9.3,2X,E9.3,2X,E9.3,2X,E9.3)
      READ(5,13)RL1,RL2,RL3,RL4,RL5
      WRITE(*,13)RL1,RL2,RL3,RL4,RL5
13    FORMAT(4X,F7.1,2X,F7.1,2X,F7.1,2X,F7.1,2X,F7.1)
      READ(5,14)Z,CN
      WRITE(*,14)Z,CN
14    FORMAT(4X,F3.1,2X,F4.2)
C*****READING INPUT FOR CROP PARAMETERS
      READ(5,*)AREAK,AREAR
      write(*,*)AREAK,AREAR
      READ(5,*)NCK,NASK,NCR,NASR
      WRITE(*,*)NCK,NASK,NCR,NASR
      READ(5,*)ICOD,ISD
      WRITE(*,*)ICOD,ISD
      READ(5,*)CSR
      WRITE(*,*)CSR
C
GO TO 150
C*****READING INPUT DATA (CANAL DIMENSIONS)
125   READ(5,41)B1,B2,B3
      WRITE(*,41)B1,B2,B3
41    FORMAT(4X,F6.3,1X,F6.3,1X,F6.3)
      READ(5,42)S1,S2,S3
      WRITE(*,42)S1,S2,S3
42    FORMAT(4X,E9.3,2X,E9.3,2X,E9.3)
      READ(5,43)RL1,RL2,RL3
      WRITE(*,43)RL1,RL2,RL3
43    FORMAT(4X,F7.1,2X,F7.1,2X,F7.1)
      READ(5,44)Z,CN
      WRITE(*,44)Z,CN
44    FORMAT(4X,F3.1,2X,F4.2)
C*****READING INPUT DATA FOR CROP PARAMETERS
      READ(5,*)AREAK,AREAR
      WRITE(*,*)AREAK,AREAR
      READ(5,*)NCK,NASK,NCR,NASR
      READ(5,*)ICOD,ISD
      READ(5,*)CSR
      GO TO 150
C*****READING INPUT DATA (CANAL DIMENSIONS)
126   READ(5,31)B1
31    FORMAT(4X,F6.3)
      WRITE(*,*)B1
      READ(5,32)S1
32    FORMAT(4X,E9.3)
      WRITE(*,32)S1
      READ(5,33)RL1
33    FORMAT(4X,F7.1)
      WRITE(*,*)RL1
      READ(5,34)Z,CN
34    FORMAT(4X,F3.1,2X,F4.2)
      WRITE(*,*)Z,CN
C*****READING INPUT DATA FOR CROP PARAMETERS
      READ(5,*)AREAK,AREAR
      READ(5,*)NCK,NASK,NCR,NASR
      READ(5,*)ICOD,ISD
      READ(5,*)CSR
C*****CALCULATING NUMBER OF IRRIGATIONS FOR BOTH
C***** KHARIF AND RABI SEASONS

```

```

150  NIK=(NCK-NASK-ICOD)/ISD+1
      NIR=(NCR-NASR-ICOD)/ISD+1
C
      DO 200 IK=1,9
      READ(5,15) NYEAR,NYEAR1
15    FORMAT(6X,I4,6X,I4)
c 18  FORMAT(I4,2X,I4)
C*****READING TRANSPLANTING DATE AND MONTH FOR BOTH THE SEASONS
      READ(5,*)NDK,NMK,kfd
      READ(5,*)NDR,NMR,rfd
      CALL DAYN(NDK,NMK,NYEAR1,NTK)
      CALL DAYN(NDR,NMR,NYEAR1,NTR)
      NY = (NYEAR1/4)*4
      IF(NYEAR1 .EQ. NY) GO TO 16
      N=365
      GO TO 17
16    N=366
C*****READING DAILY CANAL FLOW DATA (CUSEC)
17    READ(5,25)(Q(I),I=1,N)
25    FORMAT(10F8.1)
      DO 100 I=1,N
      write(*,*)i,id
C*****CONVERSION FACTOR FROM CUSEC TO CUMEC IS 0.03
C*****CALCULATING DISCHARGES AT HEADS OF
C*****DIFFERENT CANAL REACHES
      GO TO (10,20,30,40),ID
10    Q1=Q(I)*0.03
      Q2=Q1*0.847
      Q3=Q1*0.693
      Q4=Q1*0.3406
      Q5=Q1*0.182
      GO TO 500
C
20    Q1=Q(I)*0.03
      Q2=Q1*0.85
      Q3=Q1*0.749
      Q4=Q1*0.5626
      Q5=Q1*0.3356
      GO TO 500
30    write(*,*)'id=',id
c    write(*,*)'bank canal'
C
      Q1=Q(I)*0.03
      Q2=Q1*0.7632
      Q3=Q1*0.622
GO TO 500
40    Q1=Q(I)*0.03
      QF1=Q1
      GO TO 550
C
500   Q12=(Q1+Q2)/2
      QF1=Q12
C*****CALLING SUBROUTINE TO CALCULATE DEPTH OF FLOW
550   CALL HYD1 (QF1,B1,Z,S1,CN,DT1)
      DT=DT1
C*****CALLING SUBROUTINE FOR ESTIMATING SEEPAGE LOSSES FOR SECTION 1
      CALL SEPLOS(CSR,RL1,B1,DT1,Z,SL1)
      SL=SL1
      IF(ID .EQ. 4)GO TO 226

```



```

C
    Q23=(Q2+Q3)/2
    QF2=Q23
C*****CALLING SUBROUTINE TO CALCULATE DEPTH OF FLOW
    CALL HYD1 (QF2,B2,Z,S2,CN,DT2)
    DT=DT2
C*****CALLING SUBROUTINE FOR ESTIMATING SEEPAGE LOSSES FOR SECTION 2
    CALL SEPLOS(CSR,RL2,B2,DT2,Z,SL2)
    SL=SL2
C
    IF(ID .EQ. 3)GO TO 175
    Q34=(Q3+Q4)/2
    QF3=Q34
    GO TO 225

    175 QF3=Q3
C*****CALLING SUBROUTINE TO CALCULATE DEPTH OF FLOW
    225 CALL HYD1 (QF3,B3,Z,S3,CN,DT3)
    DT=DT3
C*****CALLING SUBROUTINE FOR ESTIMATING SEEPAGE LOSSES FOR SECTION 3
    CALL SEPLOS(CSR,RL3,B3,DT3,Z,SL3)
    SL=SL3
    IF(ID .EQ. 3)GO TO 250
C
    Q45=(Q4+Q5)/2
    QF4=Q45
C*****CALLING SUBROUTINE TO CALCULATE DEPTH OF FLOW
    CALL HYD1(QF4,B4,Z,S4,CN,DT4)
    DT=DT4
C*****CALLING SUBROUTINE FOR ESTIMATING SEEPAGE LOSSES FOR SECTION 4
    CALL SEPLOS(CSR,RL4,B4,DT4,Z,SL4)
    SL=SL4
C
    QF5=Q5
C*****CALLING SUBROUTINE TO CALCULATE DEPTH OF FLOW
    CALL HYD1(QF5,B5,Z,S5,CN,DT5)
    DT=DT5
C*****CALLING SUBROUTINE FOR ESTIMATING SEEPAGE LOSSES FOR SECTION 5
    CALL SEPLOS(CSR,RL5,B5,DT5,Z,SL5)
    SL=SL5
    GO TO 275
    226 DSL(I)=SL1
        sld(i) =((q1-dsl(i))*7)/100
        SEEP(I)=(DSL(I)+sld(i))*24*60*60
        GO TO 1000
    250 DSL(I)=SL1+SL2+SL3
        sld(i)=((q1-dsl(i))*7)/100
        SEEP(I)=(DSL(I)+sld(i))*24*60*60
        GO TO 1000
C*****CALCULATING SEEPAGE LOSS FOR ENTIRE CANAL REACH
    275 DSL(I)=SL1+SL2+SL3+SL4+SL5
        sld(i)=((q1-dsl(i))*7)/100
        SEEP(I)=(DSL(I)+sld(i))*24*60*60
    1000 CONTINUE
C*****FITTING OF RATING CURVE FOR ONE YEAR
    IF(IK .EQ. 2)GO TO 1200
    GO TO 100
    1200 QFLOW(I)=Q1
    130 FORMAT(I3.2X,F7.4,2X,F6.4,2X,F6.3)
    IF(QFLOW(I) .EQ. 0)GO TO 1225

```

```

      PERSL(I)=(DSL(I)/QFLOW(I))*100
C      WRITE(12,130)I,QFLOW(I),DSL(I),PERSL(I)
      GO TO 100
1225  PERSL(I)=0
C      WRITE(12,130)I,QFLOW(I),DSL(I),PERSL(I)
100   CONTINUE
      IF(IK.EQ. 2)GO TO 1250
      GO TO 1300
C*****CALLING SUBROUTINE FOR CALCULATING COEFFICIENTS
1250  CALL CURVEFIT(N,DSL,QFLOW,A,B)

C*****
C*****CALL SUBROUTINE TO FIND THE MONTHLY SEEPAGE VALUES
C*****NIRRI - NO OF IRRIGATIONS
C*****NS - STARTING OF SEASON
C*****
1300  CALL SUM (I,MN,NYEAR1,SEEP,SEEPM,TYSEEP)
      WRITE(8,23)NYEAR,(SEEPM(MN),MN=1,12)
23    FORMAT(14,2X,12(F5.3,2X))
C*****FOR KHARIF PADDY CROP IDC=10
C***** (THIS VALUE IS GIVEN FOR CONTROL STATEMENTS IN THE PROGRAMME
C***** IN ORDER TO SWITCH BETWEEN KHARIF AND RABI)
      IDC=10
      CALL PADDYIRRI(AREAK,NYEAR,NYEAR1,I,Q,DSL,IDC,NTK,NIK,ISD,KW,PIRK)
C      WRITE(*,*)(PIRK(KW),KW=1,NIK)
C*****NCAK=ACTUAL CROP SEASON(CROP SEASON-AGE OF PADDY NURSERY)
      NCAK=NCK-NASK+1
      CALL RICEIRRI(NYEAR,NYEAR1,KW,PIRK,NCAK,NIK,ISD,KI,QIRK)
C*****MNK IS MONTH NUMBER CORRESPONDING TO NORMAL YEAR FROM JANUARY
C*****FOR KHARIF SEASON
      MNK=NMK+5
      WRITE(9,35)NYEAR,NCAK,NDK,MNK,kfd
35    FORMAT(14,1X,13,1X,12,1X,12,1X,12)
      WRITE(9,36)(QIRK(KI),KI=1,NCAK)
36    FORMAT(10(F7.2))
C*****FOR RABI PADDY CROP IDC =20
      IDC=20
      CALL PADDYIRRI(AREAR,NYEAR,NYEAR1,I,Q,DSL,IDC,NTR,NIR,ISD,KW,PIRR)
C      WRITE(*,*)(PIRR(KW),KW=1,NIR)
      NCAR=NCR-NASR+1
      CALL RICEIRRI(NYEAR,NYEAR1,KW,PIRR,NCAR,NIR,ISD,KI,QIR)
C*****MNR IS MONTH NUMBER CORRESPONDING TO NORMAL YEAR FROM JANUARY
C*****FOR RABI SEASON
      MNR=NMR+5
      WRITE(10,35)NYEAR,NCAR,NDR,MNR,rfd
      WRITE(10,36)(QIR(KI),KI=1,NCAR)
200   CONTINUE
      CLOSE(5)
      CLOSE(8)
      CLOSE(9)
      CLOSE(10)
      CLOSE(11)
      CLOSE(12)
1500  CONTINUE
      STOP
      END

C      *****
C      SUBROUTINE HYD1
C      *****

```

```

C      This subroutine estimates the depth of flow from Manning's
C      equation using Newton Raphson iteration procedure
C      *****
SUBROUTINE HYD1(Q,B,Z,S0,CN,DT)
IF(Q.EQ.0)GO TO 22
D=30
C= (1./CN)*S0**(0.5)
DO 110 I9=1,500
A1 = Q*(B+2*D*(1+Z*Z)**0.5)**(2./3)
A2 = C* (B*D +Z*D*D)**(5./3)
A3=(4/3)*Q*((1+Z*Z)**0.5)*(B+2*D*(1+Z*Z)*0.5)**(-1./3)
A4 =(5*C/3)* (B+2*Z*D)*(B*D+Z*D*D)**(2./3)
DC = D- (A1-A2)/(A3-A4)
ERR = ABS(DC-D)
IF(ERR.LE..01)GO TO 21
D=DC
110 CONTINUE
21 DT =DC
GO TO 24
22 DT=0.0
24 CONTINUE
C 24 WRITE(7,23)Q,DT
C 23 FORMAT(10X,'DISCHARGE=' ,F8.5,10X,'DEPTH OF FLOW=' ,F8.5)
RETURN
END
C *****
C SUBROUTINE SEPLOS
C *****
C This calculates the seepage loss in a canal
C *****
C *****
SUBROUTINE SEPLOS(CSR,RL,B,D,Z,SL)
IF(D.EQ.0.0)GO TO 26
WAREA=RL*(B+2*D*(1+Z*Z)**0.5 )
SR=CSR/(100*24*60*60)
SL = SR * WAREA
GO TO 27
26 SL = 0.0
c WRITE(*,1) RL,SL
c 1 FORMAT(10X,'REACH LENGTH =' ,F10.3,' SEEPAGE LOSS =' ,F10.7)
27 RETURN
END
C *****
C *****PROGRAMME TO FIND THE AVERAGE MONTHLY SEEPAGE VALUES
C *****STARTING FROM JUNE (FOR WATER YEAR)
C *****
C ***** MN MONTH NUMBER
C ***** ND NUMBER OF DAYS
C ***** DB DAY BEGINNING
C ***** DL DAY LAST
C ***** BD BEGINNING OF DAY FOR COMPUTATION
C *****
SUBROUTINE SUM(I,MN,NYEAR1,SEEP,SEEPM,TYSEEP)
DIMENSION SEEP(400),SEEPM(12)
MN=1
500 GO TO(10,20,30,40,50,80,70,80,90,100,110,120),MN
10 TSEEP=0.0
ND =30
NDL =ND
NBD =1

```

```

DO 210 I =NBD,NDL
TSEEP=TSEEP+SEEP(I)
210 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
20 TSEEP=0.0
ND =31
NBD =NDL+1
NDL =NDL+ND
DO 220 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
220 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
30 TSEEP=0.0
ND =31
NBD =NDL+1
NDL =NDL+ND
DO 230 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
230 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
40 TSEEP=0.0
ND =30
NBD =NDL+1
NDL =NDL+ND
DO 240 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
240 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
50 TSEEP=0.0
ND =31
NBD =NDL+1
NDL =NDL+ND
DO 250 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
250 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
60 TSEEP=0.0
ND =30
NBD =NDL+1
NDL =NDL+ND
DO 260 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
260 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
70 TSEEP=0.0
ND =31
NBD =NDL+1
NDL =NDL+ND

```

```

DO 270 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
270 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
80 TSEEP=0.0
ND =31
NBD =NDL+1
NDL =NDL+ND
DO 280 IK= NBD,NDL
TSEEP=TSEEP+SEEP(IK)
280 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
90 TSEEP=0.0
NY=(NYEAR1/4)*4
IF(NYEAR1.EQ. NY)GO TO 91
ND =28
GO TO 92
91 ND =29
92 NBD =NDL+1
NDL =NDL+ND
DO 290 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
290 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
100 TSEEP=0.0
ND =31
NBD =NDL+1
NDL =NDL+ND
DO 300 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
300 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
GO TO 500
110 TSEEP=0.0
ND =30
NBD =NDL+1
NDL =NDL+ND
DO 310 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
310 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
MN=MN+1
120 TSEEP=0.0
ND =31
NBD =NDL+1
NDL =NDL+ND
DO 320 I= NBD,NDL
TSEEP=TSEEP+SEEP(I)
320 CONTINUE
SEEPM(MN)=TSEEP/((24*60*60)*(NDL-NBD+1))
WRITE(*,22)NYEAR1,(SEEPM(MN),MN=1,12)
22 FORMAT(I4,12(2X,F5.3))
RETURN

```

```

      END
C*****
C*****SUBROUTINE PADDYIRRI
C*****SUBROUTINE TO CALCULATE IRRIGATION DEPTHS FOR RICE FIELDS
C***** ( FOR BOTH KHARIF AND RABI SEASONS)
C*****
C****NIRRI- NO OF IRRIGATIONS
      SUBROUTINE PADDYIRRI(A,NY,NY1,I,Q,DSL,IDC,NS,NIRRI,ISD,KW,PIRRI)
      DIMENSION Q(400),DSL(400),PIRRI(150)
      KW=1
      GO TO 650
650   SLSUM=0.0
      SQSUM=0.0
      NE=NS+ISD-1
      DO 100 I=NS,NE
      SLSUM=SLSUM+DSL(I)
C**** Q(I) IS IN CUSEC,CONVERSION FACTOR 0.03 IS USED TO CONVERT TO
C**** CUMEC
      SQSUM=SQSUM+Q(I)*0.03
100   CONTINUE
      PIRRI(KW)=((SQSUM-SLSUM)-((SQSUM-SLSUM)*0.07)) (A*10000)
1     *86400*1000
      GO TO 250
250   NS=NE+1
      KW=KW+1
      IF(KW.GT. NIRRI)GO TO 200
      GO TO 650
200   RETURN
      END
C     *****
C     SUBROUTINE DAYN
C     *****
C     This converts the date of sowing to the corresponding
C     day number in the year.
C     *****
      SUBROUTINE DAYN(ND,NM,NY1,IDOS)
C**
C**   ND...Date of sowing
C**   NM... Month of sowing
C**   NYEAR...Year
C**   IDOS... Day number in the year
C**   STARTING MONTH IS JUNE (WATER YEAR, JUNE TO MAY)
C**   NM =1 FOR JUNE AND NM=12 FOR MAY
C**
      WRITE(*,*)'ENTERED SUBROUTINE DAYN'
      NYR=NY1/4*4
      IF(NY1.EQ.NYR) GO TO 830
      GO TO (831,832,833,834,835,836,837,838,839,840,841,842),NM
831   IDOS=ND
      GO TO 843
832   IDOS=30+ND
      GO TO 843
833   IDOS=61+ND
      GO TO 843
834   IDOS=92+ND
      GO TO 843
835   IDOS=122+ND
      GO TO 843
836   IDOS=153+ND
      GO TO 843

```

```

837  IDOS=183+ND
      GO TO 843
838  IDOS=214+ND
      GO TO 843
839  IDOS=245+ND
      GO TO 843
840  IDOS=273+ND
      GO TO 843
841  IDOS=304+ND
      GO TO 843
842  IDOS=334+ND
      GO TO 843
830  GO TO (851,852,853,854,855,856,857,858,859,860,861,862),NM
851  IDOS=ND
      GO TO 843
852  IDOS=30+ND
      GO TO 843
853  IDOS=61+ND
      GO TO 843
854  IDOS=92+ND
      GO TO 843
855  IDOS=122+ND
      GO TO 843
856  IDOS=153+ND
      GO TO 843
857  IDOS=183+ND
      GO TO 843
858  IDOS=214+ND
      GO TO 843
859  IDOS=245+ND
      GO TO 843
860  IDOS=274+ND
      GO TO 843
861  IDOS=305+ND
      GO TO 843
862  IDOS=335+ND
843  RETURN
      END
C*****
C*****THIS PROGRAMME IS TO PREPARE THE IRRIGATION FILE
C*****AFTER GETTING IRRIGATION DEPTHS ACCORDING TO IRRIGATION
C*****SCHEDULING DURATION FROM SUBROUTINE PADDYIRRI
C*****
      SUBROUTINE RICEIRRI(NYEAR,NYEAR1,KW,RIR,NCP,NIRR,ISD,KI,QIRR)
      DIMENSION RIR(150),QIRR(150)
10    FORMAT(I4,2X,I4)
      DO 100 KI=1,NCP
        QIRR(KI)=0.0
100   CONTINUE
      NB=1
      NL=NIRR*ISD
      I=1
      DO 200 KI=NB,NL,ISD
        QIRR(KI)=RIR(I)
        I=I+1
200   CONTINUE
      RETURN
      END
C*****
C*****PROGRAM TO ESTIMATE THE CONSTANTS OF POWER REGRESSION

```

C CURVE OF THE FORM $Y=A*(X**B)$ AND $Y=A*(B**X)$ TO ESTIMATE
 C THE FITTED VALUES OF Y FOR THE GIVEN X VALUES
 C THIS PROGRAMM ALSO FINDS OUT THE MSE,MPE,MAPE VALUES FOR
 C THE SERIES AND FITTED VALUES

C*****

```

SUBROUTINE CURVEFIT(N,Y,X,A,B)
DIMENSION X(400),Y(400),U(400),V(400),FY(400),FEY(400)
WRITE(*,*)'ENTERED SUBROUTINE CURVEFIT'
SX=0.0
SXU=0.0
SXX=0.0
SU=0.0
SV=0.0
SUV=0.0
SVV=0.0
DO 100 I=1,N
  SX=SX+X(I)
  SXX=SXX+X(I)**2
  IF(Y(I).EQ. 0 .AND. X(I).EQ. 0)GO TO 155
  U(I)=ALOG(Y(I))
  V(I)=ALOG(X(I))
  GO TO 160
155  U(I)=0.0
     V(I)=0.0
160  SU=SU+U(I)
     SXU=SXU+X(I)*U(I)
     SV=SV+V(I)
C     SUV=SUV+ALOG(X(I))*ALOG (Y(I))
     SUV=SUV+V(I)*U(I)
100  SVV=SVV+V(I)**2
     B=(SU*SV-N*SUV)/(SV**2-N*SVV)
     CA=(SU-B*SV)/N
     A=EXP(CA)
     WRITE(*,*)
     WRITE(*,*)'RESULT OF Y=A*(X**B) FORM'
     WRITE(11,*)'RESULT OF Y=A*(X**B) FORM'
     WRITE(*,*)
     WRITE(*,*)'A=',A,'B=',B
     WRITE(11,*)'A=',A,'B=',B
     DO 102 I=1,N
       IF(X(I).EQ. 0.0)GO TO 110
       FY(I)=A*(X(I)**B)
       GO TO 102
110  FY(I)=0.0
131  FORMAT(I3,2X,F7.3,2X,F6.3,2X,F6.3)
102  WRITE(12,131)I,X(I),FY(I),Y(I)

```

C

```

CALL STATTEST(N,FY,Y,AMSE,AMPE,AMAPE,CCOE)
WRITE(11,*)'MSE=',AMSE
WRITE(11,*)'MPE=',AMPE
WRITE(11,*)'MAPE=',AMAPE
WRITE(11,*)'CCOE=',CCOE
E1CB=(SU*SX-SXU*N)/(SX**2-N*SXX)
E1CA=(SU-E1CB*SX)/N
E1A=EXP(E1CA)
E1B=EXP(E1CB)
E2B=B/ALOG(2.7182818)
WRITE(*,*)
WRITE(*,*)'RESULT OF Y=A* (B**X)FORM'
WRITE(11,*)'RESULT OF Y=A*(B**X)FORM'

```



```

WRITE(*,*)
WRITE(*,*)'A=',E1A,'B=',E1B
WRITE(11,*)'A=',E1A,'B=',E1B
DO 101 I=1,N
IF(X(I) .EQ. 0.0)GO TO 115
FEY(I)=E1A*E1B**X(I)
GO TO 101
115 FEY(I)=0.0

101 WRITE(11,*)I,Y(I),FEY(I)
CALL STATTEST(N,FEY,Y,AMSE,AMPE,AMAPE,CCOE)
WRITE(11,*)'MSE=',AMSE
WRITE(11,*)'MPE=',AMPE
WRITE(11,*)'MAPE=',AMAPE
WRITE(11,*)'CCOE=',CCOE
RETURN
END
C*****
C PROGRAMME TO FIND OUT THE CORRELATION COEFFICIENT
C*****
SUBROUTINE STATTEST(N,FY,Y,AMSE,AMPE,AMAPE,CCOE)
DIMENSION FY(400),Y(400)
CALL STDEVI(I,N,Y,SDY,AVEY)
CALL STDEVI(I,N,FY,SDFY,AVEFY)
SUMDYFY=0.0
DO 200 I=1,N
DY=(Y(I)-AVEY)
DFY=(FY(I)-AVEFY)
DYFY=DY*DFY
SUMDYFY=SUMDYFY+DYFY
200 CONTINUE
COVAR=(SUMDYFY/(N))
CCOE=(COVAR/(SDY*SDFY))
WRITE(*,*)'CORRELATION COEFFICIENT=',CCOE
CALL TEST(N,Y,FY,AMSE,AMPE,AMAPE)
WRITE(*,*)'MSE=',AMSE
WRITE(*,*)'MPE=',AMPE
WRITE(*,*)'MAPE=',AMAPE
RETURN
END
C*****
C*****SUBROUTINE TO CALCULATE STANDARD DEVIATION AND MEAN
C*****
SUBROUTINE STDEVI(I,NI,VAR,SD,AVE)
DIMENSION VAR(400)
SUM=0.0
DO 100 I=1,NI
SUM=SUM+VAR(I)
100 CONTINUE
AVE=SUM/NI
SSQDEV=0.0
DO 150 I=1,NI
DEVI=VAR(I)-AVE
SQDEVI=DEVI**2
SSQDEV=SSQDEV+SQDEVI
150 CONTINUE
SD=SQRT(SSQDEV/NI)
RETURN
END
C*****

```

C PROGRAMME TO FIND OUT THE MEAN SQUARE ERROR (MSE), MEAN PERCENT
C ERROR(MPE) AND THE MEAN ABSOLUTE PERCENT ERROR (MAPE) FOR ASSESSING
C PERFORMANCE OF A MODEL

[illegible]

```

C      Y(I)      DATA SERIES
C      FY(I)     FORECAST VALUES
C      N         NUMBER OF DATA ITEMS
C      AMSE      MEAN SQUARE ERROR
C      AMPE      MEAN PERCENT ERROR
C      AMAPE     MEAN ABSOLUTE PERCENT ERROR
C      SUBROUTINE TEST(N,Y,FY,AMSE,AMPE,AMAPE)
C      DIMENSION FY(400),Y(400)
C      S=0.0
C      SS=0.0
C      SSS=0.0
C      DO 200 I=1,N
C      S=S+(FY(I)-Y(I))**2
C      IF(Y(I) .EQ. 0.0)GO TO 200
C      SS=SS+(FY(I)-Y(I))*Y(I)
C      SSS=SSS+ABS((FY(I)-Y(I))/Y(I))
200    CONTINUE
C      AMSE=S/N
C      AMPE=SS/N
C      AMAPE=SSS/N
C      RETURN
C      END

```

Daily irrigation depths estimated for all four canals using Canal Flow Model (For both Kharif and Rabi)

(a) Name of the canal: Gannavaram canal

Season : Kharif season

[illegible]

Season : Rabi

[illegible]

(d) Name of the canal: Main canal

Season : Kharif season

1995	108	14	6	50					
31.75	0.00	0.00	31.45	0.00	0.00	34.60	0.00	0.00	32.00
0.00	0.00	33.81	0.00	0.00	27.98	0.00	0.00	35.47	0.00
0.00	37.95	0.00	0.00	37.39	0.00	0.00	30.61	0.00	0.00
20.25	0.00	0.00	13.69	0.00	0.00	10.74	0.00	0.00	23.07
0.00	0.00	28.59	0.00	0.00	30.12	0.00	0.00	28.68	0.00
0.00	33.01	0.00	0.00	30.14	0.00	0.00	28.35	0.00	0.00
32.45	0.00	0.00	34.19	0.00	0.00	33.72	0.00	0.00	34.16
0.00	0.00	30.40	0.00	0.00	28.33	0.00	0.00	31.03	0.00
0.00	31.51	0.00	0.00	29.56	0.00	0.00	33.20	0.00	0.00
27.78	0.00	0.00	23.85	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		

Season : Rabi

1995	96	21	11	96					
31.64	0.00	0.00	35.18	0.00	0.00	39.68	0.00	0.00	34.39
0.00	0.00	37.13	0.00	0.00	39.34	0.00	0.00	41.05	0.00
0.00	41.48	0.00	0.00	35.89	0.00	0.00	31.80	0.00	0.00
34.28	0.00	0.00	31.21	0.00	0.00	31.50	0.00	0.00	27.92
0.00	0.00	29.44	0.00	0.00	31.54	0.00	0.00	31.91	0.00
0.00	27.13	0.00	0.00	28.19	0.00	0.00	30.21	0.00	0.00
31.78	0.00	0.00	31.75	0.00	0.00	34.83	0.00	0.00	35.21
0.00	0.00	35.60	0.00	0.00	35.15	0.00	0.00	33.02	0.00
0.00	32.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00				

APPENDIX C

Table C-1 Seasonal rainfall limits for AMC

Total	5-day antecedent rainfall	
AMC Group	Dormant Season (millimeters)	Growing Season (millimeters)
I	Less than 12.7	Less than 35.6
II	12.7 to 27.9	36.6 to 53.3
III	Over 27.9	Over 53.3

(Source : Ministry of Agriculture, 1972)

Appendix C-2. Runoff curve number for hydrologic soil cover complex

Land use	Cover		Antecedent Moisture condition II			
	Treatment or practice	Hydrologic condition	Ia=0.3s		Ia=0.1s	
			A	B	C	D
Cultivated	Straight	Row	76	86	90	93
Cultivated	contoured	Poor	70	79	84	88
		Good	65	75	82	86
Cultivated	Countoured & Terraced	Poor	66	74	80	82
		Good	62	71	77	81
Cultivated	Bunded	Poor	67	75	81	83
		Good	59	69	76	79
Cultivated	Paddy		95	95	95	95
Orchards	- (with understory cover)		39	53	67	71
	- (without understory cover)		41	55	69	73
Forest	-	Dense	26	40	58	61
	-	Open	28	44	60	64
	-	Scrub	33	47	64	67
Pasture	-	Poor	68	79	86	89
	-	Fair	49	69	79	84
	-	Good	39	61	74	80
Wasteland	-		71	80	85	88
Roads (Dirt)	-		73	83	88	90
Hard Surface Area	-		77	86	91	93

(Source : Ministry of Agriculture, 1972)

```

C *****
C PROGRAM SWB.FOR (FOR ALL CROPS)
C *****
C This program calculates daily soil water balance for
c different crops with varying combinations of soils,rain gauge
c stations and canals for specified number of years.
C This program also calculates:
C (i) daily standing water depths and daily percolation losses
C in paddy fields which serve as input to nitrogen
C transformation model.
c (ii) summary reports for preparing maps in GIS.
c (iii) monthly gross recharge values which serve as input to
C groundwater model.
C *****
C** ETO Reference Crop Evapotranspiration, mm/day
C** PET,ETM Potential Evapotranspiration,mm/day
C** AET Actual Evaptranspiration, mm/day
C** NYEAR Year
C** N Number of days in the year
C** ND Date of sowing
C** NM Month of sowing
C** FC,PWP,THETA,SMI,FSM,THETA0 all w.r.t. PWP
C** FC Field capacity,mm/cm (volume basis)
C** PWP Permanent wilting point, mm/cm (volume basis)
C** THETA Soil moisture content in the active root zone,mm/cm (MC1)
C** SMI Initial soil moisture content at the beginning of
C** the day, mm/cm
C** FSM Final soil moisture content at the end of day, mm/cm
C** THETA0 Soil moisture content in the passive soil layer(MC2),
C** mm/cm.(max. root depth -active root zone)
C** ASW Total available soil water in the active root zone,mm
C** RD Root depth,cm
C** DRD Depth of incremental root layer, cm
c** DIRR Depth of irrigation,mm
C** RDM Maximum root depth, cm
C** RDI Initial root depth, cm
C** MDT Days after sowing to reach RDM
C** NDE Number of days for establishment phase
C** NDVP End day of vegetative phase
C** NCP Crop period, days
C** NCG Number of crop group for soil water depletion factor
C** (Ref: FAO I&D Paper No.33)
C** NLAST Year upto which WB is to run
C** PERC Percolation from active layer to bottom layer
C** DPER Deep percolation out of root zone
C** R Daily rainfall, mm
C** ER Effective rainfall, mm
C** Q Runoff, mm
C** WHC Water holding vcapacity, mm/cm
C** THETAR Threshold water holding capacity (MCT)
C** P Soil water depletion factor
C** PSI Presowing irrigation, mm
C** QIRR Quantity of irrigation water applied. mm
C** CKC Crop coefficient
C** NWN,NW week number requiring irrigation
C** IDAP Days after planting
C** ICOD Cut off date for irrigation
C** BUH Bund height in paddy fields, mm
C** IDD1 Initial drainage date after transplanting
C** IDD2 second drainage date after transplanting

```

```

C**   IDD3       THIRD DRAINAGE DATE AFTER TRANSPLANTING
C**   IDD        DRINAGE DURATION
C**   DRF        DURATION OF FALLOW LAND AFTER PADDY CROP
C*****
C
C   AKCO = DAILY VALUE OF CROP COEFFICIENT FOR RICE CROP
C   AW  = AVAILABLE WATER ON FIRST DAY, mm
C   N4  = DURATION OF THE CROP SEASON, days
C   SHC = SATURATED HYDRAULIC CONDUCTIVITY, mm/day
C   FC  = FIELD CAPACITY, mm/cm
C   WP  = WILTING POINT, mm/cm
C   AS  = VOLUMETRIC MOISTURE CONTENT AT SATURATION, mm/cm
C**   ID ..... CROP IDENTIFICATION NUMBER
C**   ID FOR PADDY KHARIF IS 1
C**   ID FOR PADDY RABI IS 2
C**   ID FOR SUGARCANE IS 3
C**   ID FOR GRAM IS 4
C**   ID FOR COCONUT IS 5
C**   ID FOR BARE SOILS IS 6
C*****
COMMON /model/ I,J,K,R,RIR,ET0,CKC,SHC,FC,BUH,MON,
1      AS,PWP,M,AW,NCP,FR,DEEP,IDOS,RDM,ND,IDSOIL,
2      IDD1,IDD2,IDD3,IDD,ICOD,IDCJD,IDPOLY,NYEAR,
3      DRF,ALPHA
      DIMENSION RD(732),R(732),ET0(732),CKC(732),QIRR(732),
1NWN(52),ET(366),RFB(1000),AEB(1000)
      DIMENSION RIR(732),PFRC(1000),AET(1000),TPER(100),TAE(100)
      DIMENSION PERS(400),AETS(400),PERG(120),AETG(120)
      DIMENSION PERB(400),AETB(400),PERCN(400),AETC(400)
      DIMENSION DEFIS(400),DEFIC(400),DEFIG(200),DEFIB(400)
      DIMENSION DEFI(400),TDEFIS(15),TDEFIC(15),TDEFIG(15),TDEFIB(15)
      DIMENSION TITLES(20),RPER(150),RPET(366),TPERG(12)
      INTEGER DRF
C
      OPEN(1,FILE='GISID',STATUS='OLD')
      READ(1,3)TITLES
3      FORMAT(20A4)
      WRITE(*,*)'YEAR UPTO WHICH THE WB IS TO RUN '
      READ(*,*)NLAST
      NP=42
C      np=2
      DO 300 IDP=1,NP
      WRITE(*,*)'      POLYGON NUMBER= ',IDP
      READ(1,4)NPOLY,IDPOLY,IDSOIL,IDRAING,IDMANDAL,IDCANAL
4      FORMAT(I2,6X,I2,6X,I1,6X,I1,6X,I2,6X,I1)
      WRITE(*,*)NPOLY,IDPOLY,IDSOIL,IDRAING,IDMANDAL,IDSOIL
      IF(IDPOLY .EQ. 0)GO TO 300
      OPEN(3,FILE='PETDATA',STATUS='OLD')
      GO TO (41,42,43,44,45,46,47)IDRAING
41      OPEN(4,FILE='SKPALI',STATUS='OLD')
      GO TO 48
42      OPEN(4,FILE='MONDEP',STATUS='OLD')
      GO TO 48
43      OPEN(4,FILE='RYALI',STATUS='OLD')
      GO TO 48
44      OPEN(4,FILE='CHINTALA',STATUS='OLD')
      GO TO 48
45      OPEN(4,FILE='AINAVILI',STATUS='OLD')
      GO TO 48
46      OPEN(4,FILE='MUKKAM',STATUS='OLD')

```

```

        GO TO 48
47    OPEN(4,FILE='GOPALA',STATUS='OLD')
        GO TO 48
C    ***Read data files.
C
48    READ(3, 703)(ET0(J),J=1,365)
703    FORMAT(8F9.2)
        GO TO(101,102)IDSOIL
101    OPEN(2,FILE='SOILCLAY',STATUS='OLD')
        GO TO 103
102    OPEN(2,FILE='SOILCL',STATUS='OLD')
103    READ(2,*)SHC
        READ(2,*)FC
        READ(2,*)AS
        READ(2,*)PWP
C
        ID=1
689    GO TO(10,20,30,40,50,60),ID
10    OPEN(8,FILE='PADDYK1',STATUS='OLD')
C    OPEN(10,FILE='RICEK.OUT')
        OPEN(11,FILE='RPERK.OUT')
        OPEN(40,FILE='rperk1')
        WRITE(*,*)'CALCULATING FOR KHARIF PADDY'
        WRITE(11,*)'NYEAR,' POLYGON NO='IDPOLY
        GO TO(31,32,33,34)IDCANAL
c    *****
c    pirkg,pirka,pirkb,pirkm
c    *****
31    OPEN(5,FILE='PIRKG2',STATUS='OLD')
        IDC=10
        GO TO 699
32    OPEN(5,FILE='PIRKA2',STATUS='OLD')
        IDC=10
        GO TO 699
33    OPEN(5,FILE='PIRKB2',STATUS='OLD')
        IDC=10
        GO TO 699
34    OPEN(5,FILE='PIRKM2',STATUS='OLD')
        IDC=10
        GO TO 699
20    OPEN(8,FILE='PADDYR1',STATUS='OLD')
        WRITE(*,*)'CALCULATING FOR RABI PADDY'
C    OPEN(17,FILE='RICER.OUT')
        OPEN(18,FILE='RPERR.OUT')
        OPEN(42,FILE='mperr1')
        WRITE(18,*)'NYEAR,' POLYGON NO='IDPOLY
        GO TO (35,36,37,38)IDCANAL
35    OPEN(5,FILE='PIRRG2',STATUS='OLD')
        IDC=20
        GO TO 699
36    OPEN(5,FILE='PIRRA2',STATUS='OLD')
        IDC=20
        GO TO 699
37    OPEN(5,FILE='PIRRB2',STATUS='OLD')
        IDC=20
        GO TO 699
38    OPEN(5,FILE='PIRRM2',STATUS='OLD')
        IDC=20
        GO TO 699
30    OPEN(8,FILE='SUGARC1',STATUS='OLD')

```



```

        WRITE(*,*)'CALCULATING FOR SUGARCANE'
        OPEN(14,FILE='SPER2.OUT')
        GO TO 699
40      OPEN(8,FILE='GRAM1',STATUS='OLD')
        WRITE(*,*)'CALCULATING FOR GRAM'
        OPEN(23,FILE='GPER2.OUT')
        GO TO 699
50      OPEN(8,FILE='COCONU1',STATUS='OLD')
        WRITE(*,*)'CALCULATING FOR COCONUT'
        OPEN(15,FILE='CPER2.OUT')
        GO TO 699
60      OPEN(8,FILE='BARESO1',STATUS='OLD')
        WRITE(*,*)'CALCULATING FOR BARE SOIL'
        OPEN(16,FILE='BPER2.OUT')
699     CONTINUE
        IJK=0
        WRITE(*,*)'ID=',ID
        IF((ID .EQ. 1) .OR. (ID .EQ. 2))GO TO 100
555     DO 99 I=1,732
99      QIRR(I)=0.0
100     READ(4,701)NYEAR
        WRITE(*,*)NYEAR
        IJK=IJK+1
701     FORMAT(I4)
C***    NYEAR — YEAR
        NY=NYEAR/4*4
        IF(NYEAR.EQ.NY) GO TO 11
        N=365
        GO TO 12
11      N=366
12      READ(4,702)(R(I),I=1,N)
702     FORMAT(10F8.2)
        IF (ID .GT. 2)GOTO 110
        READ(5,26)NCP,ND,NM,drf
26      FORMAT(5X,I3,1X,I2,1X,I2,1X,I2)
        write(*,*)'drf=',drf
        READ(5,600)(RIR(I),I=1,NCP)
600     FORMAT(10(F7.2))
110     IF(IJK.GT.1) GO TO 557
        IF(N.EQ.365) GO TO 13
        DO 205 J=61,N
205      ET(J)=ET0(J-1)
        ET0(60)=ET(59)
        DO 211 J=61,N
211      ET0(J)=ET(J)
13      DO 301 J=1,365
301      ET0(J+N)=ET0(J)
        IF((ID .EQ. 1) .OR. (ID .EQ. 2))GO TO 120
        IF (ID .EQ. 5)GO TO 105
        IF (ID .EQ. 6)GO TO 550
C
C***    DATA INPUT FOR SUGARCANE AND GRAM
C
        READ(8,704)ND,NM,THETA0,RDM,MDT,NDE,NDVP,NCP,NCG,
        1PSI,FSM,ICOD,RDI,DIRR,MON
        WRITE(*,704)ND,NM,THETA0,RDM,MDT,NDE,NDVP,NCP,NCG,
        1PSI,FSM,ICOD,RDI,DIRR,MON
704     FORMAT(I2,1X,I2,1X,F5.3,1X,F5.1,1X,5(I3,1X),
        1F5.1,1X,F5.3,1X,I3,1X,F5.1,1X,F5.1,1X,I2)
        THETA0=THETA0-PWP

```

```

      FSM=FSM-PWP
      IF(N.EQ 366)ICOD=ICOD+1
      GO TO 125
C
C*** DATA INPUT FOR PADDY CROP
C
      120 READ(8,*)AW,DM,RDM,BUH,NCP,MON,ALPHA
      READ(8,*)IDD1,IDD2,IDD3,IDD,ICOD
      write(*,*)'alpha=',alpha
      125 READ(8,705)(CKC(K),K=1,NCP)
      705 FORMAT(15(F4.2,1X))
      IF((ID .EQ. 1) .OR. (ID .EQ. 2))GO TO 557
      GO TO 557
C
C*** DATA INPUT FOR COCONUT
C
      105 READ(8,712)ND,NM,THETA0,RDM,NDE,NDVP,NCG,
      1PSI,FSM,ICOD,RDI,DIRR,MON
      WRITE(*,*)ND,NM,THETA0,RDM,NDE,NDVP,NCG,
      1PSI,FSM,ICOD,RDI,DIRR,MON
      712 FORMAT(I2,1X,I2,1X,F5.3,1X,F5.1,1X,3(I3,1X),
      1F5.1,1X,F5.3,1X,I3,1X,F5.1,1X,F5.1,1X,I2)
      THETA0=THETA0-PWP
      FSM=FSM-PWP
      NCP=N
      READ(8,713)(CKC(k),k=1,NCP)
      713 FORMAT(15(F4.2,1X))
      IF(N .EQ. 366)ICOD=ICOD+1
      GO TO 557
C
C*** DATA INPUT FOR BARE SOIL
C
      550 READ(8,711)ND,NM,ALPHA,RDM,NCP,FSM,NDE,NDVP,RDI,MON
      WRITE(*,*)ND,NM,ALPHA,RDM,NCP,FSM,NDE,NDVP,RDI,MON
      711 FORMAT(I2,1X,I2,1X,F5.3,1X,F5.1,1X,I3,1X,
      1F5.3,1X,I1,1X,I1,1X,F5.1,1X,I2)
      FSM=FSM-PWP
C*** Obtain the day number corresponding to the date of sowing
      557 CALL DAYN(ND,NM,NYEAR,IDOS)
      135 N1=N+1
      NN=N+N
      READ(4,702)(R(I),I=N1,NN)
      e write(*,702)(r(i),i=1,nn)
      IF(ID .GT. 2)GO TO 140
      CALL RICEBAL
      GO TO 1000
      140 WHC=FC-PWP
      IF (ID .EQ. 5)GO TO 141
      IF (ID .EQ. 6)GO TO 115
C*****SUGARCANE AND OTHER CROPS
C
      RD(0)=RDI
      IF(PSI.GT.0)FSM=FSM+PSI.RDI
      IF(FSM.GT.WHC)GO TO 14
      THETA0=0.0
      GO TO 15
      14 FSM=WHC
      XX=(PSI/RDI-WHC)*RDI
      THETA0=THETA0+XX (RDM-RDI)
      GO TO 15
C**** COCONUT

```

```

141  WRITE(*,*)'CALCULATING FOR COCONUT CROP'
      THETA0=0.0
      IF(PSI .GT. 0)FSM=FSM+PSI/RDI
      IF(FSM .GT. WHC)FSM=FC
      THETA0=0.0
      GO TO 775
C***  BARESOIL
115   THETA0=0.0
      IF(FSM .GT. WHC)FSM=WHC
      THETA0=0.0
      GO TO 775
15    CONTINUE
C 777  FORMAT(2X,' YEAR 'J4)
C 706  FORMAT(' DAS      RD   DRD   0o  ISM   R      Q      ER   IR   DRD0o
C      1PERC ASW      0  ETo   Ke   PET   p   0*   AET   FSM')
C 707  FORMAT('          (cm) (cm) (mm) mm/cm (mm) (mm) (mm) (mm) (mm)
C      1(mm) (mm) mm.cm mm/day mm/day mm/cm mm/day mm/cm')
C 708  FORMAT('-----')
C      1-----')
      IF(ID EQ 3)GO TO 18
C      WRITE(*,*)ID,'GRAM'
C      WRITE(21,777)NYEAR
C      WRITE(21,706)
C      WRITE(21,707)
C      WRITE(21,708)
      GO TO 775
18    CONTINUE
      WRITE(*,*)ID,'SUGARCANE'
C      WRITE(7,777)NYEAR
C      WRITE(7,706)
C      WRITE(7,707)
C      WRITE(7,708)
775   TR=0.0
      TQ=0 0
      TER=0 0
C*****
C      COMPUTATIONS BEGIN FOR CROP SEASON
C*****
      DO 200 IDAP=1,NCP
      SMI=FSM
      IF(ID .GE. 5)GO TO 148
C***  ESTIMATE THE ROOT GROWTH.
      RD(IDAP)=RDM*(0.5+0.5*SIN((3.03*IDAP/MDT)-1.47))
      IF(RD(IDAP).LT. RDI)RD(IDAP)=RDI
      IF(IDAP.GT.MDT)RD(IDAP)=RDM
      GO TO 149
148   RD(IDAP)=RDM
      IF(IDAP GT. 1)GO TO 149
      DRD=RD(IDAP)-RDI
      GO TO 150
149   DRD=RD(IDAP)-RD(IDAP-1)
150   DRDT0=DRD*THETA0
      RF=R(IDOS+IDAP)
      RFB(IDAP)=R(IDOS-IDAP)
      IF(RF.LE.0.0) GO TO 560
C***  ESTIMATE THE EFFECTIVE RAINFALL FROM RAINFALL.
      CALL ERAIN(IDAP,RF,NDE,NDVP,NCP,SMI,Q,ER,FC,PWP,id)
      GO TO 599
560   Q=0.0
      ER=0.0

```

```

599  TR=TR+RF
      TQ=TQ+Q
      TER=TER+ER
      A=ER+QIRR(IDAP)
      IF(IDAP.GT. 1)GO TO 151
      B=(FC-SMI)*RDI+(FC-THETA0)*DRD
      GO TO 152
151  B=(FC-SMI)*RD(IDAP-1)+(FC-THETA0)*DRD
152  IF(A.GT.B) GO TO 203
      PERC(IDAP)=0.0
      DPER=0.0
      GO TO 204
203  PERC(IDAP)=A-B
      IF(RD(IDAP)EQ.RDM) GO TO 62
      THETA0=THETA0+PERC(IDAP)/(RDM-RD(IDAP))
      IF(THETA0.LE.WHC)GO TO 204
      DPERC=(THETA0-WHC)*RD(IDAP)
      THETA0=WHC
      GO TO 204
62   THETA0=0.0
204  IF(RD(IDAP)EQ.RDM) THETA0=0.0
      IF(IDAP.GT. 1)GO TO 153
      ASW=RDI*SMI+ER+QIRR(IDAP)+DRDT0-PERC(IDAP)
      GO TO 154
153  ASW=RD(IDAP-1)*SMI+ER+QIRR(IDAP)+DRDT0-PERC(IDAP)
154  THETA=ASW/RD(IDAP)
      IF(LK.GT.1) GO TO 558
      ET0(IDAP)=ET0(IDOS+IDAP)
558  IF(ID.EQ. 6)GO TO 561
      PET=ET0(IDAP)*CKC(IDAP)
      GO TO 565
565  ETM=PET
      GO TO 562
C*****
C****  EVAPORATION FROM UNCULTIVATED SOILS
C      AEB=ESTIMATED EVAPORATION FROM BARE SOILS
C*****
561  CALL ETBARE(IDAP,NCPALPHA,RFB,ET0,AEB)
      GO TO 202
C***  Get the soil water depletion factor corresponding to PET.
562  IF(ID.EQ. 5)GO TO 175
      CALL SWDF(NCG,ETM,P)
      THETAR=(1.0-P)*WHC
      IF(THETA.GE THETAR) GO TO 201
      AET(IDAP)=THETA/THETAR*PET
      GO TO 215
175  P=0.5
      THETAR=(1.0-P)*WHC
201  AET(IDAP)=PET
      GO TO 215
202  FSM=(SMI*RD(IDAP)+ER-PERC(IDAP)-AEB(IDAP))/RD(IDAP)
      IF(FSM.LE. 0)FSM=0.0
      PERB(IDAP)=PERC(IDAP)
      AETB(IDAP)=AEB(IDAP)
      DEFI(IDAP)=AETB(IDAP)-ER
      DEFIB(IDAP)=DEFI(IDAP)
      IF(ID.EQ. 6)GO TO 200
215  IF(IDAP.GT. 1)GO TO 156
      FSM=(SMI*RDI+ER+QIRR(IDAP)+DRDT0-PERC(IDAP)-AET(IDAP))/RD(IDAP)
      DEFI(IDAP)=PET-ER-QIRR(IDAP)

```

```

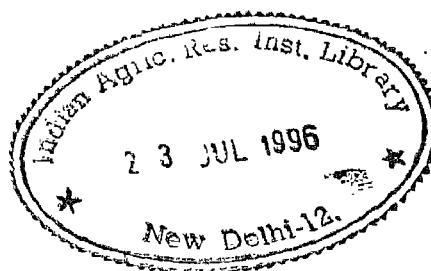
      IF(FSM .LE. 0.0)FSM=0.0
      GO TO 157
156  FSM=(SMI*RD(IDAP-1)+ER+QIRR(IDAP)+DRDT0-PERC(IDAP)-
      1 AET(IDAP))/RD(IDAP)
      DEFI(IDAP)=AET(IDAP)-ER-QIRR(IDAP)
      IF(FSM .LE. 0.0)FSM=0.0
157  IF(ID .EQ. 5)GO TO 216
      IF(ID .EQ. 3)GO TO 220
      PERG(IDAP)=PERC(IDAP)
      AETG(IDAP)=AET(IDAP)
      DEFIG(IDAP)=DEFI(IDAP)
      GO TO 217
220  PERS(IDAP)=PERC(IDAP)
      AETS(IDAP)=AET(IDAP)
      DEFIS(IDAP)=DEFI(IDAP)
      GO TO 217
216  CONTINUE
      PERCN(IDAP)=PERC(IDAP)
      AETC(IDAP)=AET(IDAP)
      DEFIC(IDAP)=DEFI(IDAP)
217  IF(FSM.LT.THETAR)GO TO 789
      IF(ID .EQ. 5)GO TO 200
      GO TO 22
C***  Get the irrigation decision after accounting 3 days advance rain
C 789  ARF=R(IDOS+IDAP+1)+R(IDOS+IDAP+2)+R(IDOS+IDAP+3)
C      AETO=3*PET
C      RZMC=(RD(IDAP+3)-RD(IDAP))*THETA0
C      IF((ARF+RZMC).LT.AETO) QIRR(IDAP+1)=DIRR
789  QIRR(IDAP+1)=DIRR
      IF((IDAP+1).GT.(ICOD-1))QIRR(IDAP+1)=0.0
      IF(ID .EQ. 5)GO TO 200
22  CONTINUE
C 700  FORMAT(1X,I3,1X,F6.2,1X,3(F4.2,1X),F5.1,1X,2(F5.2,1X),F6.1,
C      11X,F4.2,1X,F5.2,1X,F6.2,1X,4(F4.2,1X),F5.3,1X,3(F4.2,1X))
      IF(ID .EQ. 3)GO TO 23
C      WRITE(21,700)IDAP,RD(IDAP),DRD,THETA0,SMI,RF,Q,ER,QIRR(IDAP),
C      1DRDT0,PERC,ASW,THETA,ETO(IDAP),CKC(IDAP),PET,P,THETAR,AET,FSM
      GO TO 200
23  CONTINUE
C 23  WRITE(7,700)IDAP,RD(IDAP),DRD,THETA0,SMI,RF,Q,ER,QIRR(IDAP),
C      1DRDT0,PERC,ASW,THETA,ETO(IDAP),CKC(IDAP),PET,P,THETAR,AET,FSM
200  CONTINUE
235  FORMAT(I2,2X,I4,2X,I2(F5.1,2X))
      DO 500 IN=1,12
      TPER(IN)=0.0
500  CONTINUE
      IF (ID .EQ. 3)GO TO 199
      IF (ID .EQ. 4)GO TO 230
      IF (ID .EQ. 5)GO TO 231
      IF (ID .EQ. 6)GO TO 232
      GO TO 198
199  CALL SUM(IDAP,ID,NCP,NYEAR,PERS,DEFIS,MON,ND,TPER,TDEFIS)
      WRITE(14,235)IDPOLY,NYEAR,(TPER(MON),MON=1,12)
      MON=1
      GO TO 198
230  DO 2000 IN=1,12
      TPERG(IN)=0.0
      TDEFIG(IN)=0.0
2000 CONTINUE
      CALL SUM(IDAP,ID,NCP,NYEAR,PERG,DEFIG,MON,ND,TPERG,TDEFIG)

```

```

WRITE(23,235)IDPOLY,NYEAR,(TPERG(MON),MON=1,12)
MON=5
GO TO 198
231 CALL SUM(IDAP,ID,NCP,NYEAR,PERCN,DEFIC,MON,ND,TPER,TDEFIC)
WRITE(15,235)IDPOLY,NYEAR,(TPER(MON),MON=1,12)
MON=1
GO TO 198
232 CALL SUM(IDAP,ID,NCP,NYEAR,PERB,DEFIB,MON,ND,TPER,TDEFIB)
WRITE(16,235)IDPOLY,NYEAR,(TPER(MON),MON=1,12)
MON=1
198 CONTINUE
IF(ID.EQ. 6)GO TO 1000
C WRITE(*,709)NYEAR
C WRITE(9,709)NYEAR
C 709 FORMAT(2X,'WEEK NUMBERS REQUIRING IRRIGATION IN YEAR ',J4)
JJJ=0
IF(PSIGT0.0) GO TO 16
GO TO 17
16 JJJ=JJJ+1
NNN=IDOS-1
C*** Get the week number from the day number
CALL WN(NNN,N,NW)
NWN(JJJ)=NW
17 DO 206 IDAP=1,NCP
IF(QIRR(IDAP).EQ 0) GO TO 206
JJJ=JJJ+1
NID=IDAP+IDOS
CALL WN(NID,N,NW)
NWN(JJJ)=NW
206 CONTINUE
C WRITE(9,710)(NWN(KKK),KKK=1,JJJ)
C WRITE(*,710)(NWN(KKK),KKK=1,JJJ)
C 710 FORMAT(2X,10I5)
C WRITE(9,780)TR,TQ,TER
C WRITE(*,780)TR,TQ,TER
C 780 FORMAT(2X,'RAINFALL =',F7.2,'mm, RUNOFF = ',F7.2,'mm, ER ='
C 1,F7.2,'mm' )
1000 IF(NYEAR.GE NLAST) GO TO 556
IF(ID.LE. 2)GO TO 100
GO TO 555
556 rewind 4
close (5)
CLOSE (8)
ID=ID+1
IF(ID.GT. 6)GO TO 568
GO TO 689
568 CONTINUE
CLOSE(4)
CLOSE(5)
CLOSE(8)
CLOSE(3)
CLOSE(2)
300 CONTINUE
STOP
END
C *****
C SUBROUTINE DAYN
C *****
C This converts the date of sowing to the corresponding
C day number in the year.

```



```

C      *****
SUBROUTINE DAYN(ND,NM,NYEAR,IDOS)
C**
C**      ND...Date of sowing
C**      NM... Month of sowing
C**      NYEAR..Year
C**      IDOS. Day number in the year
C**
      NYR=NYEAR/4*4
      IF(NYEAR EQ NYR) GO TO 830
      GO TO (831,832,833,834,835,836,837,838,839,840,841,842),NM
831      IDOS=ND
      GO TO 843
832      IDOS=31-ND
      GO TO 843
833      IDOS=59+ND
      GO TO 843
834      IDOS=90+ND
      GO TO 843
835      IDOS=120+ND
      GO TO 843
836      IDOS=151+ND
      GO TO 843
837      IDOS=181+ND
      GO TO 843
838      IDOS=212+ND
      GO TO 843
839      IDOS=243+ND
      GO TO 843
840      IDOS=273+ND
      GO TO 843
841      IDOS=304+ND
      GO TO 843
842      IDOS=334+ND
      GO TO 843
830      GO TO (851,852,853,854,855,856,857,858,859,860,861,862),NM
851      IDOS=ND
      GO TO 843
852      IDOS=31+ND
      GO TO 843
853      IDOS=60+ND
      GO TO 843
854      IDOS=91+ND
      GO TO 843
855      IDOS=121+ND
      GO TO 843
856      IDOS=152+ND
      GO TO 843
857      IDOS=182+ND
      GO TO 843
858      IDOS=213+ND
      GO TO 843
859      IDOS=244+ND
      GO TO 843
860      IDOS=274+ND
      GO TO 843
861      IDOS=305+ND
      GO TO 843
862      IDOS=335+ND
843      RETURN

```

```

      END
C      *****
C      SUBROUTINE ERAIN
C      *****
C      This estimates the runoff and effective rainfall.
C      Procedure SCS curve number with soil moisture accounting
C      suggested by Sharpley and Williams (1991).
C      *****
C      SUBROUTINE ERAIN(IDAP,R,NDE,NDVP,NCP,PDSM,Q,ER,fc,pwp,id)
C**
C**      IDAP.. Days after sowing
C**      R..Daily rainfall, mm
C**      NDE...Nmber ofdays for vegetative phase. days
C**      NDVP...End day of the vegetative phase. days
C**      NCP.. Crop period, days
C**      PDSM... Previous day soil moisture(last day's FSM),mm/cm
C**      Q... Runoff, mm
C**      ER..Effective Rainfall, mm
C**
C**      DIMENSION R(1000)
C**      if(id eq. 6)go to 150
C**      go to 155
150      lu=4
C**      it=2
C**      ihc=2
C**      ihsg=2
C**      go to 160
155      IF (IDAP.LE.NDE) LU=1
C**      IF (IDAP.GT.NDE) LU=2
C**      IT=2
C**      IF (IDAP.LE.NDVP) IHC=1
C**      IF (IDAP.GT.NDVP) IHC=2
C**      IHS=4
160      CALL CN(LU,IT,IHC,IHSG,CN2)
C**      CN1=CN2-(20.0*(100.0-CN2)/(100-CN2+EXP(2.533-0.0636*
C**      1(100.0-CN2))))
C**      CN3=CN2*EXP(0.00673*(100.0-CN2))
C**      S1=254*(100.0/CN1-1.0)
C**      S2=254*(100.0/CN2-1.0)
C**      S3=254*(100.0/CN3-1.0)
C**      FC=4.0
C**      PWP=2.0
C**      FFC=PDSM/(FC-PWP)
C**      PDSM IS WITH RESPECT TO PWP, HENCE NO NEED TO SUBTRACT
C**      PWP AGAIN
C**      W2=2.0*(ALOG(0.5/(1.0-S2/S1)-0.5)-ALOG(1.0/(1.0-S3/S1)
C**      1-1.0))
C**      W1=ALOG(1.0/(1.0-S3/S1)-1.0)+W2
C**      S=S1*(1.0-(FFC/(FFC+EXP(W1-W2*FFC))))
C**      SS=0.3*S
C**      IF(R.GT.SS) Q=(R-SS)**2/(R+0.7*S)
C**      IF(R.LE.SS) Q=0.0
C**      ER=R-Q
C**      WRITE(6,1)IDAP,R,LU,IT,IHC,IHSG,CN2,CN1,CN3,S1,S2,S3,
C**      1PDSM,FFC,W1,W2,S,Q,ER
C**      1 FORMAT(2X,I3,1X,F5.1,2X,4(1I,2X),3(F4.1,1X),5(F6.2,1X),
C**      12(F6.3,2X),3(F6.2,1X))
C**      RETURN
C**      END
C      *****

```



```

C      SUBROUTINE CN
C      *****
C      This gives the average curve number values (CN2).
C      Ref : Land reforms, hydrology and Sedimentation
C      ( Sahu, D 1990)
C      SUBROUTINE CN(LU,IT,IHC,IHSG,CN2)
C
C      -----
C*     LU - Landuse option
C*     IT - Treatment/Mnangement practice option
C*     IHC - Hydrologic soil cover option
C*     IHSG - Hydrologic soil group option
C*     -----
C      GO TO (101,102,103,104,105,106,107,108,109,110),LU
101    IF(IHSG.EQ.1) NC=77
        IF(IHSG.EQ.2) NC=86
        IF(IHSG.EQ.3) NC=91
        IF(IHSG.EQ.4) NC=94
        GO TO 999
102    GO TO (111,112,113),IT
111    GO TO (114,115),IHC
114    IF(IHSG.EQ.1) NC=72
        IF(IHSG.EQ.2) NC=81
        IF(IHSG.EQ.3) NC=88
        IF(IHSG.EQ.4) NC=91
        GO TO 999
115    IF(IHSG.EQ.1) NC=67
        IF(IHSG.EQ.2) NC=78
        IF(IHSG.EQ.3) NC=85
        IF(IHSG.EQ.4) NC=89
        GO TO 999
112    GO TO (116,117),IHC
116    IF(IHSG.EQ.1) NC=70
        IF(IHSG.EQ.2) NC=79
        IF(IHSG.EQ.3) NC=84
        IF(IHSG.EQ.4) NC=88
        GO TO 999
117    IF(IHSG.EQ.1) NC=65
        IF(IHSG.EQ.2) NC=75
        IF(IHSG.EQ.3) NC=82
        IF(IHSG.EQ.4) NC=86
        GO TO 999
113    GO TO (118,119),IHC
118    IF(IHSG.EQ.1) NC=66
        IF(IHSG.EQ.2) NC=74
        IF(IHSG.EQ.3) NC=80
        IF(IHSG.EQ.4) NC=82
        GO TO 999
119    IF(IHSG.EQ.1) NC=62
        IF(IHSG.EQ.2) NC=71
        IF(IHSG.EQ.3) NC=78
        IF(IHSG.EQ.4) NC=81
        GO TO 999
103    GO TO (121,122,123),IT
121    GO TO (124,125),IHC
124    IF(IHSG.EQ.1) NC=65
        IF(IHSG.EQ.2) NC=76
        IF(IHSG.EQ.3) NC=84
        IF(IHSG.EQ.4) NC=88
        GO TO 999
125    IF(IHSG.EQ.1) NC=63

```

```

      IF(IHSG.EQ.2) NC=75
      IF(IHSG.EQ.3) NC=83
      IF(IHSG.EQ.4) NC=87
      GO TO 999
122  GO TO (126,127),IHC
126  IF(IHSG.EQ.1) NC=63
      IF(IHSG.EQ.2) NC=74
      IF(IHSG.EQ.3) NC=82
      IF(IHSG.EQ.4) NC=85
      GO TO 999
127  IF(IHSG.EQ.1) NC=63
      IF(IHSG.EQ.2) NC=75
      IF(IHSG.EQ.3) NC=83
      IF(IHSG.EQ.4) NC=87
      GO TO 999
123  GO TO (128,129),IHC
128  IF(IHSG.EQ.1) NC=61
      IF(IHSG.EQ.2) NC=72
      IF(IHSG.EQ.3) NC=79
      IF(IHSG.EQ.4) NC=82
      N1=N+1
      GO TO 999
129  IF(IHSG.EQ.1) NC=59
      IF(IHSG.EQ.2) NC=70
      IF(IHSG.EQ.3) NC=78
      IF(IHSG.EQ.4) NC=81
      GO TO 999
104  GO TO (131,132,133),IT
131  GO TO (134,135),IHC
134  IF(IHSG.EQ.1) NC=66
      IF(IHSG.EQ.2) NC=77
      IF(IHSG.EQ.3) NC=85
      IF(IHSG.EQ.4) NC=89
      GO TO 999
135  IF(IHSG.EQ.1) NC=58
      IF(IHSG.EQ.2) NC=72
      IF(IHSG.EQ.3) NC=81
      IF(IHSG.EQ.4) NC=85
      GO TO 999
132  GO TO (136,137),IHC
136  IF(IHSG.EQ.1) NC=64
      IF(IHSG.EQ.2) NC=75
      IF(IHSG.EQ.3) NC=83
      IF(IHSG.EQ.4) NC=85
      GO TO 999
137  IF(IHSG.EQ.1) NC=55
      IF(IHSG.EQ.2) NC=69
      IF(IHSG.EQ.3) NC=78
      IF(IHSG.EQ.4) NC=83
      GO TO 999
133  GO TO (138,139),IHC
138  IF(IHSG.EQ.1) NC=63
      IF(IHSG.EQ.2) NC=73
      IF(IHSG.EQ.3) NC=80
      IF(IHSG.EQ.4) NC=83
      GO TO 999
139  IF(IHSG.EQ.1) NC=61
      IF(IHSG.EQ.2) NC=67
      IF(IHSG.EQ.3) NC=76
      IF(IHSG.EQ.4) NC=80

```

```

GO TO 999
105 GO TO (141,142),IT
141 GO TO (143,144,145),IHC
143 IF(IHSG.EQ.1) NC=68
    IF(IHSG.EQ.2) NC=79
    IF(IHSG.EQ.3) NC=86
    IF(IHSG.EQ.4) NC=89
    GO TO 999
144 IF(IHSG.EQ.1) NC=49
    IF(IHSG.EQ.2) NC=69
    IF(IHSG.EQ.3) NC=79
    IF(IHSG.EQ.4) NC=84
    GO TO 999
145 IF(IHSG.EQ.1) NC=39
    IF(IHSG.EQ.2) NC=61
    IF(IHSG.EQ.3) NC=74
    IF(IHSG.EQ.4) NC=80
    GO TO 999
142 GO TO (153,154,155),IH
153 IF(IHSG.EQ.1) NC=47
    IF(IHSG.EQ.2) NC=67
    IF(IHSG.EQ.3) NC=81
    IF(IHSG.EQ.4) NC=88
    GO TO 999
154 IF(IHSG.EQ.1) NC=25
    IF(IHSG.EQ.2) NC=59
    IF(IHSG.EQ.3) NC=75
    IF(IHSG.EQ.4) NC=83
    GO TO 999
155 IF(IHSG.EQ.1) NC=6
    IF(IHSG.EQ.2) NC=35
    IF(IHSG.EQ.3) NC=70
    IF(IHSG.EQ.4) NC=79
    GO TO 999
106 IF(IHSG.EQ.1) NC=30
    IF(IHSG.EQ.2) NC=58
    IF(IHSG.EQ.3) NC=71
    IF(IHSG.EQ.4) NC=78
    GO TO 999
107 GO TO (163,164,165),IHC
163 IF(IHSG.EQ.1) NC=45
    IF(IHSG.EQ.2) NC=66
    IF(IHSG.EQ.3) NC=77
    IF(IHSG.EQ.4) NC=83
    GO TO 999
164 IF(IHSG.EQ.1) NC=36
    IF(IHSG.EQ.2) NC=60
    IF(IHSG.EQ.3) NC=73
    IF(IHSG.EQ.4) NC=79
    GO TO 999
165 IF(IHSG.EQ.1) NC=25
    IF(IHSG.EQ.2) NC=55
    IF(IHSG.EQ.3) NC=70
    IF(IHSG.EQ.4) NC=77
    GO TO 999
108 IF(IHSG.EQ.1) NC=59
    IF(IHSG.EQ.2) NC=74
    IF(IHSG.EQ.3) NC=82
    IF(IHSG.EQ.4) NC=86
    GO TO 999

```

```

109  IF(IHSG.EQ.1) NC=72
      IF(IHSG.EQ.2) NC=82
      IF(IHSG.EQ.3) NC=87
      IF(IHSG.EQ.4) NC=89
      GO TO 999
110  IF(IHSG.EQ.1) NC=77
      IF(IHSG.EQ.2) NC=84
      IF(IHSG.EQ.3) NC=90
      IF(IHSG.EQ.4) NC=92
999  CN2=NC
      RETURN
      END
C      *****
C      SUBROUTINE SWDF
C      *****
C      This gives the value of soil water depletion factor by
C      linear interpolation. Ref : Doorenbos and Kassam, 1979.
C      *****
C      SUBROUTINE SWDF(NCG,PET,P)
C****
C****  NCG - Number of the crop group
C****  Options are 1 , 2 , 3 or 4
C****  1.. for Onion, Pepper, Potato
C****  2.. for Banana, Cabbage, Grape, Pea, Tomato
C****  3.. for Alfalfa,Bear,Citrus,Groundnut,Pineapple,
C****  Watermelon,Wheat
C****  4 for Cotton,Maize,Olive,Safflower,Sorghum,Soybean,
C****  Sugarbeet, Sugarcane and Tobacco.
C****  PET - Potential maximum evapotranspiration (mm/day)
C****  P   - Soil water depletion factor
C*****
C*****
      GO TO (801,802,803,804),NCG
801  IF(PET.LE.2.0) GO TO 822
      IF(PET.LE.4.0) GO TO 805
      IF(PET.LE.6.0) GO TO 806
      IF(PET.LE.8.0) GO TO 807
      IF(PET.LE.9.0) GO TO 808
      P=0.2-0.025*(PET-9.0)
      GO TO 899
822  PET=0.5
      GO TO 899
805  P=0.5-0.075*(PET-2.0)
      GO TO 899
806  P=0.35-0.05*(PET-4.0)
      GO TO 899
807  P=0.25-0.025*(PET-6.0)
      GO TO 899
808  P=0.2
      GO TO 899
802  IF(PET.LE.2.0) GO TO 823
      IF(PET.LE.4.0) GO TO 809
      IF(PET.LE.5.0) GO TO 810
      IF(PET.LE.6.0) GO TO 811
      IF(PET.LE.7.0) GO TO 812
      IF(PET.LE.8.0) GO TO 813
      P=0.275-0.025*(PET-8.0)
      GO TO 899
823  P=0.675
      GO TO 899
809  P=0.675-0.1*(PET-2.0)

```

```

      GO TO 899
810  P=0.475-0.075*(PET-4.0)
      GO TO 899
811  P=0.4-0.05*(PET-5.0)
      GO TO 899
812  P=0.35-0.025*(PET-6.0)
      GO TO 899
813  P=0.325-0.05*(PET-7.0)
      GO TO 899
803  IF(PET.LE.2.0) GO TO 824
      IF(PET.LE.5.0) GO TO 814
      IF(PET.LE.6.0) GO TO 815
      IF(PET.LE.7.0) GO TO 816
      IF(PET.LE.8.0) GO TO 817
      IF(PET.LE.9.0) GO TO 818
      P=0.35-0.05*(PET-9.0)
      GO TO 899
824  P=0.80
      GO TO 899
814  P=0.8-0.1*(PET-2.0)
      GO TO 899
815  P=0.5-0.05*(PET-5.0)
      GO TO 899
816  P=0.45-0.025*(PET-6.0)
      GO TO 899
817  P=0.425-0.05*(PET-7.0)
      GO TO 899
818  P=0.375-0.025*(PET-8.0)
      GO TO 899
804  IF(PET.LE.2.0) GO TO 825
      IF(PET.LE.3.0) GO TO 819
      IF(PET.LE.5.0) GO TO 820
      IF(PET.LE.8.0) GO TO 821
      P=0.45-0.025*(PET-8.0)
      GO TO 899
825  P=0.875
      GO TO 899
819  P=0.875-0.075*(PET-2.0)
      GO TO 899
820  P=0.8-0.1*(PET-3.0)
      GO TO 899
821  P=0.6-0.05*(PET-5.0)
899  RETURN
      END
C      *****
C      SUBROUTINE WN
C      *****
C      This gives the week number corresponding to a day
C      number in an year.
C      *****
C      SUBROUTINE WN(NID,N,NW)
      IF(N.EQ.366) GO TO 80
      GO TO 81
80  IF(NID.LE.59) GO TO 81
      IF(NID.GT.N)NID=NID-N
      NKK=NID-1
      NJJ=NKK/7*7
      IF(NKK.EQ.NJJ) GO TO 84
      NW=NKK/7+1
      IF(NID.EQ.N-1)NW=52

```

```

      IF(NID.EQ.N)NW=52
      GO TO 83
84    NW=NKK/7
      IF(NKK.EQ.0)NW=1
      GO TO 83
81    IF(NID.GT.N)NID=NID-N
      NII=NID/7*7
      IF(NID.EQ.NII) GO TO 82
      NW=NID/7+1
      GO TO 83
82    NW=NID/7
      IF(NID.EQ.N)NW=52
83    IF(NW.EQ.53)NW=1
      IF(NW.EQ.0) NW=52
      RETURN
      END
C    *****
C
C    THIS PROGRAMME CALCULATES THE PERCOLATION FROM RICE FIELDS BY
C    WATER BALANCE AND DARCY'S LAW.
C
C    *****
C
C    RA  = DAILY RAINFALL
C    ETO = DAILY REFERENCE EVAPOTRANSPIRATION
C    AKCO = DAILY VALUE OF CROP COEFFICIENT FOR RICE CROP
C    AW  = AVAILABLE WATER ON FIRST DAY
C    N4  = DURATION OF THE CROP SEASON
C    SHC  = SATURATED HYDRAULIC CONDUCTIVITY
C    FC  = FIELD CAPACITY
C    WP  = WILTING POINT
C    AS  = VOLUMETRIC MOISTURE CONTENT AT SATURATION
C
C    *****
C
C    SUBROUTINE RICEBAL
C    COMMON /MODEL/ I,J,K,R,RIR,ETO,CKC,SHC,FC,BUH,MON,
1      AS,PWP,M,AW,NCP,FR,dcep,IDOS,RDM,ND,IDSOIL,
2      IDD1,IDD2,IDD3,IDD,ICOD,IDC,ID,IDPOLY,NYEAR,
3      DRF,ALPHA
C    INTEGER DRF
C    DIMENSION RIR(732),R(732),ETO(732),CKC(732)
C    DIMENSION RA(732)
C    DIMENSION SW(10),SW1(10),TPE(10),TR(10),TI(10),TRU(10)
C    DIMENSION TD(10),TA(10),TFR(10),TSHC(10),TC(100)
C    DIMENSION RPER(350),RPET(366)
C    DIMENSION TPERR(12),TAER(12),DEFIR(365),TDEFIR(12)
C    DIMENSION TPERK(12),TDEFK(12)
C    IF(IDC.EQ. 10)GO TO 75
C    WRITE(*,*)'RABI PADDY'
C    GO TO 76
75    WRITE(*,*)'KHARIF PADDY'
76    CONTINUE
      IK=5
      IF(IDSOIL.EQ. 1)GO TO 140
      SHCS=SHC/13
      GO TO 141
140    SHCS=SHC/5
141    TRAIN=0

```

```

TRUN=0
TREFET=0
TPET=0
TAET=0
TIRR=0
TDEEP=0
AM1=AS
FR=100.0
C   ROOT ZONE DEPTH Z IN MM
    Z=RDM*10
    RUNO=0
    TSW=AS*Z/10
    TSW1=TSW
    BUH=200.0
c   kdcf=duration of crop season and fallow land after paddy crop
    kdcf=nep+drf
    DO 100 I=1,kdcf
      if(i .gt. nep)go to 475
      go to 476
475   rir(i)=0.0
476   continue
2000  format(10f8.2)
      RA(I)= R(I+IDOS)+ RIR(I)
      AIRR=RIR(I)
      RUNO=0.0
      IF ((RA(I)+FR) .GT. (BUH))RUNO=RA(I)+FR-BUH
      IF(I GE IDD3 AND. I LT.(IDD3+IDD))GOTO163
      FR=FR+RA(I)-RUNO
      IF(TSW .LT. TSW1)FR=RA(i)-(TSW1-TSW)-RUNO
      GO TO 164
163   RUNO=RA(I)+FR
      FR=0.0
      if(tsw .gt. fc*z*.1)go to 166
      rper(i)=0.0
      go to 168
164   if(fr .gt. 0)go to 166
      if(tsw .gt. fc*z*.1)go to 166
      rper(i)=0.0
      go to 168
166   rper(i)=SHCS*(FR+Z)/Z
168   deep=RPER(I)
      RET= ET0(I+IDOS)
      if(i .gt. nep)go to 350
      AKC=CKC(I)
      RPET(I)=RET*AKC
      go to 400
350   call ctbare(i,kdcf,alpha,ra,ret,rpet)
400   IF(FR .GT. 0)GO TO 175
      IF(TSW .GE. FC*Z*.1)GO TO 177
      AET=((tsw/(Z*.1)-PWP)/(FC-PWP))*RPET(I)
      FR=0.0
      DEEP=0.0
      TSW=TSW-AET+RA(I)
      IF(TSW GE TSW1)TSW=TSW1
      GO TO 165
175   AET=RPET(I)
      FR=FR-AET-DEEP
      IF(FR LE. 0)GO TO 176
      TSW=TSW1
      GO TO 165

```

```

176  FR=0.0
      TSW=TSW-AET-DEEP+RA(I)
      IF(TSW .GE. TSW1)TSW=TSW1
      GO TO 165
177  AET=RPET(I)
      FR=0.0
      TSW=TSW-RPET(I)-DEEP+RA(I)
      IF(TSW .GE. TSW1)TSW=TSW1
      GO TO 165
165  RAIN=R(I+IDOS)
150  FORMAT(I3,1X,8(F8.2))
20   FORMAT(I3,F8.2,F8.2)
      IF(IDC .EQ. 10)GO TO 160
C    WRITE(17,150)I,RAIN,RUNO,AIRR,FR,DEEP,TSW,RET,AKC
      WRITE(18,20)I,FR,DEEP
      GO TO 161
C 160 WRITE(10,150)I,RAIN,RUNO,AIRR,FR,DEEP,TSW,RET,AKC
160  WRITE(11,20)I,FR,DEEP
161  DR=FR
      TRAIN=TRAIN+RA(I)-RIR(I)
      TRUN=TRUN+RUNO
      TREFET=TREFET+RET
      TPET=TPET+PET
      TAET=TAET+AET
      TIRR=TIRR+AIRR
      TDEEP=TDEEP+DEEP
      DEFIR(I)=RPET(I)+RUNO-RA(I)
100  CONTINUE
125  FORMAT(I2,2X,12(2X,F5.1))
      IF(ID .EQ. 1)GO TO 101
      GO TO 102
101  DO 250 IN=1,12
      TPERK(IN)=0.0
      TDEFIK(IN)=0.0
250  CONTINUE
      CALL SUM(1,ID,kdef,NYEAR,RPER,DEFIR,MON,ND,TPERK,TDEFIK)
      WRITE(40,125)IDPOLY,(TPERK(MON),MON=1,12)
      MON=1
      GO TO 127
102  DO 255 IN=1,12
      TPERK(IN)=0.0
      TDEFIR(IN)=0.0
255  CONTINUE
      CALL SUM(1,ID,kdef,NYEAR,RPER,DEFIR,MON,ND,TPERR,TDEFIR)
      WRITE(42,125)IDPOLY,(TPERR(MON),MON=1,12)
      MON=6
127  DELT1=TIRR+TRAIN+TSW1
      DELT2=TRUN+TDEEP+TAET
      DELT =DELT1-DELT2
      TR(IK)=TRAIN
      TI(IK)=TIRR
      TRU(IK)=TRUN
      TD(IK)=TDEEP
      TA(IK)=TAET
      TPE(IK)=TPET
      TFR(IK)=dR
      TSHC(IK)=SHCS
      SW(IK)=TSW
      SW1(IK)=TSW1

```



```

C
C***** OUTPUT
C
C      WRITE(*,45)
C 45   FORMAT(5X,'Ks',4X,'RAIN',4X,'IRRI',3X,'RUNOFF',2X,'PERCO',4X,
C      1'PET',4X,'AET',3X,'SW(INIT)',2X,'SW(FINAL)')
C      WRITE(*,*)
C      WRITE(*,50)(TSHC(M),TR(M),TI(M),TRU(M),TD(M),TPE(M),TA(M),SW1(M)
C      1,SW(M),M=4,10)
C 50   FORMAT(9(1X,F7.2))
C 101  CONTINUE
      RETURN
      END

C*****
C      SUBROUTINE TO ESTIMATE EVAPORATION FROM BARE SOILS
C      BY USING RITCHIE'S FORMULA
C*****
      SUBROUTINE ETBARE(IDAP,NCP,ALPHA,R,ET0,E)
      DIMENSION R(1000),ET0(1000),E(1000),AE(1000)
      integer t
      IF(R(IDAP) .GT. 0)GOTO 100
      IF(IDAP .EQ. 1)GO TO 115
      T=T+1
      GO TO 116
115   IF(R(IDAP) .GT. 0)GO TO 100
      T=0
      T=T+1
116   E(IDAP)=0.5*T**0.5 - 0.5 *(T-1)**0.5
      GO TO 125
100   E(IDAP)=0.8*ET0(IDAP)
      T=0
125   RETURN
      END

C*****
C*****PROGRAMME TO FIND THE AVERAGE MONTHLY CROP WATER REQUIREMENT'S
C*****AND MONTHLY PERCOLATION LOSSES(STARTING FROM JUNE (FOR WATER YEAR)
C*****
C***** MN      MONTH NUMBER
C***** ND      NUMBER OF DAYS
C***** DB      DAY BEGINNING
C***** DL      DAY LAST
C***** BD      BEGINNING OF DAY FOR COMPUTATION
C*****
      SUBROUTINE SUM(IDAP,ID,NCP,NYEAR,PERC,defi,MON,NB,TPER,TDEF)
      DIMENSION PERC(1000),AET(1000),TPER(100),TAE(100)
      DIMENSION DEFI(400),TDEF(15)
500   GO TO(10,20,30,40,50,60,70,80,90,100,110,120),MON
10    TPERC=0.0
      TDEFI=0.0
      ND =30
      IF(ID .EQ. 1)GO TO 150
      NDL =ND
      NBD =1
      GO TO 151
150   nbd=1
      ndl=nd-nb+1
151   DO 210 I =NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI+DEFI(I)

```

```

210  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
      MON=MON+1
      GO TO 500
20   TPERC=0.0
      TDEFI=0.0
      ND  =31
      NBD  =NDL+1
      NDL  =NDL+ND
      DO 220 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI+DEFI(I)
220  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
      MON=MON+1
      GO TO 500
30   TPERC=0.0
      TDEFI=0.0
      ND  =31
      NBD  =NDL+1
      NDL  =NDL+ND
      DO 230 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI+DEFI(I)
230  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
      MON=MON+1
      GO TO 500
40   TPERC=0.0
      TDEFI=0.0
      ND  =30
      NBD  =NDL+1
      NDL  =NDL+ND
      DO 240 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI+DEFI(I)
240  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
      MON=MON+1
      GO TO 500
50   TPERC=0.0
      TDEFI=0.0
      IF(ID .EQ. 4)GO TO 161
      nd=31
      NBD=NDL+1
      NDL=NDL+ND
      GO TO 165
161  nbd=1
      ND  =31
      ndl=nd-nb+1
165  DO 250 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI+DEFI(I)
250  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI

```

```

        MON=MON+1
        GO TO 500
60      TPERC=0.0
        TDEFI=0.0
        if(id eq 1)go to 185
        IF(ID .EQ. 2)GO TO 163
        ND  =30
        NBD  =NDL+1
        NDL  =NDL+ND
        GO TO 166
185     nbd=ndl+1
        ndl=ncp
        go to 166
163     nbd=1
        ND=31
        ndl=nd-nb+1
166     DO 260 I= NBD,NDL
        TPERC=TPERC+PERC(I)
        TDEFI=TDEFI+DEFI(I)
260     CONTINUE
        TPER(MON)=TPERC
        TDEF(MON)=TDEFI
        if(id eq. 1)go to 175
        MON=MON+1
        GO TO 500
70      TPERC=0.0
        TDEFI=0.0
        ND  =31
        NBD  =NDL+1
        NDL  =NDL+ND
        DO 270 I= NBD,NDL
        TPERC=TPERC+PERC(I)
        TDEFI=TDEFI+DEFI(I)
270     CONTINUE
        TPER(MON)=TPERC
        TDEF(MON)=TDEFI
        MON=MON+1
        GO TO 500
80      TPERC=0.0
        TDEFI=0.0
        ND  =31
        NBD  =NDL+1
        NDL  =NDL+ND
        DO 280 IK= NBD,NDL
        TPERC=TPERC+PERC(I)
        TDEFI=TDEFI+DEFI(I)
280     CONTINUE
        TPER(MON)=TPERC
        TDEF(MON)=TDEFI
        MON=MON+1
        GO TO 500
90      TPERC=0.0
        TDEFI=0.0
        NY=(NYEAR/4)*4
        IF(NYEAR .EQ. NY)GO TO 91
        ND  =28
        GO TO 92
91      ND  =29
92      IF(ID .EQ. 4)GO TO 172
        NBD  =NDL+1

```

```

      NDL =NDL-ND
      GO TO 173
172  NBD=NDL+1
      ndl=ncp
173  DO 290 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI-DEFI(I)
290  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
      IF(ID .EQ 4)GO TO 175
      MON=MON+1
      GO TO 500
100  TPERC=0.0
      TDEFI=0.0
      ND =31
      NBD =NDL-1
      NDL =NDL-ND
      DO 300 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI-DEFI(I)
300  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
      MON=MON+1
      GO TO 500
110  TPERC=0.0
      TDEFI=0.0
      ND =30
      NBD =NDL-1
      NDL =NDL-ND
      DO 310 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI-DEFI(I)
310  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
      MON=MON+1
      GO TO 500
120  TPERC=0.0
      TDEFI=0.0
      ND =31
      NBD =NDL-1
      ndl=ncp
      DO 320 I= NBD,NDL
      TPERC=TPERC+PERC(I)
      TDEFI=TDEFI-DEFI(I)
320  CONTINUE
      TPER(MON)=TPERC
      TDEF(MON)=TDEFI
175  RETURN
      END

```

C*****

C*****POSTPROCESSOR TO PREPARE THE INPUT FILE OF RECHARGE RATES
 C*****FOR RUNNING THE GROUNDWATER MODEL FROM THE OUTPUT OF SOIL
 C*****WATER BALANCE MODEL(MONTHLY PERCOLATION RATES) AND SEEPAGE
 C*****LOSSES OBTAINED FROM CANAL FLOW MODEL FOR ALL THE BASIC SIMULATION
 C*****UNITS. THESE RECHARGE RATES WERE ATTRIBUTED TO THE NODES OF
 C*****FINITE ELEMENT GRID IN THE PROGRAMME
 C*****ITNODE NUMBER OF INTERNAL NODES

```

C*****
      DIMENSION AREAK(12),RAREA(12),SAREA(12),GAREA(12),CAREA(12)
      DIMENSION BAREA(12),PERK(12),RPER(12),SPER(12),GPER(12),CPER(12)
      DIMENSION BPER(12),TPER(12),RMSEEP(12)
      DIMENSION RECHARGE(12),RPUMP(150)
      DIMENSION Q(100,12)
      INTEGER CHNODE(80)
      REAL MRATE,NMRATE,MSUM,NMSUM
C*****INPUT FILES FOR MONTHLY PERCOLATION (FOR ALL CROPS)
C*****FROM SOIL WATER BALANCE MODEL
      OPEN(1,FILE='MPERK1',STATUS='OLD')
      OPEN(2,FILE='MPERR1',STATUS='OLD')
      OPEN(3,FILE='SPER2 OUT',STATUS='OLD')
      OPEN(4,FILE='GPER2 OUT',STATUS='OLD')
      OPEN(5,FILE='CPER2 OUT',STATUS='OLD')
      OPEN(6,FILE='BPER2 OUT',STATUS='OLD')
C**** INPUT FILES FOR AREA UNDER ALL CROPS (FOR ALL MONYHS)
      OPEN(7,FILE='KAREA1',STATUS='OLD')
      OPEN(8,FILE='RAREA1',STATUS='OLD')
      OPEN(9,FILE='SAREA',STATUS='OLD')
      OPEN(10,FILE='GAREA1',STATUS='OLD')
      OPEN(11,FILE='CAREA1',STATUS='OLD')
      OPEN(12,FILE='BAREA',STATUS='OLD')
      OPEN(29,FILE='POLYAREA',STATUS='OLD')
C***** OUTPUT FILE FOR MONTHLY RATE OF PERCOLATION (CUMEC)
      OPEN(13,FILE='GWATER')
      NP=38
      DO 1000 IP=1,NP
        READ(29,*)IDPOLY,IDCANAL,POLYAREA,CAAREA
        GO TO(41,42,43,44)IDCANAL
41      OPEN(30,FILE='MSEEPG',STATUS='OLD')
        GO TO 85
42      OPEN(30,FILE='MSEEPA',STATUS='OLD')
        GO TO 85
43      OPEN(30,FILE='MSEEPB',STATUS='OLD')
        GO TO 85
44      OPEN(30,FILE='MSEEPM',STATUS='OLD')
85      READ(7,*)NPOLY,IDPOLY,(AREAK(I),I=1,12)
        READ(8,*)NPOLY,IDPOLY,(RAREA(I),I=1,12)
        READ(9,*)NPOLY,IDPOLY,(SAREA(I),I=1,12)
        READ(10,*)NPOLY,IDPOLY,(GAREA(I),I=1,12)
        READ(11,*)NPOLY,IDPOLY,(CAREA(I),I=1,12)
        READ(12,*)NPOLY,IDPOLY,(BAREA(I),I=1,12)
        DO 200 NY=1,9
          READ(1,5)IDPOLY,(PERK(I),I=1,12)
          READ(2,5)IDPOLY,(RPER(I),I=1,12)
5          FORMAT(I2,2X,I2(2X,F5.1))
          READ(3,25)IDPOLY,NYEAR,(SPER(I),I=1,12)
          READ(4,25)IDPOLY,NYEAR,(GPER(I),I=1,12)
          READ(5,25)IDPOLY,NYEAR,(CPER(I),I=1,12)
          READ(6,25)IDPOLY,NYEAR,(BPER(I),I=1,12)
25          FORMAT(I2,2X,I4,2X,I2(F5.1,2X))
          READ(30,35)NYEAR,(RMSEEP(I),I=1,12)
35          FORMAT(I4,12(2X,F5.3))
          DO 300 I=1,12
            RSEEP=(RMSEEP(I)*POLYAREA)/CAAREA
            GO TO(10,20,30,40,50,60,70,80,90,100,110,120)I
10          ND=30
            GO TO 150
20          ND=31

```

```

      GO TO 150
30    ND=31
      GO TO 150
40    ND=30
      GO TO 150
50    ND=31
      GO TO 150
60    ND=30
      GO TO 150
70    ND=31
      GO TO 150
80    ND=31
      GO TO 150
90    ND=28
      GO TO 150
100   ND=31
      GO TO 150
110   ND=30
      GO TO 150
120   ND=31
150   RPERK=PERK(I)*AREAK(I)*10/(ND*24*60*60)
      RPERR=RPER(I)*RAREA(I)*10/(ND*24*60*60)
      RPERT=SPER(I)*SAREA(I)*10/(ND*24*60*60)
      RPERG=GPER(I)*GAREA(I)*10/(ND*24*60*60)
      RPERC=CPER(I)*CAREA(I)*10/(ND*24*60*60)
      RPERB=BPER(I)*BAREA(I)*10/(ND*24*60*60)
      TPER(I)=(RPERK+RPERR+RPERT+RPERG+RPERC+RPERB+RSEEP)
300   CONTINUE
      WRITE(13,45)IDPOLY,(TPER(I),I=1,12)
45    FORMAT(I2,2X,12(F5.1,2X))
200   CONTINUE
      CLOSE(30)
1000  CONTINUE
      CLOSE(1)
      CLOSE(2)
      CLOSE(3)
      CLOSE(4)
      CLOSE(5)
      CLOSE(6)
      CLOSE(7)
      CLOSE(8)
      CLOSE(9)
      CLOSE(10)
      CLOSE(11)
      CLOSE(12)
      CLOSE(13)
      CLOSE(29)
      CLOSE(30)
      OPEN(25,FILE='GWATER',STATUS='OLD')
      DO 175 IP=1,38
      DO 180 NY=1,9
      READ(25,55)IDPOLY,(TPER(I),I=1,12)
55    FORMAT(I2,2X,12(F5.1,2X))
      GO TO (11,12,13,14,15,16,17,18,19)NY
11    OPEN(13,FILE='GW1987')
C     WRITE(13,55)IDPOLY,(TPER(I),I=1,12)
C*****
C     FINDING ANNUAL RECHARGE RATES AND SEASONAL RECHARGE RATES
C*****
      ANNSUM=0.0

```

```

DO 810 IM=1,12
ANNSUM=ANNSUM+TPER(IM)
810 CONTINUE
ANNRATE=ANNSUM/12
MSUM=0.0
DO 910 I=1,6
MSUM=MSUM+TPER(I)
910 CONTINUE
MRATE=MSUM/6
NMSUM=0.0
DO 1010 I=7,12
NMSUM=NMSUM+TPER(I)
1010 CONTINUE
NMRATE=NMSUM/6
WRITE(13,55)IDPOLY,(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
GO TO 180
12 OPEN(14,FILE='GW1988')
ANNSUM=0.0
DO 820 IM=1,12
ANNSUM=ANNSUM+TPER(IM)
820 CONTINUE
ANNRATE=ANNSUM/12
MSUM=0.0
DO 920 I=1,6
MSUM=MSUM+TPER(I)
920 CONTINUE
MRATE=MSUM/6
NMSUM=0.0
DO 1020 I=7,12
NMSUM=NMSUM+TPER(I)
1020 CONTINUE
NMRATE=NMSUM/6
WRITE(14,55)IDPOLY,(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
GO TO 180
13 OPEN(15,FILE='GW1989')
ANNSUM=0.0
DO 830 IM=1,12
ANNSUM=ANNSUM+TPER(IM)
830 CONTINUE
ANNRATE=ANNSUM/12
MSUM=0.0
DO 930 I=1,6
MSUM=MSUM+TPER(I)
930 CONTINUE
MRATE=MSUM/6
NMSUM=0.0
DO 1030 I=7,12
NMSUM=NMSUM+TPER(I)
1030 CONTINUE
NMRATE=NMSUM/6
WRITE(15,55)IDPOLY,(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
GO TO 180
14 OPEN(16,FILE='GW1990')
ANNSUM=0.0
DO 840 IM=1,12
ANNSUM=ANNSUM+TPER(IM)
840 CONTINUE
ANNRATE=ANNSUM/12
MSUM=0.0
DO 940 I=1,6

```

```

      MSUM=MSUM+TPER(I)
940  CONTINUE
      MRATE=MSUM/6
      NMSUM=0.0
      DO 1040 I=7,12
        NMSUM=NMSUM+TPER(I)
1040  CONTINUE
      NMRATE=NMSUM/6
      WRITE(16,55)IDPOLY,(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
      GO TO 180
15   OPEN(17,FILE='GW1991')
      ANNSUM=0.0
      DO 850 IM=1,12
        ANNSUM=ANNSUM+TPER(IM)
850  CONTINUE
      ANNRATE=ANNSUM/12
      MSUM=0.0
      DO 950 I=1,6
        MSUM=MSUM+TPER(I)
950  CONTINUE
      MRATE=MSUM/6
      NMSUM=0.0
      DO 1050 I=7,12
        NMSUM=NMSUM+TPER(I)
1050  CONTINUE
      NMRATE=NMSUM/6
      WRITE(17,55)IDPOLY,(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
      GO TO 180
16   OPEN(18,FILE='GW1992')
      ANNSUM=0.0
      DO 860 IM=1,12
        ANNSUM=ANNSUM+TPER(IM)
860  CONTINUE
      ANNRATE=ANNSUM/12
      MSUM=0.0
      DO 960 I=1,6
        MSUM=MSUM+TPER(I)
960  CONTINUE
      MRATE=MSUM/6
      NMSUM=0.0
      DO 1060 I=7,12
        NMSUM=NMSUM+TPER(I)
1060  CONTINUE
      NMRATE=NMSUM/6
      WRITE(18,55)IDPOLY,(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
      GO TO 180
17   OPEN(19,FILE='GW1993')
      ANNSUM=0.0
      DO 870 IM=1,12
        ANNSUM=ANNSUM+TPER(IM)
870  CONTINUE
      ANNRATE=ANNSUM/12
      MSUM=0.0
      DO 970 I=1,6
        MSUM=MSUM+TPER(I)
970  CONTINUE
      MRATE=MSUM/6
      NMSUM=0.0
      DO 1070 I=7,12
        NMSUM=NMSUM+TPER(I)

```



```

1070  CONTINUE
      NMRATE=NMSUM/6
      WRITE(19,55)IDPOLY.(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
      GO TO 180
18    OPEN(20,FILE='GW1994')
      ANNSUM=0.0
      DO 880 IM=1,12
      ANNSUM=ANNSUM+TPER(IM)
880   CONTINUE
      ANNRATE=ANNSUM/12
      MSUM=0.0
      DO 980 I=1,6
      MSUM=MSUM+TPER(I)
980   CONTINUE
      MRATE=MSUM/6
      NMSUM=0.0
      DO 1080 I=7,12
      NMSUM=NMSUM+TPER(I)
1080  CONTINUE
      NMRATE=NMSUM/6
      WRITE(20,55)IDPOLY.(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
      GO TO 180
19    OPEN(21,FILE='GW1995')
      ANNSUM=0.0
      DO 890 IM=1,12
      ANNSUM=ANNSUM+TPER(IM)
890   CONTINUE
      ANNRATE=ANNSUM/12
      MSUM=0.0
      DO 990 I=1,6
      MSUM=MSUM+TPER(I)
990   CONTINUE
      MRATE=MSUM/6
      NMSUM=0.0
      DO 1090 I=7,12
      NMSUM=NMSUM+TPER(I)
1090  CONTINUE
      NMRATE=NMSUM/6
      WRITE(21,55)IDPOLY.(TPER(I),I=1,12),ANNRATE,MRATE,NMRATE
180   CONTINUE
175   CONTINUE
      CLOSE(13)
      CLOSE(14)
      CLOSE(15)
      CLOSE(16)
      CLOSE(17)
      CLOSE(18)
      CLOSE(19)
      CLOSE(20)
      CLOSE(21)
      DO 250 IY=1,9
      OPEN(1,FILE='NODENUM1',STATUS='OLD')
      GO TO(61,62,63,64,65,66,67,68,69)IY
61    OPEN(13,FILE='GW1987',STATUS='OLD')
      OPEN(14,FILE='RENODE87')
      GO TO 185
62    OPEN(13,FILE='GW1988',STATUS='OLD')
      OPEN(14,FILE='RENODE88')
      GO TO 185
63    OPEN(13,FILE='GW1989',STATUS='OLD')

```

```

OPEN(14,FILE='RENODE89')
GO TO 185
64 OPEN(13,FILE='GW1990',STATUS='OLD')
OPEN(14,FILE='RENODE90')
GO TO 185
65 OPEN(13,FILE='GW1991',STATUS='OLD')
OPEN(14,FILE='RENODE91')
GO TO 185
66 OPEN(13,FILE='GW1992',STATUS='OLD')
OPEN(14,FILE='RENODE92')
GO TO 185
67 OPEN(13,FILE='GW1993',STATUS='OLD')
OPEN(14,FILE='RENODE93')
GO TO 185
68 OPEN(13,FILE='GW1994',STATUS='OLD')
OPEN(14,FILE='RENODE94')
GO TO 185
69 OPEN(13,FILE='GW1995',STATUS='OLD')
OPEN(14,FILE='RENODE95')
185 CONTINUE
sum=0.0
DO 350 IP=1,NNP
READ(1,*)IDPOLY,NN,ITNODE
READ(13,55)IDPOLY,(RECHARGE(I),I=1,12)
DO IK=1,12
IF(ITNODE EQ 0)GO TO 126
RECHARGE(IK)=RECHARGE(IK)/ITNODE
go to 125
126 RECHARGE(IK)=RECHARGE(IK)
125 CONTINUE
IF(NN EQ 0)GO TO 350
DO 450 IN=1,NN
READ(1,*)NODENUM
WRITE(14,55)NODENUM,(RECHARGE(I),I=1,12)
450 CONTINUE
350 CONTINUE
CLOSE(1)
250 CONTINUE
CLOSE (13)
CLOSE (14)
C*****
C RECHARGE DISTRIBUTION FILE IS REARRANGED
C ACCORDING TO NODE NUMBERS(ASCENDING ORDER)
C INPUT FILE CNODE GIVES CONSTANT HEAD NODE NUMBERS
OPEN(22,FILE='CNODE',STATUS='OLD')
DO 550 IY=1,9
GO TO(71,72,73,74,75,76,77,78,79)IY
71 OPEN(20,FILE='RENODE87',STATUS='OLD')
OPEN(21,FILE='REC1987')
open(23,FILE='QFLOW87')
GO TO 285
72 OPEN(20,FILE='RENODE88',STATUS='OLD')
OPEN(21,FILE='REC1988')
open(23,FILE='QFLOW88')
GO TO 285
73 OPEN(20,FILE='RENODE89',STATUS='OLD')
OPEN(21,FILE='REC1989')
open(23,FILE='QFLOW89')
GO TO 285
74 OPEN(20,FILE='RENODE90',STATUS='OLD')

```

```

OPEN(21,FILE='REC1990')
open(23,FILE='QFLOW90')
GO TO 285
75  OPEN(20,FILE='RENODE91',STATUS='OLD')
    OPEN(21,FILE='REC1991')
    open(23,FILE='QFLOW91')
    GO TO 285
76  OPEN(20,FILE='RENODE92',STATUS='OLD')
    OPEN(21,FILE='REC1992')
    open(23,FILE='QFLOW92')
    GO TO 285
77  OPEN(20,FILE='RENODE93',STATUS='OLD')
    OPEN(21,FILE='REC1993')
    open(23,FILE='QFLOW93')
    GO TO 285
78  OPEN(20,FILE='RENODE94',STATUS='OLD')
    OPEN(21,FILE='REC1994')
    open(23,FILE='QFLOW94')
    GO TO 285
79  OPEN(20,FILE='RENODE95',STATUS='OLD')
    OPEN(21,FILE='REC1995')
    open(23,FILE='QFLOW95')
285  DO 500 I=1,87
    READ(20,55)NODE,(Q(NODE,J),J=1,12)
500  CONTINUE
    DO 600 NODE=1,87
    DO 700 I=1,57
    READ(22,715)CHNODE(I)
715  FORMAT(I2)
    IF(NODE.EQ.CHNODE(I))GO TO 650
    GO TO 700
650  DO 800 J=1,12
800  CONTINUE
700  CONTINUE
    REWIND(22)
    WRITE(21,55)NODE,(Q(NODE,J),J=1,12)
600  CONTINUE
    DO 625 J=1,12
    WRITE(23,610)(Q(I,J),I=1,87)
610  FORMAT(5I7.4)
625  CONTINUE
    CLOSE(20)
    CLOSE(21)
    CLOSE(23)
550  CONTINUE
    STOP
    END

```

APPENDIX D

SOURCE LISTING FOR NITROGEN BALANCE MODEL

```

C
C PROGRAMME FOR NITROGEN BALANCE STUDIES IN
C RICE FIELDS CONSIDERING ALL N-TRANSFORMATION
C PROCESSES (FOR THE YEAR 1995 IN GODAVARI DELTA
C CENTRAL CANAL IRRIGATION PROJECT)
C PROVISION IS MADE TO IN CORPORA TE FOR BOTH THE SOILS
C (SEASONAL POLLUTANT LOADS AND MONTHLY POLLUTANT LOADS
C ARE ALSO ESTIMATED)
C
C KUH= UREA HYDROLYSIS RATE CONSTANT,1/DAY
C KNW= NITRIFICATION RATE CONSTANT,1/DAY
C KVV= VOLTALIZATION RATE CONSTANT,1/DAY
C KMS= MINERALIZATION RATE CONSTANT,1/DAY
C KNS= NITRIFICATION RATE CONSTANT(SOIL),1/DAY
C UREA-N= APPLIED UREA-N,KG/HA
C L= DEPTH OF PONDING,CM
C PMN=POTENTIALLY MINERALIZED N
C OM= ORGANIC MATTER(%)
C ET= TRANSPIRATION
C PER=PERCOLATION,mm
C TRAP=TRANSPIRATION,mm
C REAL KUH,KNW,KVV,KMI,KNS,KDI,KN
C REAL MNH4(150),MNO3(150),NUPT(150),NLEA(150),L(150)
C REAL NH4(150),NO3(150),NUP(150),N(150),LNH4(150),LEANO3(150),
C ILNO3(150),NLEAGW(150),DLNH4(150),DLNO3(150),DMNH4(150)
C DIMENSION BTNH4(150),DMNO3(150),BMNO3(150),DDNO3(150)
C DIMENSION TNH4(150),DNUP(150),TNO3(150),DNLEAGW(150),BTNO3(150)
C DIMENSION UNH4(150),UNO3(150),DUNO3(150),UNH3(150),DUNH3(150)
C REAL IUNH4,IUNO3,IBTNH4,IBTNO3,NETNH4
C DIMENSION CTNH4(150),CN(150),URNH4(150),soilnh4(150),TRAP(150)
C DIMENSION TEMP(150),AET(150),PER(150),ATEMP(150),DUNH4(150)
C DIMENSION ADN4(150),CONCNO3(150)
C DIMENSION PET(150),CKC(150)
C dimension concno3k(100),concno3r(100)
C DIMENSION TITLE(20)
C DIMENSION TNO3K(100),TNO3R(100),TYLOAD(50)
C REAL MONCONC(100),MONNO3(12)
C
C 60 FORMAT(2X,'DAY',3X,'DUNH3(I)',3X,
C 1'DDNO3(I)',3X,'DNUP(1)',3X,'DNLEAGW(I)')
C WRITE(8,*)'
C 1_____
C WRITE(8,60)
C 60 FORMAT( ' DAY UHYDR VOLATI NITRI IMMOB DENITR UPTAKE LE
C 1ACHGW')
C WRITE(8,*)'
C 1_____
C
C OPEN(25,FILE='CLOAD175.95')
C OPEN(26,FILE='BSU175.95')
C OPEN(25,FILE='Carea200.95')
C OPEN(26,FILE='BSUarea.95')
C DO 1000 ID=1,2
C OPEN(15,FILE='GISID'.STATUS='OLD')
C GO TO (11,21)ID

```

```

11  OPEN(1,FILE='PETKHAR',STATUS='OLD')
    OPEN(2,FILE='RPERK95',STATUS='OLD')
    OPEN(3,FILE='KAREA',STATUS='OLD')
    OPEN(4,FILE='PADDDYK1',STATUS='OLD')
    OPEN(6,FILE='KPRESULT.95')
    OPEN(8,FILE='KNTRANS.95')
    OPEN(10,FILE='CONCSUMK.95')
    OPEN(11,FILE='CONNODEK.95')
    OPEN(12,FILE='MLOAD')
    WRITE(8,60)
    WRITE(6,*)'*****'
    |*****
    WRITE(6,*)'POLY NO    PMN    VOLTAL    DENITRI    UPTAKE    LEACHGW
    ISOILADS NH4LEFT  NO3LEFT'
    WRITE(6,*)'*****'
    |*****
    GO TO 28
21  OPEN(1,FILE='PETRABI',STATUS='OLD')
    OPEN(2,FILE='RPERR95',STATUS='OLD')
    OPEN(3,FILE='RAREA',STATUS='OLD')
    OPEN(4,FILE='PADDDYR1',STATUS='OLD')
    OPEN(6,FILE='KPRESULT.95')
    OPEN(9,FILE='RNTRANS.95')
    OPEN(10,FILE='CONCSUMR.95')
    OPEN(17,FILE='CONNODER.95')
    WRITE(9,60)
    WRITE(6,*)'*****'
    |*****
    WRITE(6,*)'IDPOLY    PMN    VOLTAL    DENITRI    UPTAKE    LEACHGW
    ISOILADS NH4LEFT  NO3LEFT'
    WRITE(6,*)'*****'
    |*****
28  READ(4,51)NCP
51  FORMAT(17X,I3)
C   write(*,*)'ncp=',ncp
    READ(4,55)(CKC(K),K=1,NCP)
55  FORMAT(/I5(F4 2,1X))
C   write(*,56)(ckc(k),k=1,ncp)
56  format(10(1x,f4.2))
    READ(1,36)(PET(I),I=1,NCP)
36  format(8(f9.2))
C   write(*,36)(pet(i),i=1,ncp)
    READ(15,80)TITLE
80  FORMAT(20A4)
    DO 300 NP=1,42
    READ(15,81)IDSOIL
81  FORMAT(16X,I1)
    IF(IDSOIL.EQ. 0)GO TO 300
    GO TO (200,250)IDSOIL
C   write(*,*)'np=',np
200 OPEN(5,FILE='GCLAY.CON',STATUS='OLD')
    GO TO 210
250 OPEN(5,FILE='GSCLOAM.CON',STATUS='OLD')
210 READ(5,10) TIME,F1
10  FORMAT(2X,F3 1,2X,F3.1)
    READ(5,15)KUH,KNW,KVW
15  FORMAT(2X,F5.3,2X,F4.2,2X,F5.3)
    READ(5,20)KMI,KNS
20  FORMAT(2X,F5.3,2X,F5.3)
    READ(5,25)UREAN
25  FORMAT(2X,F5.1)

```

```

      READ(5,30)PH
30    FORMAT(2X,F3.1,2X,F3.1)
      READ(5,35)PMN
35    FORMAT(2X,F5.1)
      READ(5,40)OM
40    FORMAT(2X,F7.5)
      READ(5,50) DS
50    FORMAT(2X,F4.1)
      READ(5,*)RFACTOR1,RFACTOR2,RFACTOR3
      IF(ID .EQ. 1)GO TO 31
      READ(3,26)IDPOLY,PAREA
26    FORMAT(3X,I2,9X,F7.2)
c    WRITE(*,*)IDPOLY,PAREA
      GO TO 33
31    READ(3,27)IDPOLY,PAREA
c    WRITE(*,*)IDPOLY,PAREA
27    FORMAT(3X,I2,1X,F7.2)
33    CONTINUE
C***  INITILIZATION
      IUNH4 =0 0
      IUNO3 =0 0
      IBTNH4=0 0
      IBTNO3=0 0
C***  INITILIZATION OF SUMS
      SUMDUNH3 =0 0
      SUMDMNH4 =0 0
      SUMDMNO3 =0 0
      SUMDDNO3 =0 0
      SUMDNUPT =0.0
      SUMDNLEAGW =0.0
      SUMDUNH4 =0.0
      SSUMNH4 =0.0
      SUMADNH4 =0 0
C***
      PMNLEFT=PMN
      DO 100 I=1,NCP.1
      READ(2,32)NUM.L(I),PER(I)
32    FORMAT(13,F8.2,F8.2)
c    WRITE(*,*)NUM.L(I),PER(I)
      AET(I) =PET(I)*CKC(I)
C    ATEMP(I)=TEMP(I)+273.0
      CALL UREAHYD(UREAN,I,KUH,PH,TIME,DUNH4)
C    SUMDUNH4=SUMDUNH4+DUNH4(I)
      UREAN=UREAN-DUNH4(I)
      IF (I .EQ. 7) UREAN=UREAN+60 0
C    UREAN=UREAN-DUNH4(I)
      IF (I .EQ. 30) UREAN=UREAN+30.0
      IF (I .EQ. 45) UREAN=UREAN+30.0
c    IF (I .GE. 40) KNS= 0.01
      UNH4(I)=DUNH4(I)+IUNH4
      CALL NITRI(UNH4,I,KNW,TIME,DUNO3)
      UNO3(I)=DUNO3(I)+IUNO3
      CALL VOLTA(UNH4,I,KVW,TIME,DUNH3)
      SUMDUNH3=SUMDUNH3+DUNH3(I)
C***  LEACHING COMPONENT
      CALL NLEACH(UNH4,I,PER,L,1)DLNH4)
C***  UNH4 BALANCE IN FLOODED WATER
      UNH4(I)= UNH4(I)-DUNO3(I)-DUNH3(I)-DLNH4(I)
      IUNH4=UNH4(I)
      CALL NLEACH(UNO3,I,PER,L,DLNO3)
C***  UNO3 BALANCE IN FLOODED WATER

```

```

      UNO3(I)=UNO3(I)-DLNO3(I)
      IUNO3=UNO3(I)
      CALL MINERA(PMNLEFT,I,KMI,TIME,DMNH4)
      SUMDMNH4=SUMDMNH4+DMNH4(I)
      PMNLEFT= PMNLEFT-DMNH4(I)
C*****
C***** NH4 ADSORPTION ON SOIL
C*****
      CALL ADSORP (DLNH4,I,TIME,ADNH4)
      SUMADNH4=SUMADNH4+ADNH4(I)
C**** NET NH4 REMAINED IN SOIL AFTER CONSIDERING ADSORPTION
C**** FROM THE TOTAL NH4 LEACHED
      NETNH4=DLNH4(I)-ADNH4(I)
C*****
C*** TOTAL NH4 BALANCE(BOTH SOIL AND WATER)
      MNH4(I)=DMNH4(I)+NETNH4+IBTNH4
      CALL NITRI(MNH4,I,KNS,TIME,DMNO3)
      SUMDMNO3=SUMDMNO3+DMNO3(I)
C*** TOTAL NO3 BALANCE (BOTH SOIL AND WATER)
      MNO3(I)=DMNO3(I)-DLNO3(I)+IBTNO3
C
      *****
      SOILNH4(I)=MNH4(I)-MNO3(I)
      SSUMNH4=SSUMNH4+SOILNH4(I)
C
      *****
      CALL DENTRI(MNO3,I,C,M,TIME,DDNO3)
      SUMDDNO3=SUMDDNO3+DDNO3(I)
C*** NH4 BALANCE (WITHOUT UPTAKE)
      TNH4(I)=MNH4(I)-DMNO3(I)
      CALL NUPTAKE(TNH4,LAET,DS,FL,DNUPT)
      SUMDNUPT=SUMDNUPT+DNUPT(I)
C*** NH4 REMAINED AFTER ACCOUNTING NUPTAKE
      BTNH4(I)=TNH4(I)-DNUPT(I)
      IBTNH4=BTNH4(I)
C*** TOTAL NO3 BALANCE (BOTH WATER AND SOIL)
C*** (WITHOUT LEACHING COMPONENT)
      TNO3(I)=MNO3(I)-DDNO3(I)
      CALL NLEACH(TNO3,I,PER,DS,DNLEAGW)
C*** LEANO3 IS NO3 LEACHING OVER THE AREA CONSIDERED(Kg)
C*** DNLEAGW(I)=DAILY NITRATE LEACHING TO GROUNDWATER,Kg/ha
C*** PAREA= PADDY AREA CONSIDERED (ha)
      LEANO3(I)=DNLEAGW(I)*PAREA
C*** TPER = DAILY PERCOLATION FROM THE AREA CONSIDERED (ha-mm)
      TPER=PER(I)*PAREA
      IF(TPER .EQ. 0)GO TO 63
C*** CONCNO3(I) IS IN PPM (100 IS CONVERSION FACTOR)
      CONCNO3(I)=(LEANO3(I)/TPER)*100.0
      GO TO 64
63 CONCNO3(I)=0.0
C 64 WRITE(*,*)I,LEANO3(I),TPER,CONCNO3(I)
64 SUMDNLEAGW=SUMDNLEAGW+DNLEAGW(I)
      BTNO3(I)=TNO3(I)-DNLEAGW(I)
      IBTNO3=BTNO3(I)
C 65 FORMAT(1X,I3,4X,F8.2,3X,F8.2,3X,F7.2,4X,F7.2)
65 FORMAT(1X,I3,7(3X,F5.2))
      IF(ID .EQ. 2)GO TO 66
      WRITE(8,65)I,DUNH4(I),DUNH3(I),DUNO3(I),ADNH4(I),DDNO3(I),DNUPT(I)
      I,DNLEAGW(I)
      GO TO 100
66 WRITE(9,65)I,DUNH4(I),DUNH3(I),DUNO3(I),ADNH4(I),DDNO3(I),DNUPT(I)
      I,DNLEAGW(I)
      100 CONTINUE

```

```

      call seasonsum(i,concn3,nep,tconcn3,deconcn3)
c 75  FORMAT(1X,I2,3X,F6.2,3X,f6.2)
75  FORMAT(1X,I2,3X,F7.2,3X,f6.2)
      write(*,75)IDPOLY,tconcn3,deconcn3
C*****
      IF(ID.EQ.1)GO TO 1500
      GO TO 1600
1500 CALL SUM(1,ID,NCP,CONCNO3,MONNO3)
      WRITE(*,*)'ENTERED MAIN PROGRAMME AFTER SUM'
      WRITE(12,1)IDPOLY,(MONNO3(MON),MON=1,6),TCONCNO3
1    FORMAT(12,2X,6(2X,F7.2),2X,F7.2)
1600 CONTINUE
c    IF(ID .EQ. 2)GO TO 68
c    write(10,75)idpoly,tconcn3
c    GO TO 69
      WRITE(10,75)IDPOLY,TCONCNO3,deconcn3
C    WRITE(8,*)'PMN=',PMN
C    WRITE(8,*)'SUMDUNH3=',SUMDUNH3
c***  WRITE(8,*)'SUMDMNH4=',SUMDMNH4
c***  WRITE(8,*)'SUMDMNO3=',SUMDMNO3
C    WRITE(8,*)'SUMDDNO3=',SUMDDNO3
C    WRITE(8,*)'SUMDNUPT=',SUMDNUPT
C    WRITE(8,*)'SUMDNLEAGW=',SUMDNLEAGW
C    WRITE(8,*)'SUMADNH4=',SUMADNH4
C    WRITE(8,*)'IBTNH4=',IBTNH4
C    WRITE(8,*)'IBTNO3=',IBTNO3
      WRITE(6,67)IDPOLY,PMNLEFT,SUMDUNH3,SUMDDNO3,SUMDNUPT,SUMDNLEAGW,
1SUMADNH4,IBTNH4,IBTNO3
67  FORMAT(12,7X,F6.2,3X,F5.2,5X,F5.2,4X,F6.2,6X,F5.2,2X,F5.2,
15X,F5.2,3X,F5.2)
      CLOSE(5)
300  CONTINUE
      WRITE(6,*)'*****'
1    *****'
      CLOSE(1)
      CLOSE(2)
      CLOSE(3)
      CLOSE(4)
      CLOSE(5)
      CLOSE(6)
      CLOSE(8)
      CLOSE(10)
      CLOSE(15)
1000 CONTINUE
      CLOSE(15)
      CLOSE(10)
C*****
C****  ALLOCATION OF BASIC SIMULATION UNIT VALUES TO ALL NODES
C****  IN FINITE ELEMENT GRID
C*****
      OPEN(15,FILE='CONCSUMK.95',STATUS='OLD')
      OPEN(16,FILE='CONCSUMR.95',STATUS='OLD')
      OPEN(12,FILE='NODENUM1',STATUS='OLD')
      DO 350 IP=1,38
      READ(12,*)ID,NN,ITNODE
C    WRITE(*,*)ID,NN
77  FORMAT(1X,I2,F7.2)
      READ(15,75)ID,TNO3K(IP),CONCNO3K(IP)
      READ(16,75)ID,TNO3R(IP),CONCNO3R(IP)
      TYLOAD(IP) =(TNO3K(IP)+TNO3R(IP))

```



```

MONCONC(IP)=(TNO3K(IP)+TNO3R(IP))/12
WRITE(26,77)IP,TYLOAD(IP)
IF(NN .EQ. 0)GOTO 350
DO 450 IN=1,NN
  READ(12,*)NODENUM
  C   WRITE(*,*)NODENUM
  WRITE(11,76)NODENUM,CONCNO3K(IP)
  WRITE(17,76)NODENUM,CONCNO3R(IP)
  WRITE(25,76)NODENUM,MONCONC(IP)
76   FORMAT(I2,2X,F6.2)
450   CONTINUE
350   CONTINUE
      STOP
      END
C   *****
C   SUBROUTINE UREAHYD(UREAN,I,KUH,PH,TIME,URNH4)
C   *****
C   THIS SUBROUTINE CALCULATES AMOUNT OF NH4 PRODUCED FROM
C   UREA HYDROLYSIS
C
      REAL UREAN,KUH,PH,TIME,URNH4
      DIMENSION URNH4(150)
      C   WRITE(*,*)'UREAN=',UREAN,'KUHL=',KUHL
      C   WRITE(*,*)'ENTERED SUBROUTINE UREA HYDROLYSIS'
      C   VMAX= -1010+467PH-1.7*PH*PH
      C   KM  =  67.5-7.9*PH
      C   KI  = -0.96*PH+0.24*PH*PH
      C   UL  =  U/L
      C   KU  =  VMAX/(1+(KM/UL)+(UL/KI))
      URNH4(I) = UREAN * (1.0-EXP(-KUHL*TIME))
      RETURN
      END
C   *****
C   SUBROUTINE NITRI(NH4,I,KN,TIME,NO3)
C   *****
C   THIS SUBROUTINE CALCULATES NO3 PRODUCED FROM UREA NH4-N
C
      REAL NH4,KN,TEMP,TIME,NO3
      DIMENSION NH4(150),TEMP(150),NO3(150)
      C   WRITE(*,*)'ENTERED SUBROUTINE NITRIFICATION'
      C
      IF(TEMP .GE. 0.0 .AND. TEMP .LE. 35.0)THEN
      C   KN=(0.032*TEMP-0.12)*KN
      C   ELSEIF(TEMP .GE. 0.0 .AND. TEMP .LE. 10.0)THEN
      C   KN=(0.0105*TEMP+0.00095*TEMP*TEMP)*KN
      C   ELSEIF(TEMP .GE. 35.0 .AND. TEMP .LE. 45.0) THEN
      C   KN=(-0.1*TEMP+4.5)*KN
      C   ENDIF
      NO3(I)=NH4(I)*(1.-EXP(-KN*TIME))
      RETURN
      END
C   *****
C   SUBROUTINE VOLTA(UNH4,I,KVW,TIME,UNH3)
C   *****
C   THIS SUBROUTINE CALCULATES NH3 PRODUCED FROM UNH4
C
      REAL UNH4,KVW,TIME,UNH3
      DIMENSION UNH4(150),UNH3(150)
      C   WRITE(*,*)'ENTERED SUBROUTINE VOLTALIZATION'
      C

```

```

C      UNH3(I)= UNH4(I)*(1.0-EXP(-K*VW*TIME))
C
C      P  = 5.8(10**(PH-10))
C      UNH3 = P*UNH4
C      RETURN
C      END
C      *****
C      SUBROUTINE MINERA(PMN,I,KMI,TIME,DMNH4)
C      *****
C      THIS SUBROUTINE CALCULATES NH4 PRODUCED FROM MINERALIZATION
C
C      REAL PMN,KMI,TIME
C      DIMENSION DMNH4(150)
C      WRITE(*,*)'ENTERED SUBROUTINE MINERALIZATION'
C      KMI= EXP(15.807-(6350.0/ATEMP))
C
C      KMI= 24.0*(17.753-(6350.5/ATEMP))/168.0
C
C      DMNH4(I)= PMN*(1.0-EXP(-KMI*TIME))
C
C      RETURN
C      END
C      *****
C      SUBROUTINE DENITRI(MNO3,I,OM,TIME,DNO3)
C      *****
C      THIS SUBROUTINE CALCULATES DENITRIFICATION LOSSES FROM
C      MNO3
C      REAL MNO3,OM,TEMP,TIME,DNO3
C      DIMENSION MNO3(150),TEMP(150),DNO3(150),DKT(150)
C      WRITE(*,*)'ENTERED SUBROUTINE DENITRIFICATION'
C
C      SC= OM/0.1724
C      DK= 24.0*(0.011*SC+0.0025)
C      DB= ALOG(DK)- 2.4255
C      DKT(I)=EXP(0.0693*TEMP(I)+DB)
C
C      DNI=0.12
C      DNO3(I)=MNO3(I)*(1.0-EXP(-DKT(I)*(TIME-0.0)))
C      DNO3(I)=MNO3(I)*(1.0-EXP(-DNI*(TIME-0.5)))
C      RETURN
C      END
C      *****
C      SUBROUTINE NUPTAKE(TNH4,I,ET,D,FI,NUP)
C      *****
C      THIS SUBROUTINE CALCULATES NUPTAKE
C
C      REAL TNH4,ET,D,FI,NUP
C      DIMENSION TNH4(150),ET(150),NUP(150),CTNH4(150),tr(150)
C      WRITE(*,*)'ENTERED SUBROUTINE NUPTAKE'
C      CTNH4(I)=TNH4(I)/D
C      A=0.5198
C      B=-4.4146
C      C=0.2513
C      WRITE(*,*)A,B,C
C      TR(I)=1.0/(A*(AET(I)+B)**2+C)
C      NUP(I)=TR*CTNH4(I)*FI/10.0
C      NUP(I)= ET(I)*CTNH4(I)*FI/10.0
C      WRITE(*,*)'TR=',TR(I)
C      RETURN
C      END

```

```

C *****
C SUBROUTINE NLEACH(N,I,PER,D,NLEA)
C *****
C THIS SUBROUTINE CALCULATES NO3 LEACHING
C
C REAL N,PER,D,NLEA
C DIMENSION N(150),PER(150),NLEA(150),CN(150)
C WRITE(*,*)i,'ENTERED SUBROUTINE NLEACH'
C
C CN(I) = N(I)*D
C NLEA(I)=CN(I)*PER(I)
C WRITE(*,*) 'NLEACH(I)=' ,NLEA(I),n(i),d,en(i),per(i)
C RETURN
C END
C *****
C SUBROUTINE ADSORP (DLNH4,I,TIME,ADNH4)
C *****
C THIS SUBROUTINE CALCULATES THE AMOUNT OF AMMONIUM ADSORBED
C ON THE SOIL SURFACE FROM THE LEACHED AMMONIUM
C
C DIMENSION DLNH4(150),ADNH4(150)
C WRITE(*,*)'ENTERED SUBROUTINE ADSORP'
C ADNH4(I)= 4*(DLNH4(I)*0.66)
C ADR=0.15
C ADNH4(I) = DLNH4(I)*(1 -EXP(-ADR*TIME))
C WRITE(*,*)'DLNH4(I)=' ,DLNH4(I), 'ADNH4(I)=' ,ADNH4(I)
C WRITE(*,*)ADR
C RETURN
C END
C *****
C SUBROUTINE SEASONSUM(I,CONCNO3,NCP,TCONCNO3,dconeno3)
C DIMENSION CONCNO3(150)
C TCONCNO3=0.0
C DO 150 I=1,NCP
C TCONCNO3=TCONCNO3+CONCNO3(I)
150 CONTINUE
C DCONCNO3=TCONCNO3/4
C RETURN
C END
C *****
C *****PROGRAMME TO FIND THE MONTHLY POLLUTION LOADS
C *****
C ***** MN MONTH NUMBER
C ***** ND NUMBER OF DAYS
C ***** DB DAY BEGINNING
C ***** DL DAY LAST
C ***** BD BEGINNING OF DAY FOR COMPUTATION
C *****
C SUBROUTINE SUM(IDAP,ID,NCP,NYEAR,PERC,MON,NB,TPER)
C SUBROUTINE SUM(I,ID,NCP,CONCNO3,MONNO3)
C DIMENSION CONCNO3(200)
C REAL MONNO3(12)
C WRITE(*,*)'ENTERED SUBROUTINE SUM'
C WRITE(*,*)'NCP=' ,NCP,'ID=' ,ID
C MON=1
C NB=25
C ND =30
C IF(ID .EQ. 1)GO TO 150

```

```

        NDL =ND
        NBD =1
        GO TO 151
150    NBD=1
        NDL=ND-NB+1
C      NBD =NB
C      NDL =ND
151    DO 210 I =NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
        WRITE(*,*)I,TLOAD
210    CONTINUE
        MONNO3(MON)=TLOAD
        MON=MON+1
        GO TO 500
20    TLOAD=0.0
        ND =31
        NBD =NDL+1
        NDL =NDL+ND
C      IF(ID .EQ. 4)GO TO 302
        DO 220 I= NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
        WRITE(*,*)I,TLOAD
220    CONTINUE
        MONNO3(MON)=TLOAD
        MON=MON+1
        GO TO 500
30    TLOAD=0.0
        ND =31
        NBD =NDL+1
        NDL =NDL+ND
C      IF(ID .EQ. 4)GO TO 303
        DO 230 I= NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
        WRITE(*,*)I,TLOAD
230    CONTINUE
        MONNO3(MON)=TLOAD
        MON=MON+1
        GO TO 500
40    TLOAD=0.0
        ND =30
        NBD =NDL+1
        NDL =NDL+ND
C      IF(ID .EQ. 4)GO TO 305
        DO 240 I= NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
        WRITE(*,*)I,TLOAD
240    CONTINUE
        MONNO3(MON)=TLOAD
        MON=MON+1
        GO TO 500
50    TLOAD=0.0
        IF(ID .EQ. 4)GO TO 161
C      IF(ID .EQ. 2)GO TO 163
C      IF(ID .EQ. 1)GO TO 162
        ND=31
        NBD=NDL+1
        NDL=NDL+ND
        GO TO 165
C 162  NBD=NDL+1
C      NDL=NB+NCP-1

```

```

C      GO TO 165
161    NBD=1
C      NBD=NB
      ND =31
      NDL=ND-NB+1
C      NDL=ND
C      GO TO 165
165    DO 250 I= NBD,NDL
      TLOAD=TLOAD+CONCNO3(I)
      WRITE(*,*)I,TLOAD
250    CONTINUE
      MONNO3(MON)=TLOAD
C      IF (ID .EQ. 1)GO TO 175
      MON=MON+1
      GO TO 500
60     TLOAD=0.0
      IF(ID .EQ. 1)GO TO 185
      IF(ID .EQ. 2)GO TO 163
      ND =30
      NBD =NDL+1
      NDL =NDL+ND
      GO TO 166
185    NBD=NDL+1
C      NDL=NB+NCP-1
      NDL=NCP
      GO TO 166
163    NBD=1
C      NBD=NB
      ND=31
      NDL=ND-NB+1
C      NDL=ND
166    DO 260 I= NBD,NDL
      TLOAD=TLOAD+CONCNO3(I)
260    CONTINUE
      MONNO3(MON)=TLOAD
      IF(ID .EQ. 1)GO TO 175
      MON=MON+1
      GO TO 500
70     TLOAD=0.0
      ND =31
      NBD =NDL+1
      NDL =NDL+ND
      DO 270 I= NBD,NDL
      TLOAD=TLOAD+CONCNO3(I)
270    CONTINUE
      MONNO3(MON)=TLOAD
      MON=MON+1
      GO TO 500
80     TLOAD=0.0
      ND =31
      NBD =NDL+1
      NDL =NDL+ND
      DO 280 IK= NBD,NDL
      TLOAD=TLOAD+CONCNO3(I)
280    CONTINUE
      MONNO3(MON)=TLOAD
      MON=MON+1
      GO TO 500
90     TLOAD=0.0
      NY=(NYEAR/4)*4

```

```

        IF(NYEAR .EQ. NY)GO TO 91
        ND =28
        GO TO 92
    91    ND =29
C  92    IF(ID .EQ. 2)GO TO 171
    92    IF(ID .EQ. 4)GO TO 172
        NBD =NDL+1
        NDL =NDL+ND
        GO TO 173
C  171    NBD=NDL+1
C        NDL=NB+NCP-1
C        GO TO 173
    172    NBD=NDL+1
        NDL=NCP
C        NDL=NB+NCP-1
    173    DO 290 I= NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
    290    CONTINUE
        MONNO3(MON)=TLOAD
C        IF(ID .EQ. 2)GO TO 175
        IF(ID .EQ. 4)GO TO 175
        MON=MON+1
        GO TO 500
    100    TLOAD=0.0
        ND =31
        NBD =NDL+1
        NDL =NDL+ND
        DO 300 I= NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
    300    CONTINUE
        MONNO3(MON)=TLOAD
        MON=MON+1
        GO TO 500
    110    TLOAD=0.0
        ND =30
        NBD =NDL+1
        NDL =NDL+ND
        DO 310 I= NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
    310    CONTINUE
        MONNO3(MON)=TLOAD
        MON=MON+1
        GO TO 500
    120    TLOAD=0.0
        ND =31
        NBD =NDL+1
C        NDL =NDL+ND
C        NDL=NB+NCP-1
        NDL=NCP
        DO 320 I= NBD,NDL
        TLOAD=TLOAD+CONCNO3(I)
    320    CONTINUE
        MONNO3(MON)=TLOAD
C        TYPERC=TLOAD1+TLOAD2+TLOAD3+TLOAD4+TLOAD5+TLOAD8+TLOAD7
C        1+TLOAD8+TLOAD9+TLOAD10+TLOAD11+TLOAD12
        CONTINUE
C        WRITE(8,21)TYPERC
C  21    FORMAT('YEARLY TOTAL=' ,F7.3)
    175    RETURN
        END

```

APPENDIX-E

Finite Element Method

Finite element method is based on integral approach. In this method the region of interest is discretized into a number of small subdomains which are called finite elements. The governing groundwater flow equation (equation 6.1) is a partial differential equation. However, the equations in integral form are not directly available. Hence the first step in finite element approach is to derive the approximate integral equation that corresponds to equation 6.1. The integral equation can be derived based on Galerkin's weighted residual approach (Ziekiewicz, 1971 and Pinder and Gray, 1977). The fundamental idea of the method is to replace exact continuous solution of the original partial differential equation (Eqn. 6.1) by an approximate piece-wise-continuous function. The piece wise continuous function is described by coefficients of the function that are specified at a finite number of discrete points called nodes. Functional values between these nodes are calculated using the piece-wise continuous interpolating functions defined over a finite number of subdomains called elements. For a finite number of nodes, the approximation will not exactly satisfy the original partial differential equation, and there will be a residual. The finite element method forces this residual to zero in an average sense, through selection of coefficients for the interpolating functions. A brief description of Galerkin method of weighted Residuals is given below.

a. Galerkin Method of Weighted Residuals

Let the function h be the exact solution of the partial differential equation

$$\frac{\delta}{\delta x} \left[T \frac{\delta h}{\delta x} \right] + \frac{\delta}{\delta y} \left[T \frac{\delta h}{\delta y} \right] + N = S \frac{\delta h}{\delta t} \quad (1)$$

$$f(h) = 0 \quad (2)$$

Where, h represents the solution in the domain W , which is enclosed by the boundary $\Gamma = \Gamma_1 \cup \Gamma_2$. The boundary conditions are as given below for the recharge boundary, Γ ,

$$T \frac{\delta h}{\delta n} = q_b (\Gamma_1) \text{ on } \Gamma_1, \text{ and} \quad (3)$$

for the constant head boundary, Γ_2 ,

$$h = h_b (\Gamma_2) \text{ on } \Gamma_2$$

To solve Eqn. 2 a trial solution of the form given below is assumed

$$h \simeq \hat{h} = \sum_{i=1}^n H_i \phi_i \quad (4)$$

where,

$h =$ a series approximation to h ,

$\phi_i =$ linearly independent trial functions defined over the domain W , and

$H_i =$ unknown coefficients, (n numbers)

Since ϕ_i are known functions in the domain Ω , the problem of finding solution to the partial differential equation (Eqn. 2) is reduced to the problem of finding values for the coefficient H_i . For a finite series, the series approximation will not satisfy the Eqn. 4 and there will be a residual R , defined as,

$$R = \hat{f(h)} - f(h) \quad (5)$$

Since, $f(h) = 0$, R is given by the expression

$$R = \hat{f(h)} \quad (6)$$

This method in essence, attempts to force the residual to zero to bring trial solution close to the exact solution on an average over the domain Ω , through the selection of unknown coefficients H_i . This is accomplished with a relation such as

$$\int_{\Omega} R d\Omega = 0 \quad (7)$$

n equations are required to obtain n values of H_i . To obtain the n equations, the H_i are calculated by setting the weighted integrals of the residual to zero by an expression of the form

$$\int_e R W_i d\Omega = 0 \quad (i=1,2, \dots, n) \quad (8)$$

Where the w_i are linearly independent weighting functions, and the symbol $\int_e$ denotes that the integration is carried over an element.

In Galerkin method, the trial functions themselves are used as weighting functions, i.e.

$$w_i(x) = \phi_i(x) \quad (9)$$

introducing Eqn. 9 into Eqn. 10 yields.

$$\int_{\Omega} R_i d\Omega = 0 \quad (i=1,2, \dots, n) \quad (10)$$

One can obtain n equations from Eqn. 10, which can be solved for the n values of H_i .

b. Trial Functions in Two Dimensions

Triangular elements with straight edges are commonly used to describe complex, irregular two-dimensional solution domains. Hence two dimensional simplex (Oden, 1972) are used in conjunction with linear trial functions (SeegerLind, 1976) which enable the evaluation of integration over the elements by simple integration formula. The two-dimensional simplex element and linear trial functions are shown in Figs. E-1 and E-2. The trial functions from a pyramid at each node with a polygonal base. The base is formed by the triangular elements that share the particular node. At the node in Fig. E2a, the trial function has a value of unity. At all other nodes in the solution domain, the trial function has a value of zero. Within each of the

triangular elements common to node i, the trial function varies linearly from unity at node i to zero at the other nodes.

Over a particular element, this trial function is described by a plane that passes through the three points $(x_i, y_i, 1)$, $(x_j, y_j, 0)$ and $(x_m, y_m, 0)$. The plane is described by the linear function.

$$\phi_i^e = a_i + b_i x + c_i y \quad (11)$$

Where a_i , b_i and c_i are coefficients to be determined from the knowledge of nodal coordinates. The superscript 'e' indicates that ϕ_i^e describes that part of ϕ_i associated with element e (Fig. E-2b). Thus complete trial function is formed by the union of all such elemental trial functions associated with node i.

The three coefficients of equation 11 can be obtained by solving the three equations, one for each node (i, j and m) for element e, are expressed as

$$\begin{aligned} a_i &= \frac{1}{2A^e} (x_j y_m - x_m y_j) \\ b_i &= \frac{1}{2A^e} (y_j - y_m) \\ c_i &= \frac{1}{2A^e} (x_m - x_j) \end{aligned} \quad (12)$$

and

where

$$2A^e = (x_j y_i - x_i y_j) + (x_m y_i - x_i y_m) + (x_j y_m - x_m y_j) \quad (13)$$

and A^e is the area of the triangular element. Substitution of eqn. 12 into eqn. 11 defines the elemental trial function at the node i as

$$\phi_i^e = \frac{1}{2A^e} [(x_j y_m - x_m y_j) + (y_j - y_m)x + (x_m - x_j)y] \quad (14a)$$

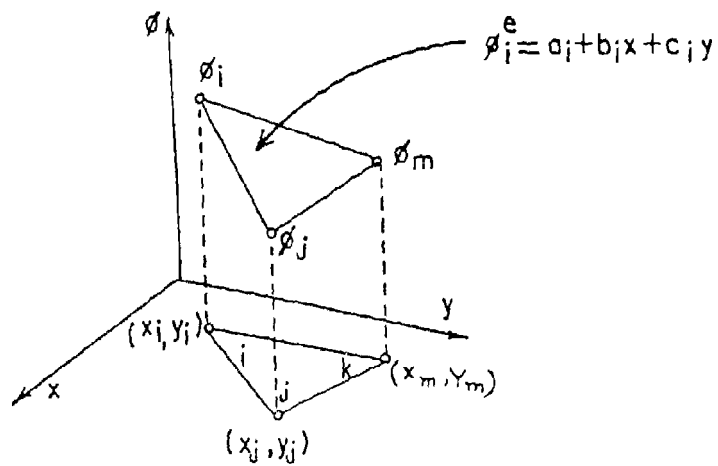


Fig. E-1 Two dimensional simplex element

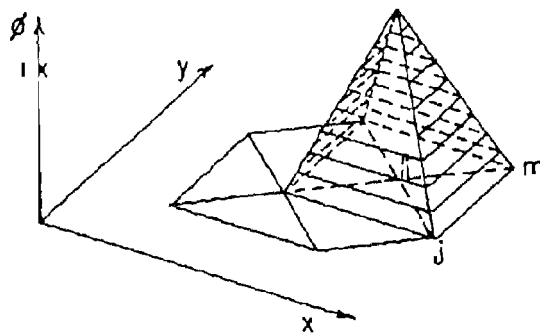


Fig. E-2a Linear trial function at node $-i$.

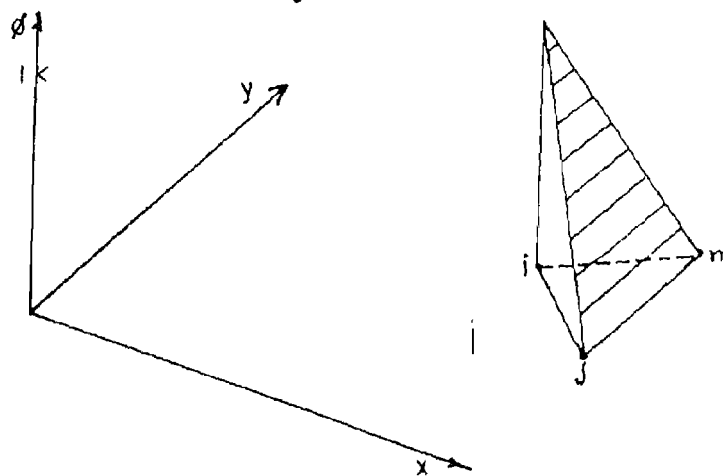


FIG. E- 2 b

Elemental trial function

Similarly, at the nodes j and m of element e , the trial functions are defined as,

$$\phi_j^e = \frac{1}{2A^e} [(x_m y_j - x_j y_m) + (y_m - y_j)x + (x_i - y_m)y] \quad (14b)$$

and

$$\phi_m^e = \frac{1}{2A^e} [(x_j y_i - x_j y_i) + (y_i - y_j)x + (x_j - x_i)y] \quad (14c)$$

B. Application of FEM to Transient-state Two Dimensional Ground Water Flow Equation

Following the procedure outlined above, first, a trial solution is assumed as

$$\hat{h}(x,y,t) = \sum_{i=1}^n H_i \phi_i(x, y, t) \quad (15)$$

Time dependence can be introduced through the coefficients of series approximation. Thus the trial solution can be written as

$$h(x,y,t) = \sum_{i=1}^n H_i(t) \phi_i(x, y) \quad (16)$$

Applications of Galerkin procedure to eqn. 16 leads to a system of ordinary differential equations, which can be solved in time by finite-difference methods.

The next step is to formulate integral equations by applying Galerkin method, that leads to

$$\iint_{\Omega} \left[\frac{\delta}{\delta x} \left(T \frac{\hat{\delta h}}{\delta x} \right) + \frac{\delta}{\delta y} \left(T \frac{\hat{\delta h}}{\delta y} \right) + N - S \frac{\hat{\delta h}}{\delta t} \right] \phi_i dx dy = 0 \quad (17)$$

($i = 1, 2, \dots, n$)

Where Ω is the solution domain and n is the number of nodes.

After applying integration by parts to eliminate second order term in the above equation, the Eqn. 17 can be written as

$$\begin{aligned} & \iint_{\Omega} \left[T \frac{\delta \phi_i}{\delta x} \frac{\delta h}{\delta x} + T \frac{\delta \phi_i}{\delta y} \frac{\delta h}{\delta y} \right] dx dy - \iint_{\Omega} N \phi_i dx dy \\ & - \int_{\Gamma} \frac{\delta h}{\delta n} \phi_i d\Gamma + \iint_{\Omega} S \frac{\delta h}{\delta t} \phi_i dx dy = 0 \end{aligned} \quad (18)$$

(i=1,2, ..., n)

where Γ is the boundary of the flow domain.

Eqn. 18 can be expanded by the following relations

$$\frac{\delta h}{\delta x} = \sum_{j=1}^n H_j(t) \frac{\delta \phi_j(x,y)}{\delta x} \quad (19a)$$

$$\frac{\delta h}{\delta y} = \sum_{j=1}^n H_j(t) \frac{\delta \phi_j(x,y)}{\delta y} \quad (19b)$$

$$\frac{\delta h}{\delta t} = \sum_{j=1}^n \frac{dH_j}{dt} (t) \phi_j(x,y) \quad (19c)$$

(H_j is function of only t)

Substituting above relationships into Eqn. 18 yield

$$\begin{aligned} & \sum_{j=1}^n \iint_{\Omega} \left[T \frac{\delta \phi_i}{\delta x} \frac{\delta \phi_j}{\delta x} + T \frac{\delta \phi_i}{\delta y} \frac{\delta \phi_j}{\delta y} \right] H_j(t) dx dy \\ & - \iint_{\Omega} N \phi_i dx dy - \int_{\Gamma} \frac{\delta h}{\delta n} \phi_i d\Gamma + \sum_{j=1}^n \iint_{\Omega} S \frac{dH_j}{dt} \phi_i \phi_j dx dy = 0 \end{aligned} \quad (20)$$

(i=1,2, ..., n)

Eqn. 20 can be expressed in matrix notation as

$$[A] \{H\} + [B] \left\{ \frac{dh}{dt} \right\} = \{F\} \quad (21)$$

Where $[A]$ and $[B]$ are $[n \times n]$ dimensionless matrices and $\{dH/dt\}$, $\{H\}$ and $\{F\}$ are $[n \times 1]$ dimensional vectors. $[A]$ is the stiffness matrix, $[B]$ is the mass matrix, and $[F]$ is the load vector

Typical elements of $[A]$, $[B]$ and $[F]$ are

$$A_{ij} = \iint_{\Omega} \left[T \frac{\delta \phi_i}{\delta x} \frac{\delta \phi_j}{\delta x} + T \frac{\delta \phi_i}{\delta y} \frac{\delta \phi_j}{\delta y} \right] dx dy \quad (22a)$$

$$B_{ij} = \iint_{\Omega} S \phi_i \phi_j dx dy \quad (22b)$$

and

$$F_i = \iint_{\Omega} N \phi_i dx dy + \int_{\Gamma} T \frac{\hat{\delta h}}{\delta n} \phi_i d\Gamma \quad (22c)$$

Assembly of solutions

In order to generate the set of algebraic equations represented by Eqn. 21, it is necessary to perform integrations of the trial functions of the form

$$\iint_{\Omega} \frac{\delta \phi_i}{\delta x} \frac{\delta \phi_j}{\delta x} dx dy, \iint_{\Omega} \phi_i dx dy,$$

and

$$\int_{\Gamma} \phi_i d\Gamma$$

To facilitate the integrations, they are performed on an elemental basis with T and S assumed to be constant over an element. Elemental matrices are generated and the results are then transferred to the global matrix. Since there are three nodes in an element, each elemental matrix will be of order three.

Stiffness matrix [A]. A typical elemental stiffness matrix (Eqn. 22a) $[A]^e$ will be the form

$$[A]^e = T^e \iint_{\Omega} \begin{bmatrix} \frac{\delta\phi_1^e}{\delta x} & \frac{\delta\phi_1^e}{\delta x} & \frac{\delta\phi_1^e}{\delta x} & \frac{\delta\phi_2^e}{\delta x} & \frac{\delta\phi_1^e}{\delta x} & \frac{\delta\phi_3^e}{\delta x} \\ \frac{\delta\phi_2^e}{\delta x} & \frac{\delta\phi_1^e}{\delta x} & \frac{\delta\phi_2^e}{\delta x} & \frac{\delta\phi_2^e}{\delta x} & \frac{\delta\phi_2^e}{\delta x} & \frac{\delta\phi_3^e}{\delta x} \\ \frac{\delta\phi_3^e}{\delta x} & \frac{\delta\phi_1^e}{\delta x} & \frac{\delta\phi_3^e}{\delta x} & \frac{\delta\phi_2^e}{\delta x} & \frac{\delta\phi_3^e}{\delta x} & \frac{\delta\phi_3^e}{\delta x} \end{bmatrix} dx dy$$

$$+ T^e \iint_{\Omega} \begin{bmatrix} \frac{\delta\phi_1^e}{\delta y} & \frac{\delta\phi_1^e}{\delta y} & \frac{\delta\phi_1^e}{\delta y} & \frac{\delta\phi_2^e}{\delta y} & \frac{\delta\phi_1^e}{\delta y} & \frac{\delta\phi_3^e}{\delta y} \\ \frac{\delta\phi_2^e}{\delta y} & \frac{\delta\phi_1^e}{\delta y} & \frac{\delta\phi_2^e}{\delta y} & \frac{\delta\phi_2^e}{\delta y} & \frac{\delta\phi_2^e}{\delta y} & \frac{\delta\phi_3^e}{\delta y} \\ \frac{\delta\phi_3^e}{\delta y} & \frac{\delta\phi_1^e}{\delta y} & \frac{\delta\phi_3^e}{\delta y} & \frac{\delta\phi_2^e}{\delta y} & \frac{\delta\phi_3^e}{\delta y} & \frac{\delta\phi_3^e}{\delta y} \end{bmatrix} dx dy$$

Where T^e is transmissivity within an element, which is assumed to be constant. The indices used in elemental stiffness matrix are local. They pertain to nodes numbered counter clock-wise around the triangular element.

The global stiffness matrix is obtained by summing, for a given global node, the contribution of that node from each of the elemental matrices. This operational procedure is repeated for each node in an element and for all elements in the domain Ω

The integrations of Eqn. 23, however, are performed in the global coordinate system. First derivative of the elemental trial functions are taken to obtain

$$\frac{\delta \phi_1^e}{\delta x} = \frac{\delta}{\delta x} (a_1 + b_1 x + c_1 y) \quad (24)$$

However,

$$\frac{\delta \phi_1^e}{\delta x} = b_1 \quad (25)$$

$$\text{or} \quad \frac{\delta \phi_1^e}{\delta x} = \frac{1}{2A^e} (y_j - y_m) \quad (26)$$

Similarly,

$$\frac{\delta \phi_1^e}{\delta x} = \frac{1}{2A^e} (x_m - x_j) \quad (27)$$

Second, Eqns. 26 and 27 are substituted into Eqn. 22 to obtain

$$A_{ij}^e = T^e \iint_e b_i b_j \, dx \, dy + T^e \iint_{\Omega} c_i c_j \, dx \, dy \quad (28)$$

However, because the b_i 's and c_i 's are constant over an element.

$$A_{ij}^e = T^e b_i b_j \iint_e dx \, dy + T^e c_i c_j \iint_e dx \, dy \quad (29)$$

or

$$A_{ij}^e = \frac{T^e}{4A^e} [(y_j - y_m)(y_m - y_j) + (x_m - x_j)(x_j - x_m)] \quad (30)$$

Mass matrix [B] : For the elemental mass matrices, integration of the form (22b)

$$\iint_e s \phi_i^e \phi_j^e \, dx \, dy ; \text{ are required.}$$

A typical elemental mass matrix $[B^e]$ will be of the form

$$[B^e] = S^e \iint \begin{bmatrix} \phi_1^e \phi_1^e & \phi_1^e \phi_2^e & \phi_1^e \phi_3^e \\ \phi_2^e \phi_1^e & \phi_2^e \phi_2^e & \phi_2^e \phi_3^e \\ \phi_3^e \phi_1^e & \phi_3^e \phi_2^e & \phi_3^e \phi_3^e \end{bmatrix} dx \, dy \quad (31)$$

S^e is the storage coefficient within an element, which is assumed to be constant over an element.

The integrations in Eqn. 31 can be performed by the formula (Zienkiewicz, 1966)

$$\iint_e \phi_i^e \phi_j^e \, dx \, dy = \frac{A^e}{12} \quad \text{for } i \neq j \quad (32)$$

and

$$\iint_e \phi_i^e \phi_i^e \, dx \, dy = \frac{A^e}{6} \quad (33)$$

Load vector {F} : Eqn. 22c denotes the typical element equation of load vector {F}. The first term $\iint_{\Omega} N \phi_i \, dx \, dy$ represents distributed sources or sinks such as areal recharge from precipitation, but it can also represent point sources or sinks such as discharge from a well. The sources or sinks are described by the expression

$$N(x,y) = - \sum_k Q_k \delta(x-x_k, y-y_k) \quad (34)$$

where, Q_k is discharge from a well located at the coordinates, x_k and y_k , and δ is the Dirac delta function. Minus sign in the above eqn. arises because Q_k is treated as extraction from the aquifer. Dirac delta function is expressed as

$$\delta(x-x_k, y-y_k) = \begin{cases} 1 & \text{at } (x_k, y_k) \\ 0 & \text{elsewhere} \end{cases} \quad (35)$$

and

$$\iint_{\Omega} \delta(x-x_k, y-y_k) \, dx \, dy = 1 \quad (36)$$

Hence,

$$\iint_{\Omega} N \phi_i \, dx \, dy = Q_k \quad (37)$$

Then, for sources and sinks, the global force vector is assembled by simply adding Q_k to F_i , where Q_k is located at the node i .

The second term in the eqn. 22c, is specified-flux boundary, which appears in the load vector $\{F\}$ as a result of integration by parts to reduce the order of terms in the original partial differential equation. Typical component of the elemental load vector $\{F^e\}$ will be of the form

$$\{F^e\} = \int_0^L \begin{bmatrix} \phi_1^e \\ \phi_2^e \end{bmatrix} d\Gamma \quad (38)$$

where q_b is the inward ground water discharge into the flow domain normal to the boundary; and L is the length of the boundary segment. $\phi_1^e(x,y)$ along the boundary represented by one dimensional function $\phi_1^e(\Gamma)$. This has a value of unity at node i and varies linearly to zero at node j . Similarly, $\phi_2^e(\Gamma)$ has a value of unity at node j and zero at node i consequently $\{F^e\}$ is expressed as

$$\{F^e\} = \begin{bmatrix} q_b L/2 \\ q_b L/2 \end{bmatrix} \quad (39)$$

$$\left(\int_0^L \phi_1^e d\Gamma = L/2 \right)$$

The global load vector is given as

$$\{F\} = \{Q\} + \int_{\Gamma} (q_b) d\Gamma \quad (40)$$

Although the matrices $[A]$ and $[B]$ and vector $\{F\}$ of Eqn. 21 can be evaluated as described above, to obtain the solution for Eqn. 21 we must still solve a system of ordinary-differential equations.

$$[A] \{H\} + [B] \{dH/dt\} = \{F\} \quad (41)$$

The time derivative in the above equation can be approximated using finite difference approximation

$$\left\{ \frac{dH}{dt} \right\} = \frac{1}{\Delta t} \{ H^{t+\Delta t} - H^t \} \quad (42)$$

Substituting 42 into 41, yields the first order correct, implicit-difference scheme, which is unconditionally stable (Narasimhan and Witherspoon, 1982).

$$\left[[A] + \frac{1}{\Delta t} [B] \right] \{ H^{t+\Delta t} \} = \frac{1}{\Delta t} [B] \{ H^t \} + \{ F \} \quad (43)$$

Eqn. 43 can be restated as

$$[L] \{ H^{t+\Delta t} \} = \{ R \} \quad (44)$$

where,

$$[L] = [A] + \frac{1}{\Delta t} [B] \quad (45)$$

and

$$\{ R \} = \frac{1}{\Delta t} [B] \{ H^t \} + \{ F \} \quad (46)$$

A solution to the original partial differential equation can be obtained by marching the solution through time. At any time t , $[A]$, $[B]$ and $\{ F \}$ are evaluated using head at time t , $1/\Delta t [B]\{ H^t \}$ is evaluated and Eqn. 44 is solved for $\{ H^{t+\Delta t} \}$. The time is updated by Δt , and the process is repeated until the required time domain is simulated. At the start of the simulation, $\{ H^t \}$ is the initial condition $\{ H^0 \}$.

APPENDIX - F

Variables for different subroutines of main program of Finite Element Groundwater Flow Model

A. VARIABLES FOR SUBROUTINE FDATA

VARIABLE	TYPE	DEFINITION
BASE	Real array	Altitude of aquifer base at nodes
CHEAD	Real array	Water levels at constant-head nodes
CHNODE	Integer array	Constant-head nodes
CLOSE	Real scalar	Closure criterion for iterations, which is compared with the maximum for all nodes of the difference between heads at two successive iteration
DELT	Real scalar	Time step
HO	Real array	Altitude of initial water level at nodes
IN	Integer array	Element incidence
KO	Real array	Hydraulic conductivity over elements
MAXIT	Integer scalar	Maximum number of iterations per time step
MAXKNS	Integer scalar	Number of time steps
NCEN	Integer scalar	Number of constant-head nodes
NE	Integer scalar	Number of elements
NN	Integer scalar	Number of nodes
NQSET	Integer scalar	Number of source-sink data sets
QSET	Real array	Recharge or discharge at nodes
TITLE	Real array	Identification of problem
X	Real array	X - coordinate of node
Y	Real array	Y - coordinate of node

B. VARIABLES FOR SUBROUTINE FMODEL

VARIABLE	TYPE	DEFINITION
A	Real array	Global stiffness matrix
AE	Real array	Elemental stiffness matrix
B	Real array	Global mass matrix
BE	Real array	Elemental mass matrix
CCHLH	Real array	Left-hand side constant -head coefficient
CCHRH	Real array	Right-hand-side constant -head coefficient
H	Real array	Computed waterlevel at time $t + \Delta t$
HL	Real array	Computed waterlevel at time t
HLIT	Real array	Computed waterlevel at time $t + \Delta t$
KNS	Integer scalar	Time step
L	Real array	Left-hand-side matrix
R	Real array	Right-hand-side vector
THK	Real array	Aquifer thickness

C. VARIABLES FOR SUBROUTINE FSHAPE

VARIABLE	TYPE	DEFINITION
AREA	Real array	Area for element
BB	Real array	Coefficient b of trial function
CC	Real array	Coefficient c of trial function
THKE	Real scalar	Average aquifer thickness for element
XE	Real array	X - coordinate for node

YE Real array Y - coordinate for node

D. VARIABLES FOR SUBROUTINE FSBAND

VARIABLE	TYPE	DEFINITION
H	Real array	Solution vector and intermediate solution vector
L	Real array	Left-hand-side matrix
R	Real array	Right-hand-side vector

E. VARIABLES FOR SUBROUTINE FCHEAD

VARIABLE	TYPE	DEFINITION
CCHLH	Real array	Left-hand-side constant-head coefficient
CCHRH	Real array	Right-hand-side constant-head coefficient
QCH	Real array	Discharge at constnt-head node.

SOURCE LISTING FOR GROUNDWATER FLOW MODEL

```

C      PROGRAM FLOW
C.....
C*****TNODE—TOTAL NUMBER OF NODES IN THE STUDY AREA
C*****BNODE—NUMBER OF BOUNDARY NODES
C*****ITNODE—NUMBER OF INTERNAL NODES
C*****Bounode—Boundary nodes
C.....
C      COMMON/MODEL/NN,NE,NB,MAXKNS,MAXIT,NCHN,NQSET,NSET,
1      CLOSE,DELT,X,Y,IN,K0,S0,BASE,H,HL,H0,
2      FACTOR,CHNODE,CHEAD,CCHRH,CCHLH,
3      QSET,FACSET,ISAVE
C
C      INTEGER IN(160,3),CHNODE(60),NSET(30)
C      REAL X(120),Y(120),BASE(120),H(120),HL(120),H0(120)
C      REAL K0(160),S0(160)
C      REAL CHEAD(60),CCHRH(120),CCHLH(120)
C      REAL QSET(120,12),FACSET(30)
C      DIMENSION Xx(100),Yy(100),OX(100),FY(100)
C      INTEGER BOUNODE(60)
C      INTEGER TNODE
C      INTEGER BNODE
C
C      CALL FDATA
C      CALL FMODEL
C      close(9)
C      OPEN(1,FILE='WTPOST95',STATUS='OLD')
C      OPEN(2,FILE='WTPRE96',STATUS='OLD')
C      OPEN(3,FILE='BOUNODE',STATUS='OLD')
C      OPEN(4,FILE='DEV195')
C      READ(3,35)TNODE,BNODE,ITNODE
35  FORMAT(4X,I2,4X,I2,4X,I2)
C      READ(2,55)(XX(NODE),NODE=1,TNODE)
C      READ(1,55)(yy(NODE),NODE=1,TNODE)
55  FORMAT(10f6.3)
C      IK=1
C      DO 100 NODE=1,TNODE
C      REWIND(3)
C      READ(3,35)TNODE,BNODE,ITNODE
C      DO 300 I=1,BNODE
C      READ(3,15)bounode(I)

```

```

15  FORMAT(I2)
   IF(NODE .EQ. bouNODE(I))GO TO 100
300  CONTINUE
      OX(IK)=Xx(NODE)
      FY(IK)=Yy(NODE)
      DIFF=Xx(NODE)-Yy(NODE)
      IK=IK+1
      WRITE(4,25)NODE,Xx(NODE),Yy(NODE),DIFF
      write(*,25)node,xx(node),yy(node),diff
25  FORMAT(I2,4X,F6.3,4X,F6.3,4X,F5.2)
100  CONTINUE
      CALL STDEV(IK,ITNODE,OX,SDX,AVEX)
      CALL STDEV(IK,ITNODE,FY,SDY,AVEY)
      SUMDXY=0.0
      DO 200 I=1,ITNODE
      DX=(OX(I)-AVEY)
      DY=(FY(I)-AVEY)
      DXY=DX*DY
      SUMDXY=SUMDXY+DXY
200  CONTINUE
      COVAR=(SUMDXY/(ITNODE))
      CCOE=(COVAR/(SDX*SDY))
      WRITE(*,*)'CORRELATION COEFFICIENT=',CCOE
      WRITE(4,*)'CORRELATION COEFFICIENT=',CCOE
      CALL TEST(ITNODE,OX,FY,AMSE,AMPE,AMAPE)
      WRITE(*,*)'MSE=',AMSE
      WRITE(*,*)'MPE=',AMPE
      WRITE(*,*)'MAPE=',AMAPE
      WRITE(4,*)'MSE=',AMSE
      WRITE(4,*)'MPE=',AMPE
      WRITE(4,*)'MAPE=',AMAPE
      STOP
      END
C
C-----
C  SUBROUTINE FDATA
C-----
C
C.....DIMENSIONED FOR THE FOLLOWING PROBLEM SIZE:
C  NUMBER OF NODES=87
C  NUMBER OF ELEMENTS=103
C  NUMBER OF CONSTANT-HEAD NODES=
C  NUMBER OF TIME STEPS =30
C  NUMBER OF SOURCE-SINK DATA SETS =12
C
C  COMMON/MODEL/NN,NE,NB,MAXKNS,MAXIT,NCHN,NQSET,NSET,
1    CLOSE,DELT,X,Y,IN,K0,S0,BASE,H,HL,H0,
2    FACTOR,CHNODE,CHEAD,CCHRH,CCHLH,
3    QSET,FACSET,ISAVE
C
C  INTEGER IN(160,3),CHNODE(60),NSET(30)
C  REAL X(120),Y(120),BASE(120),H(100),HL(120),H0(120)
C  REAL K0(160),S0(160)
C  REAL CHEAD(60),CCHRH(120),CCHLH(120)
C  REAL QSET(120,12),FACSET(30)
C  real rpump(87)
C  REAL TITLE(20)
C
C  LOGICAL UNIT NUMBERS
C  IR=5
C  IW=6

```

```

OPEN(IR,FILE='GMODEL95.DAT',STATUS='OLD')
OPEN(8,FILE='QFLOW95',STATUS='OLD')
OPEN(7,FILE='CGPUMP1',STATUS='OLD')
OPEN(10,FILE='COMPHEAD.95')
OPEN(IW,FILE='RESULT95.OUT')
OPEN(9,FILE='WTPOST95')
OPEN(11,FILE='NFLOW.95')
C.....BASIC DEFINITION OF SOLUTION DOMAIN
C
    READ(IR,900) (TITLE(I),I=1,20)
    WRITE(IW,901) (TITLE(I),I=1,20)
900  FORMAT(20A4)
901  FORMAT(1H1,10X,20A4/1H ,10X,80('-')/)
C
C    TIME STEP (DAYS),NUMBER OF TIME STEPS, NUMBER OF ITERATIONS,
C    CLOSURE CRITERION ON ITERATIONS(METRE), AND SWITCH FOR SAVING
C    HEADS AND SOURCE-SINK FLUXES(1=YES AND 0=NO)
    READ(IR,902) DELT,MAXKNS,MAXIT,CLOSE
    WRITE(IW,903) DELT,MAXKNS,MAXIT,CLOSE
    DELT=DELT*3600.0*24.0
902  FORMAT(F6.0,I2,2X,I2,2X,F3.1)
903  FORMAT(1H0,10X,'TIME PARAMETERS'/10X,15('-')/1H0,10X,
1    'TIME STEP(DAYS)',21X,F8.1/1H ,10X,'NUMBER OF TIME STEPS'.
2    21X,I4/
3    1H ,10X,'NUMBER OF ITERATIONS',20X,I5/
4    1H ,10X, 'CLOSURE CRITERION FOR ITERATIONS(M)',F6.3/
5    1H ,10X,'SAVE HEADS AND SOURCE-SINK FLUXES',6X,I6)
C
C    NUMBER OF NODES AND ELEMENTS
C
    READ(IR,904) NN,NE
    WRITE(IW,905) NN,NE
904  FORMAT (2I6)
905  FORMAT(1H0,10X,'FINITE-ELEMENT DATA'/1H ,10X,19('-')/1H0,10X,
1    'NUMBER OF NODES ',I10/1H ,10X,'NUMBER OF ELEMENTS',I10)
C
C    NODE COORDINATES (METRE)
C
    READ(IR,906) FACX,FACY
    READ(IR,907) (I,X(I),Y(I),I=1,NN)
    DO 100 I=1,NN
        X(I)=X(I)*FACX
        Y(I)=Y(I)*FACY
100  CONTINUE
    WRITE(IW,908)FACX,FACY
    WRITE(IW,909)(I,X(I),Y(I),I=1,NN)
906  FORMAT(2E12.0)
c 907  FORMAT(3(I6,2F6.1,6X))
C 907  FORMAT(3(I6,F6.1,F7.2,5X))
907  FORMAT(3(I6,F7.2,F7.3,4X))
908  FORMAT(1H0,10X,'NODE COORDINATES (METRE)'/1H ,10X,23('-')/
1    1H0,10X,'FACTOR FOR X- COORDINATE',1PE11.3/
2    1H ,10X,'FACTOR FOR Y- COORDINATE',1PE11.3/
3    1H0,10X,3('NODE',11X,'X',11X,'Y',5X)/)
909  FORMAT((1H ,10X,3(I4,2F12.1,5X)))
C
C    ELEMENT INCIDENCES (COUNTER CLOCK WISE)
C
    READ(IR,910) (I,(IN(I,J),J=1,3),I=1,NE)
    WRITE(IW,911)
    WRITE(IW,912)(I,(IN(I,J),J=1,3),I=1,NE)

```

```

910 FORMAT(2(4I6,6X))
911 FORMAT(1H0,10X,'ELEMENT INCIDENCES (COUNTER CLOCK WISE)'/
  1 1H ,10X,38('-')/
  2 1H0,10X,3('ELEM',13X,'CORNERS',9X)/)
912 FORMAT((6X,3(I4,2X,3I6,9X)))
C
C   FIND HALF BAND WIDTH
C
      NB=0
      DO 102 L=1,NE
      IMAX=0
      IMIN=10000
      DO 101 I=1,3
      II=IN(L,I)
      IMAX=MAX0(IMAX,II)
      IMIN=MIN0(IMIN,II)
101  CONTINUE
      NB=MAX0((IMAX-IMIN+1),NB)
102  CONTINUE
      WRITE(IW,913)NB
913  FORMAT(1H0,10X,'HALF-BAND WIDTH',I9)
C
C   HYDRAULIC CONDUCTIVITY (METRE PER DAY)
C
      READ(IR,914) FACK
      READ(IR,915) (K0(I),I=1,NE)
      DO 103 I=1,NE
      K0(I)=K0(I)*FACK
103  CONTINUE
      WRITE(IW,917)FACK
      WRITE(IW,918)(I,K0(I),I=1,NE)
      DO 104 I=1,NE
      K0(I)=K0(I)/(3600 0*24.0)
104  CONTINUE
914  FORMAT(E12.0)
915  FORMAT(10F6.0)
917  FORMAT(1H0,10X,'HYDRAULIC CONDUCTIVITY (METRE PER DAY)'/
  1 1H ,10X,37('-')/
  2 1H0,10X,'FACTOR FOR CONDUCTIVITY',1PE11.3/
  3 1H0,10X,5('ELEM',7X,'VALUE',4X)/)
918  FORMAT((1H ,10X,5(I4,3X,F9.1,4X)))
C
C   SPECIFIC YIELD ( DIMENSIONLESS )
C
      READ(IR,919) FACS
      READ(IR,920) (S0(I),I=1,NE)
      DO 105 I=1,NE
      S0(I)=S0(I)*FACS
105  CONTINUE
      WRITE(IW,922)FACS
      WRITE(IW,923)(I,S0(I),I=1,NE)
919  FORMAT(E12.0)
920  format(10f6.2)
922  FORMAT(1H0,10X,'SPECIFIC YIELD (DIMENSIONLESS)'/
  1 1H ,10X,31('-')/
  2 1H0,10X,'FACTOR FOR STORAGE',1PE11.3/
  3 1H0,10X,5('ELEM',7X,'VALUE',4X)/)
923  FORMAT((1H ,10X,5(I4,3X,F9.2,4X)))
C
C   ALTITUDE FOR BASE OF AQUIFER(METRE ABOVE DATUM)

```



```

C      READ(IR,925) (BASE(I),I=1,NN)
      do 800 i=1,nn
      base(i)=base(i)-40.0
800    continue
      WRITE(IW,926)
      WRITE(IW,927) (I,BASE(I),I=1,NN)
925    format(10f6.1)
926    FORMAT(1H0,10X,'BASE OF AQUIFER(METRE ABOVE DATUM)'/
      1 10X,34('-')/
      2 1H0,10X,5('NODE',7X,'VALUE',4X)/)
927    FORMAT((10X,5(I4,3X,F9.3,4X)))
C
C      INITIAL WATER LEVELS (METRE)
C
      READ(IR,928) (H0(I),I=1,NN)
      WRITE(IW,929)
      WRITE(IW,9301)(I,H0(I),I=1,NN)
928    format(10f6.3)
929    FORMAT(1H0,10X,'INITIAL WATER LEVELS(METRE ABOVE DATUM)'/
      1 1H ,10X,39('-')/
      2 1H0,10X,5('NODE',7X,'VALUE',4X)/)
9301   FORMAT((1H ,10X,5(I4,3X,F9.2,4X)))
C
C      DEFINITION OF CONSTANT-HEAD BOUNDARIES
C
C      NUMBER OF CONSTANT-HEAD NODES,LEAKANCE FACTOR(METRE SQUARED PER
C      DAY),AND CONSTANT-HEADVALUES(METRE ABOVE DATUM)
C
      READ(IR,930) NCHN,FACTOR
      IF(NCHN.EQ.0) GO TO 3001
      READ(IR,931) (CHNODE(I),CHEAD(I),I=1,NCHN)
      WRITE(IW,932) FACTOR
      WRITE(IW,933)(CHNODE(I),CHEAD(I),I=1,NCHN)
930    FORMAT(I6,E12.0)
931    FORMAT(I6,1X,F6.3)
932    FORMAT(1H0,10X,'CONSTANT-HEAD NODES'/1H ,10X,19('-')/
      1 1H0,10X,'LEAKANCE FACTOR(METRE SQUARED PER DAY)',1PE12.3/
      2 1H0,10X,'NODE',8X,'HEAD(METRE ABOVE DATUM)'/)
933    FORMAT(1H ,10X,I4,F9.2)
C
C      INITIALIZE MATRIX DIAG(CCHLH) AND VECTOR(CCHRH)
C
      3001 DO 300 I=1,NN
      CCHRH(I)=0.0
      CCHLH(I)=0.0
300    CONTINUE
C
      IF (NCHN.EQ.0) GO TO 3011
C
C      COMPUTE LEFT-HAND AND RIGHT HAND COEFFECIENT
C      MATRIX DIAG(CCHLH) AND VECTOR(CCHRH)
C
      DO 301 I=1,NCHN
      J=CHNODE(I)
      CCHLH(J)=FACTOR
      CCHRH(J)=FACTOR*CHEAD(I)
301    CONTINUE
3011 CONTINUE

```

```

C
C.....DEFINITION OF SOURCES AND SINKS
C
C      NUMBER OF SOURCE-SINK PERIODS AND FACTOR FOR SOURCE-SINK STRENGTHS
C
      READ(IR,940) NQSET,FACQ
      IF(NQSET.EQ.0) GO TO 4012
      WRITE(IW,941)NQSET,FACQ
940  FORMAT(I6,E12.0)
941  FORMAT(1H0,10X,'SOURCES AND SINKS(CUBIC METRE PER SECOND)'/
      1 1H ,10X,40('-')/
      2 1H0,10X,'NUMBER OF SOURCE-SINK DATA SETS',I5/
      3 1H ,10X,'FACTOR FOR SOURCES AND SINKS',10X,1PE11.3)
C
C      SOURCE-SINK DATA SETS(CUBIC METRE PER SECOND) WITH IN (+) AND OUT(-)
C
      DO 401 J=1,NQSET
      DO 400 I=1,NN
      QSET(I,J)=0.0
400  CONTINUE
401  CONTINUE
      DO 403 J=1,NQSET
      READ(8,953) (QSET(I,J),I=1,NN)
      DO 402 I=1,NN
      READ(7,975)INODE,RPUMP(I)
975  FORMAT(I3,2X,F6.4)
      QSET(I,J)=QSET(I,J)*FACQ-RPUMP(I)*1.00
402  CONTINUE
      REWIND(7)
      WRITE(IW,954) J
      WRITE(IW,955)(I,QSET(I,J),I=1,NN)
      WRITE(11,953)(QSET(I,J),I=1,NN)
403  CONTINUE
953  FORMAT(5F7.4)
954  FORMAT(1H0,10X,'SOURCE-SINK DATA SET',I5/10X,20('-')/1H0,10X,
      1 5('NODE',3X,'VALUE',4X)/)
955  FORMAT((10X,5(I4,F9.4,4X)))
C
C      TIME-STEP INDICATORS AND MUYLTIPLIERS
C
C      WRITE(IW,957)
C
C      DO 960 J=1,MAXKNS
      READ(IR,956) (I,NSET(I),FACSET(I),I=1,MAXKNS)
      WRITE(IW,958) (I,NSET(I),FACSET(I),I=1,MAXKNS)
956  FORMAT(I6,I6,F6.0)
957  FORMAT(1H0,10X,'TIME-STEP INDICATORS AND MULTIPLIERS'/10X,
      1 37('-')/1H0,10X,'STEP',7X,'SET',4X,'FACTOR (DIMENSIONLESS)'/)
958  FORMAT( (1H , 10X,I4,7X,I3,4X,F6.3) )
4012 CONTINUE
C
C      WRITE(*,*) ' END DATA INPUT '
C
C      RETURN
C      END
C
C      SUBROUTINE FMODEL
C
C.....DIMENSIONED FOR THE FOLLOWING PROBLEM SIZE:
C      NUMBER OF NODES =87

```

```

C      NUMBER OF ELEMENTS 103
C      NUMBER OF CONSTANT-HEAD NODES 11
C      NUMBER OF TIME STEPS =30
C      MAXIMUM HALF-BAND WIDTH=14
C
      COMMON/MODEL/NN,NE,NB,MAXKNS,MAXIT,NCHN,NQSET,NSET,
1  CLOSE,DELT,X,Y,IN,K0,S0,BASE,H,HL,H0,
2  FACTOR,CHNODE,CHEAD,CCHRH,CCHLH,
3  QSET,FACSET,ISAVE
C
      INTEGER IN(160,3),CHNODE(60),NSET(30)
      REAL  X(120),Y(120),BASE(120),H(100),HL(120),H0(120)
      REAL  K0(160),S0(160)
      REAL  CHEAD(60),CCHRH(120),CCHLH(120)
      REAL  QSET(120,12),FACSET(30)
C
      REAL  L(120,21),A(120,21),B(120,21),R(120)
      REAL  AE(3,3),BE(3,3)
      REAL  THK(120),Q(100),HLIT(120)
      REAL  K(160),S(160)
      EQUIVALENCE (K,K0)
      EQUIVALENCE (S,S0)
C
C
C      LOGICAL UNIT NUMBERS
C
      IR=5
      IW=6
      IW2=10
      IF(ISAVE.EQ.1) REWIND IW2
C
C      INITIAL WATER LEVELS
C
      DO 400 I=1,NN
        HL(I)=H0(I)
        H(I)=H0(I)
400  CONTINUE
C
C.....BEGIN TIME STEP LOOP
C
      KNS=0
401  KNS=KNS+1
      IF(KNS.GT.MAXKNS) RETURN
C
C      INTERCHANGE WATER LEVELS
C
      DO 402 I=1,NN
        HL(I)=H(I)
402  CONTINUE
C
C      COMPUTE VALUES FOR SOURCE/SINK VECTOR (Q) AND
C      COMPUTE CONSTANT-HEAD COEFFECIENTS(CCHRH)AND(CCHLH)
C
      DO 505 I=1,NN
        Q(I)=0.0
505  CONTINUE
      IF(NQSET.EQ.0) GO TO 506
      JJ=NSET(KNS)
      DO 504 I=1,NN
        Q(I)=QSET(I,JJ)*FACSET(KNS)

```

```

504 CONTINUE
506 CONTINUE
C
C.....BEGIN ITERATION LOOP
C
      DO 4171 I=1,NN
      HLIT(I)=HL(I)
4171 CONTINUE
C
      DO 421 ITER=1,MAXIT
C
C
C      UPDATE AQUIFER-THICKNESS VALUES
C
      DO 404 I=1,NN
      THK(I)=H(I)-BASE(I)
C****SET MINIMUM THICKNESS
      IF(THK(I).LE. 10.0) THK(I)=10.0
404 CONTINUE
C
C      INITIALISE MATRICES (A) AND (B)
C
      DO 406 I=1,NN
      DO 405 J=1,NB
      A(I,J)=0.0
      B(I,J)=0.0
405 CONTINUE
406 CONTINUE
C
C.....BEGIN LOOP OVER ELEMENTS
C
C
      DO 412 LL=1,NE
C
C      ELEMENT STIFFNESS MATRIX(AE) AND DYNAMIC MATRIX(E)
C
      CALL FSHAPE(LL,IN,X,Y,THK,K,S,AE,BE)
C
C      GLOBAL STIFFNESS MATRIX(A) AND MASS MATRIX(B)
      DO 411 I=1,3
      II=IN(LL,I)
      DO 410 J=1,3
      JJ=IN(LL,J)-II+1
      IF(JJ.LT.1) GO TO 410
      A(II,JJ)=A(II,JJ)+AE(I,J)
      B(II,JJ)=B(II,JJ)+BE(I,J)
410 CONTINUE
411 CONTINUE
412 CONTINUE
C
      DO 414 I=1,NN
      DO 413 J=1,NB
      B(I,J)=B(I,J)/DELT
413 CONTINUE
414 CONTINUE
C
C.....END LOOP OVER ELEMENTS
C
C      MULTIPLICATION OF GLOBAL MASS MATRIX(B) AND
C      LAST-WATER-LEVEL VECTOR (HL) TO PRODUCE VECTOR (R)

```

```

C
DO 417 I=1,NN
R(I)=B(I,1)*HL(I)
DO 416 J=2,NB
II=I+J-1
IF (II.GT.NN) GO TO 415
R(II)=R(I)+B(I,J)*HL(II)
415 II=I-J+1
IF(II.LT.1) GO TO 416
R(II)=R(II)+B(II,J)*HL(II)
416 CONTINUE
417 CONTINUE

C
C   CONSTRUCT LEFT-HAND-SIDE MATRIX (L)=(A)+(B)+DIAG(CCHLH)
C
DO 419 I=1,NN
DO 418 J=1,NB
L(I,J)=A(I,J)+B(I,J)
418 CONTINUE
L(I,1)=L(I,1)+CCHLH(I)
419 CONTINUE

C
C   CONSTRUCT RIGHT-HAND-SIDE VECTORAA(R)=(B)+(HL0)+(Q)+(CCHRH0)
C
DO 420 I=1,NN
R(I)=R(I)+Q(I)+CCHRH(I)
420 CONTINUE

C
C   COMPUTE NEW WATER-LEVEL VECTOR (H)
C
CALL FSBAND(L,R,H,NN,NB)

C
C   CHECK FOR CLOUSRE
C
DELMAX=0.0
DO 4201 I=1,NN
DELH=ABS(H(I)-HLIT(I))
IF(DELH.GT.DELMAX) DELMAX=DELH
HLIT(I)=H(I)
4201 CONTINUE
IF(DELMAX.LE.CLOSE) GO TO 4211
421 CONTINUE
IF(ITER.GT.MAX/10) ITER=ITER-1
4211 CONTINUE

C
C.....END ITERATION LOOP
C
C   DISPLAY WATER LEVELS AND AQUIFER THICKNESS
C
423 CONTINUE
TIME=KNS*DELT/(3600.0*24.0)
WRITE(IW,980)KNS,TIME,ITER,DELMAX
WRITE(IW,981)(I,H(I),I=1,NN)
WRITE(10,986)(H(I),I=1,NN)
986 FORMAT (10F6.2)
C.....
C****INPUT FILE FOR FINDING OUT CORRELATION COEFFICIENT
C****WRITING COMPUTED WATERTABLE ELEVATIONS TO OUTPUT FILE
      if (kns .eq. maxkns)go to 977
      GO TO 978

```

```

C
  BB(1)=YE(2)-YE(3)
  BB(2)=YE(3)-YE(1)
  BB(3)=YE(1)-YE(2)
  CC(1)=XE(3)-XE(2)
  CC(2)=XE(1)-XE(3)
  CC(3)=XE(2)-XE(1)
C
C   AREA OF ELEMENT
C
  AREA=abs((BB(1)*XE(1)+BB(2)*XE(2)+BB(3)*XE(3))/2.0)
C—AREA INTEGRATIONS
C
  DO 409 I=1,3
  DO 408 J=1,3
  AE(I,J)=THKE*K(LL)*BB(I)*BB(J)/(4.0*AREA)
  I +THKE*K(LL)*CC(I)*CC(J)/(4.0*AREA)
  BE(I,J)=S(LL)*AREA/12.0
  IF(I.EQ.J) BE(I,J)=BE(I,J)*2.0
408 CONTINUE
409 CONTINUE
C
  RETURN
  END
C
  SUBROUTINE FSBAND(L,R,H,NN,NB)
C
C
C—DIMENSIONED FOR THE FOLLOWING PROBLEM SIZE:
C   NUMBER OF THE NODES=100
C   MAXIMUM HALF-BAND WIDTH=21
C
C
  REAL L(120,21),R(120),H(120)
C
C   LOGICAL UNIT NUMBERS
  IR=5
  IW=6
C—UPPER TRINGULARIZE MATRIX OF COFFICIENTS[L]
C   UPPER TRIANGULARIZED MATRIX TEMPORALILY STORED IN (L)
  DO 221 I=1,NN
  IP=NN-I+1
  IF(NB.LT.IP) IP=NB
  DO 220 J=1,IP
  IQ=NB-J
  IF((I-1).LT.IQ) IQ=I-1
  SUM=L(I,J)
  IF(IQ.LT.1) GO TO 450
  DO 440 K=1,IQ
  II=I-K
  JZ=J+K
  SUM=SUM-L(II,K+1)*L(II,JZ)
440 CONTINUE
450 IF(J.NE.1) GO TO 230
  IF(SUM.LE.0.0)GO TO 260
  TEMP=1.0/SQRT(SUM)
  L(I,J)=TEMP
  GO TO 220
230 L(I,J)=SUM*TEMP
220 CONTINUE

```

```

221 CONTINUE
GO TO 261
260 WRITE(IW,910)
STOP
C
910 FORMAT(1H1,10X,' UPPER TRIANGULARIZATION FAILS AT ROW;',I4)
C
C-----INTERMEDIATE SOLUTION VECTOR (Y)
C VECTOR(Y) TEMPORARILY STORED IN (H)
261 CONTINUE
DO 320 I=1,NN
J=I-NB+1
IF((I+1).LE.NB) J=1
SUM=R(I)
K1=I-1
IF(J.GT.K1) GO TO 340
DO 330 K=J,K1
II=I-K+1
SUM=SUM-L(K,II)*H(K)
330 CONTINUE
340 H(I)=SUM*L(I,1)
320 CONTINUE
C
C-----BACK SUBSTITUTION TO OBTAIN VECTOR (H)
C
DO 540 II=1,NN
I=NN-II+1
J=I+NB-1
IF(J.GT.NN) J=NN
SUM=H(I)
K2=I+1
IF(K2.GT.J) GO TO 250
DO 550 K=K2,J
KK=K-I+1
SUM=SUM-L(I,KK)*H(K)
550 CONTINUE
250 H(I)=SUM*L(I,1)
540 CONTINUE
C
RETURN
END
C
SUBROUTINE FCHEAD(CCHRH,CCHLH,Q,H,CHNODE,NCHN)
C
C DIMENSIONED FOR THE FOLLOWING PROBLEM SIZE:
C NUMBER OF NODES= 87
C NUMBER OF CONSTANT-HEAD NODES=20
C
INTEGER CHNODE(60)
REAL CCHRH(120),CCHLH(120),Q(120),H(120)
REAL QCH(60)
C
C LOGICAL UNIT NUMBERS
C
IR=5
IW=6
C
C COMPUTE CONSTANT-HEAD FLUXES AND UPDATE SOURCE-SINK VECTOR
C
IF(NCHN.EQ.0) RETURN

```

```

      SUMCH=0
      DO 150 I=1,NCHN
      J=CHNODE(I)
      QCH(I)=CCHRH(J)-CCHLH(J)* H(J)
      SUMCH=SUMCH+QCH(I)
      Q(J)=Q(J)+QCH(I)
150  CONTINUE
C
C      PRINT CONSTANT-HEAD FLUXES
C
C
C      WRITE(IW,950)SUMCH
      WRITE(IW,951)(CHNODE(I),QCH(I),I=1,NCHN)
950  FORMAT(1H0,10X,'CONSTANT-HEAD NODES'/1H ,10X,19('-')/1H0,10X,
1  'CUMULATIVE RATE (CUBIC METRE PER SECOND)'.F9.4/1H0,10X,
2  'NODE',8X,'RATE(CUBIC METRE PER SECOND)'/)
951  FORMAT(1H ,10X,I4,F12.4)
      RETURN
      END
C.....
C*****SUBROUTINE TO CALCULATE STANDARD DEVIATION AND MEAN
C.....
      SUBROUTINE STDEVI(I,NI,VAR,SD,AVE)
      DIMENSION VAR(100)
      SUM=0.0
      DO 100 I=1,NI
      SUM=SUM+VAR(I)
100  CONTINUE
      AVE=SUM/NI
      SSQDEV=0.0
      DO 150 I=1,NI
      DEVI=VAR(I)-AVE
      SQDEVI=DEVI**2
      SSQDEV=SSQDEV+SQDEVI
150  CONTINUE
      SD=SQRT(SSQDEV/NI)
      RETURN
      END
C.....
C      PROGRAMME TO FIND OUT THE MEAN SQUARE ERROR (MSE), MEAN PERCENT
C      ERROR(MPE) AND THE MEAN ABSOLUTE PERCENT ERROR (MAPE) FOR ASSESSING
C      PERFORMANCE OF A MODEL
C.....
C      X(I)   DATA SERIES
C      FX(I)  FORECAST VALUES
C      N      NUMBER OF DATA ITEMS
C      AMSE   MEAN SQUARE ERROR
C      AMPE   MEAN PERCENT ERROR
C      AMAPE  MEAN ABSOLUTE PERCENT ERROR
C      SUBROUTINE TEST(N,X,FX,AMSE,AMPE,AMAPE)
      DIMENSION FX(100),X(100)
      S=0.0
      SS=0.0
      SSS=0.0
      DO 200 I=1,N
      S=S+(FX(I)-X(I))**2
      IF(X(I) .EQ. 0.0)GO TO 200
      SS=SS+(FX(I)-X(I))/X(I)
      SSS=SSS+ABS((FX(I)-X(I))/X(I))
200  CONTINUE

```


AMSE=S/N
 AMPE=SS/N
 AMAPE=SSS/N
 RETURN
 END

GROUNDWATER-FLOW PROBLEM INPUT DATA FILE FOR THE STUDY AREA

30.012 08 0.1

87 103

1 0E+03 1 0E+04

1	7.0	6.775	2	6.75	7.0	3	8.25	6.5
4	8.0	7.225	5	9.25	5.5	6	8.75	5.80
7	10.0	6.0	8	10.0	6.20	9	9.5	6.675
10	10.5	6.5	11	14.0	4.5	12	13.0	4.85
13	13.75	5.10	14	12.75	5.225	15	14.25	6.0
16	15.75	5.025	17	15.0	5.5	18	15.0	5.875
19	18.0	4.34	20	17.75	4.725	21	16.75	5.425
22	20.0	4.0	23	20.0	4.5	24	20.0	5.5
25	20.0	5.25	26	21.25	3.5	27	22.75	3.375
28	23.5	5.0	29	23.5	2.775	30	25.0	2.65
31	25.0	3.0	32	25.0	3.25	33	25.0	3.5
34	25.0	4.0	35	25.0	4.5	36	25.75	2.80
37	25.5	3.125	38	25.75	4.85	39	27.0	3.15
40	26.5	3.325	41	28.25	3.05	42	28.25	3.15
43	28.25	4.5	44	30.5	2.725	45	30.0	3.0
46	30.0	3.5	47	30.0	4.0	48	30.0	4.5
49	31.0	1.65	50	30.5	2.0	51	31.75	2.5
52	32.25	4.575	53	35.0	1.80	54	35.0	2.0
55	35.0	2.5	56	35.0	3.0	57	35.0	3.5
58	35.0	4.0	59	35.0	4.5	60	38.25	2.0
61	40.0	2.5	62	40.0	3.0	63	40.0	3.5
64	40.0	4.0	65	40.0	4.275	66	42.0	2.225
67	43.75	4.175	68	45.0	2.5	69	45.0	3.0
70	45.0	3.5	71	45.0	4.0	72	45.75	2.65
73	47.25	4.40	74	50.0	3.0	75	50.0	3.5
76	50.0	3.70	77	50.0	4.0	78	51.25	3.625
79	51.5	4.30	80	53.25	3.0	81	52.5	3.825
82	55.0	3.5	83	56.75	3.10	84	60.0	3.5
85	60.0	3.85	86	62.5	3.60	87	63.0	3.875

1	2	9	4	2	1	9	2
3	3	9	1	4	3	10	9
5	8	10	3	6	8	15	10
7	7	15	8	8	7	18	15
9	7	17	18	10	6	17	07
11	05	17	06	12	14	17	05
13	14	16	17	14	12	16	13
15	11	16	12	16	22	23	19
17	11	19	23	18	11	23	20
19	11	20	16	20	23	24	16
21	16	24	25	22	16	25	21
23	16	21	17	24	17	21	18
25	29	30	31	26	29	31	27
27	31	32	27	28	32	33	26
29	26	33	22	30	22	33	34
31	22	34	23	32	34	35	23
33	23	35	24	34	35	28	24
35	24	28	25	36	30	36	31
37	31	40	33	38	37	42	40

12	3.250
11	3.250
19	3.000
22	2.750
09	0.300
10	0.375
15	0.800
18	2.020
21	2.500
25	2.500
28	2.000
38	2.000
43	2.000
48	2.000
52	1.750
59	1.500
65	1.500
12	1.0
1	1.0
2	1.0
3	1.0
4	1.0
5	1.0
6	1.0
7	1.0
8	1.0
9	1.0
10	1.0
11	1.0
12	1.0

1 GROUNDWATER-FLOW PROBLEM OUTPUT DATA FILE

0 TIME PARAMETERS

0	TIME STEP(DAYS)	30.0
	NUMBER OF TIME STEPS	12
	NUMBER OF ITERATIONS	8
	CLOSURE CRITERION FOR ITERATIONS(M)	0.100
	SAVE HEADS AND SOURCE-SINK FLUXES	
0	FINITE-ELEMENT DATA	

0	NUMBER OF NODES	87
	NUMBER OF ELEMENTS	103

0 INITIAL WATER LEVELS(METRE ABOVE DATUM)

0	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE
	1	4.60	2	4.85	3	4.40	4	4.90	5	6.00
	6	5.80	7	5.80	8	5.60	9	5.50	10	4.20
	11	5.50	12	6.00	13	6.00	14	6.00	15	5.50
	16	5.00	17	3.80	18	5.05	19	4.50	20	5.50
	21	5.50	22	4.50	23	5.50	24	3.50	25	3.90
	26	2.25	27	2.00	28	3.50	29	2.00	30	2.00
	31	1.75	32	3.50	33	3.70	34	4.00	35	3.90
	36	1.75	37	1.50	38	3.00	39	1.50	40	4.00
	41	1.50	42	3.00	43	3.50	44	1.50	45	3.00
	46	3.40	47	3.20	48	3.00	49	0.00	50	0.75
	51	1.25	52	3.00	53	0.00	54	1.00	55	1.70

56	2.50	57	2.90	58	2.70	59	3.00	60	0.00
61	1.50	62	2.80	63	3.00	64	3.00	65	2.50
66	0.00	67	1.25	68	0.00	69	1.50	70	2.50
71	2.50	72	0.00	73	1.25	74	1.00	75	1.50
76	1.50	77	1.70	78	0.75	79	0.75	80	0.00
81	0.75	82	0.75	83	0.00	84	0.00	85	0.50
86	0.00	87	0.00						

1 TIME STEP 1

0 ELAPSED TIME (DAYS) 30.0
 NUMBER OF ITERATIONS 2
 WATER-LEVEL CHANGE ON LAST ITERATION (M) 0 0183
 0 COMPUTED WATER LEVELS (METRE ABOVE DATUM)

0 NODE VALUE NODE VALUE NODE VALUE NODE VALUE NODE VALUE

1	1.178	2	1.422	3	1.244	4	0.788	5	3.138
6	2.583	7	2.187	8	1.856	9	1.553	10	1.471
11	3.864	12	3.725	13	3.299	14	3.434	15	2.148
16	5.370	17	5.451	18	2.915	19	3.718	20	6.532
21	3.409	22	3.365	23	5.795	24	3.325	25	3.148
26	2.493	27	2.138	28	2.778	29	2.066	30	2.077
31	1.937	32	3.283	33	4.110	34	4.140	35	4.165
36	1.868	37	1.679	38	2.426	39	1.829	40	4.532
41	1.775	42	3.178	43	2.337	44	1.894	45	2.994
46	3.265	47	3.274	48	2.518	49	0.124	50	0.833
51	1.360	52	2.463	53	0.152	54	0.641	55	1.407
56	2.684	57	2.946	58	2.938	59	2.262	60	0.917
61	1.275	62	2.737	63	3.155	64	2.964	65	2.084
66	0.306	67	1.717	68	0.266	69	1.650	70	2.581
71	2.343	72	0.514	73	1.476	74	0.874	75	1.526
76	2.779	77	2.107	78	1.392	79	1.038	80	0.282
81	1.311	82	0.834	83	0.245	84	0.232	85	0.686
86	0.277	87	0.270						

0 AQUIFER THICKNESS (METRE)

0 NODE VALUE NODE VALUE NODE VALUE NODE VALUE NODE VALUE

1	27.081	2	27.018	3	28.146	4	26.291	5	33.639
6	32.884	7	32.488	8	30.456	9	28.150	10	29.172
11	35.063	12	34.527	13	33.803	14	33.837	15	32.153
16	35.864	17	35.733	18	32.915	19	35.222	20	37.030
21	33.411	22	35.866	23	36.793	24	32.825	25	32.449
26	35.993	27	35.938	28	32.079	29	37.466	30	37.977
31	37.136	32	37.782	33	38.010	34	37.140	35	35.663
36	32.368	37	36.678	38	32.927	39	37.029	40	39.042
41	37.274	42	38.681	43	34.338	44	38.393	45	38.995
46	38.265	47	36.775	48	34.818	49	38.624	50	38.633
51	38.560	52	34.963	53	38.652	54	38.941	55	38.907
56	39.284	57	38.446	58	36.937	59	35.262	60	39.117
61	38.976	62	39.737	63	38.756	64	37.663	65	36.284
66	38.606	67	39.217	68	38.266	69	39.150	70	39.081
71	38.043	72	38.413	73	36.976	74	38.675	75	38.725
76	39.694	77	38.609	78	38.391	79	37.237	80	37.982
81	38.011	82	38.034	83	37.645	84	37.532	85	37.687
86	37.577	87	37.270						

0 CONSTANT-HEAD NODES

0 CUMULATIVE RATE (CUBIC METRE PER SECOND) -29.7543
 0 NODE RATE(CUBIC METRE PER SECOND)

49	-0.1243	
53	-0.1519	
60	-0.9169	
66	-0.3062	
68	-0.2665	
72	-0.5137	
80	-0.2823	
83	-0.2449	
84	-0.2317	
86	-0.2773	
87	-0.2698	
26	-0.2429	
27	-0.1381	
29	-0.0664	
30	-0.0770	
31	-0.1866	
36	-0.1178	
37	-0.1790	
39	-0.3295	
41	-0.2749	
44	-0.3938	
51	-0.1103	
50	-0.0827	
85	-0.1864	
82	-0.0838	
78	-0.6420	
81	-0.5614	
79	-0.2876	
73	-0.2258	
67	-0.4670	
4	-0.6879	
2	-0.8221	
1	-0.6780	
3	-0.8442	
8	-1.3558	
7	-1.5871	
6	-0.9829	
5	-0.8875	
14	-0.6839	
13	-0.2995	
12	-0.4745	
11	-0.6136	
19	-0.7182	
22	-0.6154	
9	-1.2528	
10	-1.0959	
15	-1.3476	
18	-0.8954	
21	-0.9086	
25	-0.6481	
28	-0.7780	
38	-0.4255	
43	-0.3370	
48	-0.5183	
52	-0.7128	
59	-0.7619	
65	-0.5837	
1	TIME STEP	2
0	ELAPSED TIME (DAYS)	60.0

NUMBER OF ITERATIONS 2
 WATER-LEVEL CHANGE ON LAST ITERATION (M) 0.0637
 0 COMPUTED WATER LEVELS (METRE ABOVE DATUM)

0	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE
	1	0.771	2	0.875	3	0.721	4	0.387	5	2.784
	6	2.135	7	1.244	8	0.982	9	0.705	10	0.785
	11	3.623	12	3.639	13	3.377	14	3.281	15	1.370
	16	5.482	17	5.303	18	2.538	19	3.869	20	7.723
	21	3.233	22	3.092	23	6.431	24	3.366	25	3.194
	26	2.568	27	2.251	28	2.905	29	2.169	30	2.176
	31	2.073	32	3.774	33	4.540	34	4.197	35	4.457
	36	1.970	37	1.801	38	2.500	39	1.977	40	5.740
	41	1.905	42	3.842	43	2.437	44	2.261	45	3.632
	46	3.208	47	3.344	48	2.487	49	0.207	50	0.899
	51	1.413	52	2.851	53	0.227	54	0.647	55	1.197
	56	3.087	57	3.160	58	3.261	59	2.300	60	2.223
	61	1.520	62	3.205	63	3.591	64	3.171	65	2.336
	66	0.734	67	2.063	68	0.594	69	2.079	70	2.851
	71	2.609	72	0.891	73	1.779	74	1.046	75	1.815
	76	5.063	77	3.147	78	2.025	79	1.424	80	0.460
	81	1.826	82	0.978	83	0.449	84	0.437	85	0.886
	86	0.482	87	0.478						

0 AQUIFER THICKNESS (METRE)

	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE
	1	26.671	2	26.475	3	27.621	4	25.887	5	33.285
	6	32.435	7	31.545	8	29.582	9	27.305	10	28.485
	11	34.820	12	34.439	13	33.877	14	33.681	15	31.372
	16	35.981	17	35.597	18	32.537	19	35.368	20	38.239
	21	33.233	22	35.592	23	37.433	24	32.865	25	32.494
	26	36.068	27	36.051	28	32.204	29	37.569	30	38.076
	31	37.271	32	38.277	33	38.441	34	37.197	35	35.957
	36	32.470	37	36.799	38	32.999	39	37.176	40	40.267
	41	37.404	42	39.354	43	34.437	44	38.760	45	39.637
	46	38.207	47	36.844	48	34.787	49	38.707	50	38.699
	51	38.612	52	35.351	53	38.727	54	38.946	55	38.696
	56	39.687	57	38.659	58	37.261	59	35.300	60	40.424
	61	39.220	62	40.207	63	39.192	64	37.871	65	36.536
	66	39.033	67	39.562	68	38.593	69	39.579	70	39.351
	71	38.310	72	38.790	73	37.278	74	38.846	75	39.012
	76	42.026	77	39.652	78	39.022	79	37.622	80	38.160
	81	38.524	82	38.177	83	37.849	84	37.736	85	37.886
	86	37.782	87	37.478						

0 CONSTANT-HEAD NODES

0 CUMULATIVE RATE (CUBIC METRE PER SECOND) -30.4979
 0 NODE RATE(CUBIC METRE PER SECOND)

49	-0.2072
53	-0.2273
60	-2.2226
66	-0.7336
68	-0.5938
72	-0.8909
80	-0.4603

83	-0.4495
84	-0.4366
86	-0.4819
87	-0.4777
26	-0.3185
27	-0.2515
29	-0.1688
30	-0.1759
31	-0.3226
36	-0.2202
37	-0.3013
39	-0.4772
41	-0.4050
44	-0.7612
51	-0.1626
50	-0.1488
85	-0.3857
82	-0.2280
78	-1.2752
81	-1.0758
79	-0.6737
73	-0.5288
67	-0.8130
4	-0.2866
2	-0.2753
1	-0.2710
3	-0.3211
8	-0.4818
7	-0.6442
6	-0.5353
5	-0.5340
14	-0.5305
13	-0.3766
12	-0.3888
11	-0.3726
19	-0.8685
22	-0.3424
9	-0.4052
10	-0.4099
15	-0.5698
18	-0.5176
21	-0.7326
25	-0.6937
28	-0.9048
38	-0.4997
43	-0.4369
48	-0.4872
52	-1.1005
59	-0.8002
65	-0.8360

APPENDIX G

Variables for different subroutines of main program of Finite Element Groundwater Transport Model

A. VARIABLES FOR SUBROUTINE TDATA

VARIABLE	TYPE	DEFINITION
TITLE	Real array	Identification of problem
DELT	Real scalar	Hydraulic time step
MAXKNS	Integer scalar	Number of hydraulic time steps
NN	Integer scalar	Number of nodes
NE	Integer scalar	Number of elements
X	Real array	X - coordinate of node
Y	Real array	Y - coordinate of node
IN	Integer array	Element incidence
K	Real array	Hydraulic conductivity over elements
BASE	Real array	Altitude of aquifer base at nodes
NDELT	Integer scalar	Number of solute time steps per hydraulic time steps
POR	Real array	Porosity over element
CO	Real array	Initial concentration at node
DL	Real scalar	Longitudinal dispersivity
DT	Real scalar	Transverse dispersivity
NSS	Integer scalar	Number of source-sink data sets
CSET	Real array	Concentration of recharge and discharge at nodes
NSET	Integer array	Source-sink data-set indicators
FACSET	Real array	Multipliers for source-sink data-sets

B. VARIABLES FOR SUBROUTINE TMODEL

VARIABLE	TYPE	DEFINITION
KNS	Integer scalar	Time step
H	Real array	Waterlevels for hydraulic time step
Q	Real array	Source-sink strengths for time step
C	Real array	Computed concentration at time $t + \Delta t$
CL	Real array	Computed concentration at time t
A	Real array	Global stiffness matrix
AE	Real array	Elemental stiffness matrix
B	Real array	Global mass matrix
BE	Real array	Elemental mass matrix
L	Real array	Left-hand-side matrix
R	Real array	Right-hand-side vector
THK	Real array	Aquifer thickness

C. VARIABLES FOR SUBROUTINE TSHAPE

VARIABLE	TYPE	DEFINITION
XE	Real array	X - coordinate for node
YE	Real array	Y - coordinate for node
AREA	Real array	Area for element
BB	Real array	Coefficient b of trial function
CC	Real array	Coefficient c of trial function
QX	Real scalar	Groundwater discharge in x direction
QP	Real scalar	Groundwater discharge in y direction
VX	Real scalar	Groundwater velocity in x direction
VY	Real scalar	Groundwater velocity in y direction

DXX	Real scalar	Components of dispersion tensor
DXY		
DYX		
DYY		
POR	Real array	Aquifer porosity
THKE	Real scalar	Average aquifer thickness for element

D. VARIABLES FOR SUBROUTINE TABAND

VARIABLE	TYPE	DEFINITION
L	Real array	Left-hand-side matrix
R	Real array	Right-hand-side vector
C	Real array	Solution vector and intermediate solution vector

SOURCE LISTING FOR GROUNDWATER TRANSPORT PROBLEM

```

C  PROGRAMME SOLUTE TRANSPORT
C  -----
C      COMMON  MODEL, MAXKNS,NN,NE,NB,NBM1,NB2,NDELT,NSS,
1          DL,DT,DELT,
2          X,Y,CO,BASE,
3          K,POR,IN,
4          CSET,NSET,FACSET,
5          AE,BE,A,B,Q,QC,C,CL,P,H,F,THK
C
      INTEGER  IN (150,3),NSET (30)
      REAL    X(100), Y(100), CO(100),BASE(100)
      REAL    K (150), POR(150)
      REAL    CSET (100,12), FACSET (30)
      REAL    AE(3,3),BE(3,3)
      REAL    A(100,29),B(100,29)
      REAL    Q(100),QC(100),C(100),CL(100),P(100),H(100),F(100),
1  THK(100),GSRL(100)
      REAL    TITLE (20)
      DIMENSION  XX(100),YY(100) OX(100),FY(100)
      INTEGER  BOUNODE(60)
      INTEGER  TNODE
      INTEGER  BNODE

      CALL TDATA
      CALL TMODEL
      CLOSE(11)
C*****
C      PROGRAMME TO CONVERT THE RECHARGE FILE TO REQUIRED
C      FORMAT (RECHARGE IS READ AS ZERO AT CONSTANT NODES)
C*****TNODE---TOTAL NUMBER OF NODES IN THE STUDY AREA
C*****BNODE---NUMBER OF BOUNDARY NODES
C*****ITNODE---NUMBER OF INTERNAL NODES
C*****Bounode---Boundary nodes
C*****
      OPEN(1,FILE='COMPCONC',STATUS='OLD')
      OPEN(2,FILE='NO3POST',STATUS='OLD')
      OPEN(3,FILE='BOUNNODE',STATUS='OLD')
      OPEN(4,FILE='CONC95')
      READ(3,35)TNODE,BNODE,ITNODE
35  FORMAT(4X,I2,4X,I2,4X,I2)
      READ(2,55)(XX(NODE),NODE=1,TNODE)
55  FORMAT(10F5.2)
      IK=1

```

```

DO 100 NODE=1,TNODE
REWIND(3)
READ(3,35)TNODE,BNODE,ITNODE
10  FORMAT(F6,2)
    READ(1,10)Yy(NODE)
    DO 300 I=1,BNODE
      READ(3,15)bouNODE(I)
15  FORMAT(I2)
      IF(NODE.EQ. bouNODE(I))GO TO 100
300  CONTINUE
      OX(IK)=Xx(NODE)
      FY(IK)=Yy(NODE)
      DIFF=Xx(NODE)-Yy(NODE)
      IK=IK+1
      WRITE(4,25)NODE,Xx(NODE),Yy(NODE),DIFF
25  FORMAT(I2,4X,F6,3,4X,F6,3,4X,F5,2)
100  CONTINUE
      CALL STDEV1(IK,ITNODE,OX,SDX,AVEX)
      CALL STDEV1(IK,ITNODE,FY,SDY,AVEY)
      SUMDXY=(0)
      DO 200 I=1,ITNODE
        DX=(OX(I)-AVEX)
        DY=(FY(I)-AVEY)
        DXY=DX*DY
        SUMDXY=SUMDXY+DXY
200  CONTINUE
      COVAR=(SUMDXY/(ITNODE))
      CCOE=(COVAR/(SDX*SDY))
      WRITE(4,*)'CORRELATION COEFFICIENT=' ,CCOE
      CALL TEST(ITNODE,OX,FY,AMSE,AMPE,AMAPE)
      WRITE(*,*)'MSE=' ,AMSE
      WRITE(*,*)'MPE=' ,AMPE
      WRITE(*,*)'MAPE=' ,AMAPE
      WRITE(4,*)'MSE=' ,AMSE
      WRITE(4,*)'MPE=' ,AMPE
      WRITE(4,*)'MAPE=' ,AMAPE
      STOP
      END

C  -----
C  SUBROUTINE  TDATA
C  -----
COMMON / MODEL/  MAXKNS,NN,NE,NB,NBM1,NB2,NDELT,NSS,
1  DL,DT,DELT,
2  X,Y,CO,BASE,
3  K,POR,IN,
4  CSET,NSET,FACSET,
5  AE,BE,A,B,Q,QC,C,CL,P,H,F,THK

C  INTEGER  IN (150,3),NSET (30)
REAL X(100), Y(100), CO(100),BASE(100)
REAL K (150), POR(150)
REAL CSET (100,12), FACSET (30)
REAL AE(3,3),BE(3,3)
REAL A(100,29),B(100,29)
REAL Q(100),QC(100),C(100),CL(100),P(100),H(100),F(100),
1  THK(100),GSRL(100)
REAL TITLE (20)

C  DIMENSIONED FOR THE FOLLOWING SIZE.
C  NUMBER OF THE NODES      =      87
C  NUMBER OF THE ELEMENTS   =      103

```

```

C      NUMBER OF TIME STEPS                =      30
C      NUMBER OF SOURCE -SINK DATA SETS =      4
C
C      LOGICAL UNIT NUMBERS
C
C      IR = 5
C      IW = 6
C      OPEN(5,FILE='SOLUTE95.DAT',STATUS='OLD')
C      OPEN(10,FILE='COMPHEAD',STATUS='OLD')
C      OPEN(7,FILE='QFLOW95',STATUS='OLD')
C      FILE NFLOW95(i.e. NET FLOW)INCLUDES PUMPING ALSO
C      OPEN(7,FILE='nflow95',status='old')
C      OPEN(8,FILE='NO3PRE95',STATUS='OLD')
C      OPEN(9,FILE='CONNODEK',STATUS='OLD')
C      OPEN(9,FILE='CONCLOAD 95',STATUS='OLD')
C
C      OPEN(6,FILE='CPOST95 OUT')
C      OPEN(11,FILE='COMPCONC')
C
C      INPUT HYDRAULIC DATA
C
C      BASIN NAME
C
C      READ (5,900) (TITLE (I), I=1,20)
C      WRITE (6,901) (TITLE (I), I=1,20)
900    FORMAT (20A4)
901    FORMAT (1H1,10X,20A4 1H ,10X,80 ('-'))
C
C      HYDRAULIC TIME STEP (DAYS) AND NUMBER OF TIME STEPS
C
C      READ(5,902) DELT ,MAXKNS
C      WRITE(6,903) DELT,MAXKNS
C      DELT= DELT*3600 0*24 0
902    FORMAT (F6 0,1X,12,2X,12,2X,F3 1)
903    FORMAT (1H0,10X,'TIME PARAMETERS' 1H ,10X, 15('-') 1H0,10X,
1      'TIME STEP(DAYS)' , 21X,F8.1 1H , 10X, 'NUMBER OF TIME STEPS',
2      21X,14)
C
C      NUMBER OF NODES AND ELEMENTS
C
C      READ (5,904) NN,NE
C      WRITE (6,905) NN,NE
904    FORMAT (2I6)
905    FORMAT (1H0,10X, 'FINITE ELEMENT DATA' 1H ,10X,19 ('-') 1H0,10X,
1      'NUMBER OF NODES ' 110 1H ,10X, 'NUMBER OF ELEMENTS' 110)
C
C      READ(5,899)AQUTHK
899    FORMAT(4X,F4.1)
C      NODE COORDINATES (METRE)
C
C      READ (5,906) FACX,FACY
C      READ (5,907) (IX(I),Y(I), I=1,NN)
C
C      DO 100 I =1,NN
C      X(I)=X(I)*FACX
C      Y(I)=Y(I)*FACY
100    CONTINUE
C      WRITE (6,908) FACX,FACY
C      WRITE (6,909) (IX(I),Y(I),I=1,NN)

```

```

906  FORMAT (2E12.0)
907  FORMAT (3(I6,F6.1,F7.2,5X))
908  FORMAT (1H0,10X,' NODE COORDINATES (METRE) ' 1H ,10X, 23('-')
1      1H0,10X, 'FACTOR FOR X-COORDINATE',1PE11.3
2      1H ,10X,'FACTOR FOR Y-COORDINATE',1PE11.3
3      1H0, 10X,3('NODE',11X,'X',11X,'Y',5X))
909  FORMAT ( ( 1H , 10X,3(I4,F12.1,F12.1,5X)))

C
C      ELEMENT INCIDENCES (COUNTER CLOCKWISE)
C
      READ(5,910) (I,(IN(I,J),J=1,3),I=1,NE)
      WRITE (6,911)
      WRITE (6,912) (I, (IN(I,J),J=1,3), I=1,NE)
910  FORMAT (2(4I6,6X))
911  FORMAT (1H0,10X, 'ELEMENT INCIDENCES (COUNTER CLOCKWISE) '
1      1H ,10X, 38 ('-')
2      1H0, 10X,3('ELEM', 13X,'CORNERS' , 9X))
912  FORMAT ((1H ,10X,3(I4,2X,3I6,9X)))

C
C      FIND HALF BAND WIDTH
C
      NB=0
      DO 102 L= 1,NE
      IMAX=0
      IMIN=10000
      DO 101 I=1,3
      II =IN(L,I)
      IMAX=MAX0(IMAX,II)
      IMIN=MIN0(IMIN,II)
101  CONTINUE
      NB=MAX0((IMAX-IMIN+1),NB)
102  CONTINUE
      NBM1=NB-1
      NB2=NB*2-1
C      WRITE(6,913)NB
913  FORMAT (1H0,10X,'HALF-BAND WIDTH', 19)

C
C      HYDRAULIC CONDUCTIVITY ( METRE PER DAY)
C
      READ (5,914) FACK
      READ (5,915) (K(I),I=1,NE)
      DO 103 I=1,NE
      K(I)=K(I)*FACK
103  CONTINUE
      WRITE (6,917) FACK
      WRITE (6,918) (I,K(I),I=1,NE)
      DO 104 I=1,NE
      K(I)=K(I)/(3600.0*24.0)
104  CONTINUE
914  FORMAT (E12.0)
915  FORMAT (10F6.0)
917  FORMAT (1H0,10X,'HYDRAULIC CONDUCTIVITY(METRE PER DAY) '
1      1H ,10X ,37 ('-')
2      1H0 ,10X,'FACTOR FOR CONDUCTIVITY',1PE11.3
3      1H0, 10X,5('ELEM',7X,'VALUE',4X))
918  FORMAT ((1H ,10X,5(I4,3X,F9.1,4X)))

C
C      ALTITUDE FOR BASE OF AQUIFER (METRE ABOVE DATUM)
C
      READ (5,925) (GSRL(I),I=1,NN)

```

```

DO 99 I=1,NN
BASE(I)=GSRL(I)-AQUITHK
99  CONTINUE
WRITE (6,926)
WRITE (6,927) (I,BASE(I),I=1,NN)
925  FORMAT (10F6.1)
926  FORMAT (11H0, 10X,'BASE OF AQUIFER (METRE ABOVE DATUM)')
1    1H ,10X,34('-')
2    1H0,10X,5('NODE',7X,'VALUE' , 4X)/
927  FORMAT ((1H ,10X,5(I4,3X,F9.1,4X)))

C
C    SOLUTE -TRANSPORT DATA
C
READ(5,952) NDELT
WRITE(6,953) NDELT
DELT2=DELT/NDELT
952  FORMAT (I6)
953  FORMAT (11H0,10X,'TIME PARAMETERS',11H ,10X,15('-')
2    1H ,10X, 'NUMBER OF SOLUTE TIME STEPS',2X,110)

C
C    AQUIFER POROSITY
C
READ (5,940) FACPOR
READ (5,940) (POR(I),I=1,NE)
DO 1001 I= 1,NE
POR(I)=POR(I)*FACPOR
1001 CONTINUE
WRITE (6,941) FACPOR
WRITE (6,942) (I,POR(I),I=1,NE)
940  FORMAT (10F6.1)
9401 FORMAT (F6.0)
941  FORMAT (11H0,10X,'AQUIFER POROSITY' ,11H ,10X,16('-')
1    1H0,10X,'FACTOR FOR POROSITY',1PE11.3
2    1H0,10X,5('ELEM',7X,'VALUE',4X)/
942  FORMAT ((1H ,10X, 5(I4,3X,F9.1,4X)))

C
C    INITIAL CONCENTRATION (ANY CONSISTENT UNITS)
C
READ (8,921) (CO(I), I=1,NN)
WRITE(6,922)
WRITE (6,923) (I,CO(I),I=1,NN)
921  FORMAT (10F5.2)
922  FORMAT (11H0,10X, 'INITIAL CONCENTRATION',11H , 10X,21('-')
1    1H0,10X, 5('NODE',7X,'VALUE',4X)/
923  FORMAT ((1H ,10X,5 (I4,3X,F9.1,4X)))

C
C    LONGITUDINAL AND TRANSVERSE DISPERSIVITY (METRE)
C
READ (5,935) DL,DT
WRITE (6,936)DL,DT
935  FORMAT (2F6.1)
936  FORMAT (11H0,10X,'DISPERSIVITY',11H ,10X,12('-')
1    11H0, 10X,'LONGITUDINAL', F6.0/
2    11H , 10X,'TRANSVERSE',F6.0)

C
C    NUMBER OF SOURCE-SINK DATA SETS AND FACTOR FOR
C    CONCENTRATIONS
C
READ(5,964) NSS,FACC
WRITE(6,965) NSS,FACC

```

```

964  FORMAT (I6,2F6.0)
965  FORMAT (1H0,10X,'RECHARGE AND DISCHARGE',1H ,10X,22('-'))
1    1H0,10X,'NUMBER OF DATA SETS',110/
2    1H , 10X,'FACTOR FOR C',7X,1PE10.3)

C
C    SOURCES (+) AND SINKS (-) STRENGTH (CUBIC METRE PER SECOND)
C    AND CONCENTRATION (ANY CONSISTENT UNITS)
C
      DO 105 J=1,NSS
      DO 106 I=1,NN
      CSET(I,J)=0.0
106  CONTINUE
105  CONTINUE
      DO 107 J=1,NSS
      READ(9,977)(I,CSET(I,J),I=1,NN)
      DO 1061 I=1,NN
      CSET (I,J)=CSET (I,J)*FACC
1061 CONTINUE
      WRITE (6,980)J
      WRITE (6,981) (I,CSET(I,J),I=1,NN)
107  CONTINUE
976  FORMAT(I6)
C 977  FORMAT (4(I6,F6.0))
977  FORMAT(I4,F6.2)
980  FORMAT (1H0,10X, 'CONCENTRATION SET', 15 1H ,10X,22('-'))
1    1H0, 10X , 5('NODE',7X,'VALUE',4X))
981  FORMAT ((1H ,10X,5(I4,3X,F9.1,4X)))

C
C    TIME-STEP INDICATORS AND MULTIPLIERS
C
      READ (5,932) (INSET(I),FACSET(I),N=1,MAXKNS)
      WRITE(6,933)
      WRITE(6,934) (I,NSET(I),FACSET(I),I=1,MAXKNS)
932  FORMAT (16,I6,F6.0)
933  FORMAT (1H0,10X,'TIME-STEP INDICATORS AND MULTIPLIERS',
1    1H ,10X,37('-') 1H0,10X,'STEP',7X,'SET',4X,'FACTOR')
934  FORMAT ((1H ,10X,I4,7X,I3,4X,F6.3))

C
C    END DATA INPUT
C
      RETURN
      END

C
C    SUBROUTINE TMODEL
C
C    DIMENSIONED FOR THE FOLLOWING PROBLEM SIZE.
C    NUMBER OF NODES           =      100
C    NUMBER OF ELEMENTS        =      150
C    NUMBER OF TIME STEPS      =      30
C    NUMBER OF SOURCE-SINK DATA SETS =      4
C
      COMMON / MODEL/ MAXKNS,NN,NE,NB,NBM1,NB2,NDELT,NSS,
1      DL,DT,DELT,
2      X,Y,CO,BASE,
3      K,POR,IN,
4      CSET,NSET,FACSET,
5      AE,BEA,B,Q,QC,C,CL,P,H,F,THK

C
      INTEGER IN(150,3),NSET(30)

```

```

      REAL X(100),Y(100),CO(100),BASE(100)
      REAL K(150),POR(150)
      REAL CSET (100,12),FACSET(30)
C
      REAL AE(3,3),BE(3,3)
      REAL A(100,29),B(100,29)
      REAL Q(100),QC(100),C(100),CL(100),P(100),H(100),F(100),
1 THK(100),GSRL(100)
C
      REAL XE(3),YE(3),XB(3),XC(3)
      REAL L(100,29),R(100)
C
C      LOGICAL UNIT NUMBERS
C
C      IR=5
C      IW=6
C      IR2=10
      REWIND IR2
C      INITIAL CONCENTRATION
C
      DO 2001 I =1,NN
      CL(I) = CO (I)
      C(I)=C0(I)
2001 CONTINUE
      SKNS2=0
      DELT2=DELT*FLOAT(NDELT)
C
C      BEGIN HYDRAULIC TIME-STEP LOOP
C
      KNS=0
400 KNS=KNS+1
      IF (KNS GT MAXKNS) RETURN
C
C      HYDRAULIC HEADS AND SOURCE-SINK STRENGTHS FROM
C      HYDRAULIC MODEL
C
      READ(IR2,926) (H(I),I=1,NN)
      READ(7,927) (Q(I),I=1,NN)
926 FORMAT(10F6.2)
927 FORMAT(5F7.4)
C      WRITE(6,926)(H(I),I=1,NN)
C      WRITE(6,927)(Q(I),I=1,NN)
C
C      THICKNESS OF AQUIFER
C
      DO 325 I=1,NN
      THK (I)=H(I)-BASE(I)
      IF(THK(I).LT 10.0) THK(I)=10.0
e 325 CONTINUE
C
C      INITIALIZE MATRICES (A) AND (B)
C
      DO 4102 I =1,NN
      DO 4101 J =1,NB2
      A(I,J)=0.0
      B(I,J)=0.0
4101 CONTINUE
      F(I)=0.0
4102 CONTINUE
C

```



```

C      SOURCE (QC) AND SINK (Q) VECTORS
C
      JJ=NSET(KNS)
      DO 455 I=1,NN
      QC(I)=Q(I)*CSET(I,JJ)*FACSET(KNS)
455    CONTINUE
      WRITE(6,951) KNS
951    FORMAT (1H0,10X,'HYDRAULIC PARAMETERS',1H ,10X,20('-')
1      1H0,10X,'HYDRAULIC TIME STEP',16/
2      1H0,10X,'ELEM',13X,'QX', 13X,'QY',12X,'DXX',12X,'DXY',12X,
3      'DYY')
C
C      BEGIN LOOP OVER ELEMENTS
C
C      WRITE(6,*) 'ELEMENT INCIDENCES'
C      WRITE(6,*)(1,(IN(I,J),J=1,3),I=1,NE)
C 912    FORMAT ((1H,10X,3(14,2X,316,9X)))
      DO 412 LI = 1,NE
      CALL TSLAPE (LI,LI,N,X,Y,THK,POR,K,H,DL,DT,AE,BE)
C
C      GLOBAL STIFFNESS MATRIX (A) AND DYNAMIC MATRIX (B)
C
      DO 411 I=1,3
      II=IN(LL,I)
      DO 410 J =1,3
      JJ=IN(LL,J)-II+NB
      A(II,JJ)=A(II,JJ)+AE(I,J)
      B(II,JJ)=B(II,JJ)+BE(I,J)*DELT2
410    CONTINUE
411    CONTINUE
412    CONTINUE
C
C      END LOOP OVER ELEMENTS
C
C      CONSTRUCT LEFT-HAND -SIDE MATRIX (A)
C      AND UPPER TRIANGULARIZE
C
      DO 430 I=1,NN
      IF (Q(I) LE 0.0) A(I,NB)=A(I,NB)-Q(I)
      DO 429 J=1,NB2
      A(I,J)=A(I,J)+B(I,J)
429    CONTINUE
430    CONTINUE
      CALL TABAND (1,A,F,NN,NBM1)
C
C      BEGIN SOLUTE -TRANSPORT TIME-STEP LOOP
C
      KNS2=0
300    KNS2=KNS2+1
      IF(KNS2 .GT. NDELT) GO TO 400
      SKNS2=SKNS2+1
C
C      MULTIPLICATION OF DYNAMIC MATRIX (B) AND
C      LAST-CONCENTRATION VECTOR (CL) AND ADD
C      TO RIGHT-HAND-SIDE VECTOR (F)
C
      DO 419 I=1,NN
      J1=1
      IF(I-NB .GE. 0) GO TO 416
      J1=NB-I+1

```

```

416 J2=NB2
   IF(I+NB-1 .LE. NN) GO TO 417
   J2=NB+NN-I
417 P(I)=0.0
   DO 418 J=J1,J2
   P(I)=P(I)+B(I,J)*CL(I-NB+J)
418 CONTINUE
   F(I)= P(I)*1.025
419 CONTINUE
C
C   ADD SOURCE-SINK LOAD TO RIGHT-HAND-SIDE VECTOR (F)
C
   DO 420 I=1,NN
   IF (QC(I) GT 0.0 ) F(I)=F(I)+QC(I)
420 CONTINUE
C
C   SOLVE FOR NEW CONCENTRATION VECTOR (C)
C
   CALL TABAND (2,A,F,NN,NB,M1)
C
C   INTERCHANGE CONCENTRATIONS
C
   DO 310 I=1,NN
   C(I)=F(I)
   CL(I)=C(I)
310 CONTINUE
C
C   DISPLAY RESULTS
C
   TIME=SKNS2*DELT2 (3600.0*24.0)
   WRITE(6,978) SKNS2,TIME
   WRITE(6,979) (C(I),I=1,NN)
C*****
   IF(SKNS2 EQ MAXKNS)GO TO 1005
   GO TO 1006
1005 WRITE(11,990)(C(I),I=1,NN)
990 FORMAT(F6.2)
1006 CONTINUE
C*****
978 FORMAT (1H0,10X,'TIME STEP',F4.0/1H0 ,10X,13('-')/
1 1H0,10X,'ELAPSED TIME',F10.2, 1X, 'DAYS'/
2 1H0,10X,'COMPUTED CONCENTRATION'/1H0 ,10X,22('-')/
3 1H0,10X,5('NODE',7X,'VALUE',4X)/
979 FORMAT((1H ,10X,5(I4,3X,F9.1,4X)))
   GO TO 300
C
C ..... END SOLUTE-TRANSPORT TIME-STEP LOOP
C .... END HYDRAULIC TIME-STEP LOOP
C
   END
C
C
C-----
SUBROUTINE TSHAPE (LL,I,IN,X,Y,THK,POR,K,H,DL,DTAE,BE)
C-----
C..... DIMENSIONED FOR THE FOLLOWING PROBLEM SIZE.
C   NUMBER OF NODES      =      100
C   NUMBER OF ELEMENTS   =      150
C
C   INTEGER IN(150,3)
C   REAL X(100),Y(100),THK(100),H(100)

```

```

      REAL POR (150),K(150)
      REAL AE(3,3),BE(3,3),XE(3),YE(3),BB(3),CC(3)
C
C ..... ELEMENT COORDINATES, GROUND-WATER VELOCITY, AND
C HYDRODYNAMIC DISPERSION
C
C WRITE(6,*)'ELEMENT INCIDENCES'
C WRITE(6,*)(I,(IN(I,J),J=1,3),I=1,NE)
C 912 FORMAT(11H,10X,3(14,2X,316.9X))
      DO 407 I=1,3
        II=IN(LL,I)
        XE(I)=X(II)
        YE(I)=Y(II)
      407 CONTINUE
        BB(1)=YE(2)-YE(3)
        BB(2)=YE(3)-YE(1)
        BB(3)=YE(1)-YE(2)
        CC(1)=XE(3)-XE(2)
        CC(2)=XE(1)-XE(3)
        CC(3)=XE(2)-XE(1)
        AREA=ABS((BB(1)*XE(1)+BB(2)*XE(2)+BB(3)*XE(3))*0.5)
C
C GROUND-WATER VELOCITY
C
      QX=0.0
      QY=0.0
      THKE=0.0
      DO 380 I=1,3
        II=IN(LL,I)
        QX=QX-H(II)*BB(I)
        QY=QY-H(II)*CC(I)
        THKE=THKE+THK(II)
      380 CONTINUE
        THKE=THKE/3.0
        T=THKE*K(LL)
        QX=-QX*T*0.5/AREA
        QY=-QY*T*0.5/AREA
        VX=ABS(QX/THKE)
        VY=ABS(QY/THKE)
        VV=SQRT(VX*VX+VY*VY)
C
C DISPERSION COEFFICIENTS
C
      DXX=DT*VV+(DL-DT)*VX*VX/VV
      DXY=(DL-DT)*VX*VY/VV
      DYX=DXY
      DYY=DT*VV+(DL-DT)*VY*VY/VV
C
      WRITE(6,952) LL,QX,QY,DXX,DXY,DYY
      952 FORMAT(11H,10X,14,5(1PE15.3))
C
C ..... ELEMENT STIFFNESS MATRIX AND DYNAMIC MATRIX
C
      DO 409 J=1,3
        DO 408 J=1,3
          AE(I,J)=-QX*BB(I)/6.0-QY*CC(I)/6.0
            1 +THKE*POR(LL)*DXX*BB(J)*BB(I)/(4.0*AREA)
            2 +THKE*POR(LL)*DXY*CC(J)*BB(I)/(4.0*AREA)
            3 -THKE*POR(LL)*DYX*BB(J)*CC(I)/(4.0*AREA)
            4 +THKE*POR(LL)*DYY*CC(J)*CC(I)/(4.0*AREA)

```

```

      BE(I,J)=POR(LL)*THKE*AREA/12.0
      IF(I .EQ. J) BE(I,J)=BE(I,J)*2.0
408  CONTINUE
409  CONTINUE
      RETURN
      END

C-----
C      SUBROUTINE  TABAND  (KKK,L,R,NEQ,IHALFB)
C-----
C      DIMENSIONED FOR THE FOLLOWING PROBLEM SIZE
C      NUMBER OF NODES      =      87
C      FULL-BAND WIDTH      =      14
C
      REAL  L(100,29),R(100)
      NRS=NEQ-1
      IHBP=IHALFB+1
      IF (KKK .EQ. 2) GO TO 30

C      TRINGULARIZE MATRIX A USING A DOOLITTLE METHOD
C
      DO 10 K=1,NRS
        PIVOT=L(K,IHBP)
        KK=K+1
        KC=IHBP
        DO 20 I=KK,NEQ
          KC=KC-1
          IF(KC .LE. 0) GO TO 10
C-      -L(I,KC)/PIVOT
          L(I,KC)=C
          KI=KC+1
          LIM=KC+IHALFB
          DO 20 J= KI,LIM
            JC=IHBP+J-KC
20      L(I,J)=L(I,J)-C*L(K,JC)
10      CONTINUE
          GO TO 100

C
C      MODIFY LOAD VECTOR R
C
      30  NN=NEQ+1
          IBAND=2*IHALFB+1
          DO 40 I=2,NEQ
            JC=IHBP-I+1
            JI=1
            IF (JC .LE. 0) GO TO 50
            GO TO 60
50      JC=1
            JI=I-IHBP+1
60      SUM=0.0
            DO 70 J =JC,IHALFB
              SUM=SUM+L(I,J)*R(JI)
70      JI=JI+1
40      R(I)=R(I)+SUM

C
C      BACK SOLUTION
C
      R(NEQ)=R(NEQ)/L(NEQ,IHBP)
      DO 80 IBACK=2,NEQ
        I=NN-IBACK
        JP=I

```

```

      KR=IHBP+1
      MR=MIN0(IBAND,IHALFB+IBACK)
      SUM=0.0
      DO 90 J= KR,MR
      JP=JP+1
90    SUM=SUM+L(I,J)*R(JP)
80    R(I)=(R(I)-SUM)/L(I,IHBP)
100   RETURN
      END
C*****
C*****SUBROUTINE TO CALCULATE STANDARD DEVIATION AND MEAN
C*****
      SUBROUTINE STDEVI(I,N1,VAR,SD,AVE)
      DIMENSION VAR(100)
      SUM=0.0
      DO 100 I=1,N1
      SUM=SUM+VAR(I)
100   CONTINUE
      AVE=SUM/N1
      SSQDEV=0.0
      DO 150 I=1,N1
      DEVI=VAR(I)-AVE
      SQDEV=DEVI**2
      SSQDEV=SSQDEV+SQDEV
150   CONTINUE
      SD=SQRT(SSQDEV/N1)
      RETURN
      END
C*****
C      PROGRAMME TO FIND OUT THE MEAN SQUARE ERROR (MSE), MEAN PERCENT
C      ERROR(MPE) AND THE MEAN ABSOLUTE PERCENT ERROR (MAPE) FOR ASSESSING
C      PERFORMANCE OF A MODEL
C*****
C      X(I)   DATA SERIES
C      FX(I)  FORECAST VALUES
C      N      NUMBER OF DATA ITEMS
C      AMSE   MEAN SQUARE ERROR
C      AMPE   MEAN PERCENT ERROR
C      AMAPE  MEAN ABSOLUTE PERCENT ERROR
C      SUBROUTINE TEST(N,X,FX,AMSE,AMPE,AMAPE)
C      DIMENSION FX(100),X(100)
C      S=0.0
C      SS=0.0
C      SSS=0.0
C      DO 200 I=1,N
C      S=S+(FX(I)-X(I))**2
C      IF(X(I).EQ.0.0)GO TO 200
C      SS=SS+(FX(I)-X(I))/X(I)
C      SSS=SS+ABS((FX(I)-X(I))/X(I))
200   CONTINUE
C      AMSE=S/N
C      AMPE=SS/N
C      AMAPE=SSS/N
C      RETURN
C      END

```

GROUNDWATER-TRANSPORT PROBLEM INPUT DATA FILE

```

30.0    04 08    0.1
87      103

```

40 0

1. 0E+031 0E+04

1	7 0	6 775	2	6 75	7 0	3	8.25	6 5
4	8 0	7.225	5	9 25	5 5	6	8.75	5.80
7	10 0	6 0	8	10.0	6 20	9	9 5	6 675
10	10.5	6 5	11	14.0	4 5	12	13.0	4 85
13	13 75	5 10	14	12 75	5 225	15	14 25	6.0
16	15 75	5 025	17	15 0	5 5	18	15.0	5 875
19	18 0	4 34	20	17 75	4.725	21	16.75	5.425
22	20 0	4 0	23	20 0	4.5	24	20.0	5.5
25	20 0	5 25	26	21.25	3 5	27	22.75	3.375
28	23 5	5 0	29	23 5	2 775	30	25.0	2.65
31	25 0	3 0	32	25 0	3 25	33	25.0	3.5
34	25 0	4 0	35	25 0	4.5	36	25 75	2.80
37	25 5	3 125	38	25 75	4.85	39	27.0	3.15
40	26 5	3 325	41	28 25	3 05	42	28.25	3 15
43	28 25	4 5	44	30 5	2 725	45	30 0	3 0
46	30 0	3 5	47	30 0	4 0	48	30 0	4.5
49	31 0	1 65	50	30 5	2 0	51	31 75	2.5
52	32 25	4 575	53	35 0	1 80	54	35 0	2.0
55	35 0	2 5	56	35 0	3 0	57	35 0	3 5
58	35 0	4 0	59	35 0	4 5	60	38 25	2.0
61	40 0	2 5	62	40 0	3.0	63	40.0	3.5
64	40 0	4 0	65	40.0	4 275	66	42.0	2.225
67	43 75	4 175	68	45 0	2 5	69	45.0	3 0
70	45 0	3 5	71	45 0	4 0	72	45 75	2.65
73	47 25	4 40	74	50.0	3.0	75	50 0	3.5
76	50 0	3 70	77	50 0	4.0	78	51.25	3.625
79	51 5	4 30	80	53.25	3 0	81	52 5	3.825
82	55.0	3 5	83	56 75	3 10	84	60.0	3 5
85	60 0	3.85	86	62 5	3 60	87	63 0	3.875

1	2	9	4	2	1	9	2
3	3	9	1	4	3	10	9
5	8	10	3	6	8	15	10
7	7	15	8	8	7	18	15
9	7	17	18	10	6	17	07
11	05	17	06	12	14	17	05
13	14	16	17	14	12	16	13
15	11	16	12	16	22	23	19
17	11	19	23	18	11	23	20
19	11	20	16	20	23	24	16
21	16	24	25	22	16	25	21
23	16	21	17	24	17	21	18
25	29	30	31	26	29	31	27
27	31	32	27	28	32	33	26
29	26	33	22	30	22	33	34
31	22	34	23	32	34	35	23
33	23	35	24	34	35	28	24
35	24	28	25	36	30	36	31
37	31	40	33	38	37	42	40
39	39	45	42	40	45	46	33
41	33	46	34	42	46	47	34
43	34	47	35	44	47	48	35
45	35	43	38	46	35	38	28
47	44	45	41	48	49	53	54
49	49	54	50	50	50	54	51
51	54	55	51	52	51	55	56
53	44	51	56	54	44	56	45

0.1	0.1	0.1
600.0	200.0	
1	1.0	
1	1	1.0
2	1	1.0
3	1	1.0
4	1	1.0
5	1	1.0
6	1	1.0
7	1	1.0
8	1	1.0
9	1	1.0
10	1	1.0
11	1	1.0
12	1	1.0

GROUNDWATER-TRANSPORT PROBLEM OUTPUT DATA FILE

TIME PARAMETERS

TIME STEP(DAYS)	30.0
NUMBER OF TIME STEPS	4
FINITE ELEMENT DATA	

NUMBER OF NODES	87
NUMBER OF ELEMENTS	103
INITIAL CONCENTRATION(INPUT DATA)	

NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE
1	30.0	2	30.0	3	30.0	4	32.5	5	30.0
6	30.0	7	30.0	8	30.0	9	30.0	10	30.0
11	34.0	12	32.5	13	32.5	14	32.5	15	32.5
16	33.5	17	32.5	18	32.5	19	40.0	20	30.0
21	32.5	22	37.5	23	37.5	24	37.5	25	37.5
26	37.5	27	37.5	28	37.5	29	30.0	30	27.5
31	32.5	32	37.5	33	40.0	34	40.0	35	40.0
36	27.5	37	35.0	38	40.0	39	35.0	40	40.0
41	32.5	42	35.0	43	40.0	44	27.5	45	32.5
46	40.0	47	40.0	48	40.0	49	20.0	50	20.0
51	22.5	52	40.0	53	22.5	54	22.5	55	22.5
56	25.0	57	32.5	58	40.0	59	40.0	60	22.5
61	27.5	62	22.5	63	25.0	64	37.5	65	40.0
66	27.5	67	37.5	68	35.0	69	30.0	70	25.0
71	37.5	72	35.0	73	40.0	74	32.5	75	30.0
76	32.5	77	37.5	78	32.5	79	40.0	80	32.5
81	37.5	82	32.5	83	32.5	84	32.5	85	32.5
86	32.5	87	32.5						

NUMBER OF DATA SETS	1
FACTOR FOR C	1.000E+00
CONCENTRATION SET	1

NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE
1	60.4	2	60.4	3	60.4	4	60.4	5	59.7
6	59.7	7	60.4	8	60.4	9	60.4	10	60.4
11	58.7	12	58.7	13	58.7	14	58.7	15	60.4
16	60.8	17	61.8	18	57.4	19	58.7	20	60.8
21	57.4	22	60.8	23	60.8	24	56.5	25	56.5

26	60.8	27	60.8	28	56.5	29	60.8	30	60.8
31	60.8	32	60.8	33	62.3	34	66.9	35	66.9
36	60.8	37	60.8	38	61.4	39	62.3	40	62.3
41	62.3	42	62.3	43	61.4	44	62.3	45	62.3
46	62.3	47	66.9	48	61.4	49	115.7	50	115.7
51	115.7	52	61.4	53	115.7	54	115.7	55	115.7
56	60.4	57	60.2	58	56.7	59	56.7	60	115.7
61	114.6	62	115.7	63	60.4	64	56.7	65	56.7
66	114.6	67	56.7	68	114.6	69	57.3	70	57.3
71	56.7	72	57.3	73	56.7	74	57.3	75	57.3
76	57.3	77	57.3	78	57.3	79	56.7	80	57.3
81	57.3	82	57.3	83	57.3	84	57.3	85	57.3
86	57.3	87	57.3						

HYDRAULIC PARAMETERS

HYDRAULIC TIME STEP

ELEM	QX	QY	DXX	DXY	DYY
1	2.434E-05	1.232E-07	5.378E-04	1.815E-06	1.793E-04
2	-7.055E-06	-2.696E-08	1.544E-04	3.933E-07	5.147E-05
3	7.136E-06	-1.140E-08	1.541E-04	1.641E-07	5.136E-05
4	-4.027E-06	-4.127E-08	8.481E-05	5.795E-07	2.828E-05
5	3.842E-05	2.001E-07	7.879E-04	2.736E-06	2.626E-04
6	-4.383E-05	4.006E-07	8.596E-04	5.237E-06	2.866E-04
7	-1.080E-03	9.080E-06	2.045E-02	1.146E-04	6.818E-03
8	-8.224E-06	7.360E-08	1.517E-04	9.052E-07	5.059E-05
9	1.861E-06	4.003E-05	2.387E-04	2.205E-05	7.120E-04
10	3.830E-05	1.458E-07	6.818E-04	1.730E-06	2.273E-04
11	6.948E-05	5.326E-07	1.223E-03	6.249E-06	4.077E-04
12	4.773E-06	-2.206E-07	8.320E-05	2.562E-06	2.789E-05
13	3.942E-05	-6.558E-08	6.729E-04	7.463E-07	2.243E-04
14	-6.235E-05	1.373E-07	1.077E-03	1.581E-06	3.591E-04
15	-9.075E-06	-1.519E-07	1.549E-04	1.728E-06	5.167E-05
16	-4.066E-05	-3.034E-05	6.446E-04	2.705E-04	4.840E-04
17	-2.004E-05	-5.551E-05	4.069E-04	2.112E-04	9.159E-04
18	-2.037E-05	-1.849E-07	3.368E-04	2.038E-06	1.123E-04
19	-3.633E-05	-6.448E-08	6.058E-04	7.167E-07	2.019E-04
20	1.773E-03	1.514E-05	3.025E-02	1.722E-04	1.008E-02
21	-4.305E-04	3.980E-06	7.661E-03	4.722E-05	2.554E-03
22	1.125E-04	7.098E-07	1.991E-03	8.373E-06	6.639E-04
23	-1.198E-04	1.595E-07	2.053E-03	1.822E-06	6.842E-04
24	-1.179E-02	4.039E-05	2.079E-01	4.748E-04	6.930E-02
25	1.651E-06	2.606E-06	2.585E-05	1.486E-05	3.991E-05
26	5.545E-06	-8.410E-11	9.028E-05	9.129E-10	3.009E-05
27	-7.525E-03	-3.439E-05	1.222E-01	3.722E-04	4.073E-02
28	-2.853E-03	-2.148E-05	4.595E-02	2.305E-04	1.532E-02
29	9.275E-06	-1.355E-07	1.519E-04	1.480E-06	5.068E-05
30	-9.894E-06	-3.855E-07	1.604E-04	4.163E-06	5.368E-05
31	-9.786E-06	-3.088E-05	2.093E-04	1.019E-04	4.988E-04
32	2.068E-05	-3.806E-07	3.396E-04	4.166E-06	1.133E-04
33	1.986E-05	1.511E-05	3.224E-04	1.371E-04	2.465E-04
34	5.616E-05	3.303E-05	9.664E-04	3.397E-04	5.885E-04
35	-3.219E-06	3.831E-06	5.637E-05	3.038E-05	6.699E-05
36	-1.764E-03	2.488E-06	2.954E-02	2.778E-05	9.846E-03
37	-5.291E-05	-2.868E-05	8.052E-04	2.650E-04	4.599E-04
38	1.903E-04	-8.286E-07	2.995E-03	8.693E-06	9.983E-04
39	-2.572E-05	-1.175E-07	4.037E-04	1.229E-06	1.346E-04
40	1.121E-05	-3.736E-06	1.722E-04	3.689E-05	7.379E-05
41	1.103E-05	-3.938E-07	1.750E-04	4.164E-06	5.852E-05

42	1.130E-05	2.576E-13	1.812E-04	2.755E-12	6.042E-05
43	1.103E-05	-3.805E-07	1.812E-04	4.164E-06	6.060E-05
44	2.048E-05	9.311E-06	3.345E-04	9.483E-05	1.690E-04
45	2.428E-06	2.025E-07	-4.241E-05	2.352E-06	1.440E-05
46	-5.307E-05	2.751E-07	9.489E-04	3.279E-06	3.163E-04
47	-1.499E-04	-7.008E-07	2.353E-03	7.335E-06	7.845E-04
48	5.674E-06	-1.648E-05	1.091E-04	5.540E-05	2.508E-04
49	2.839E-06	-1.323E-05	7.605E-05	2.867E-05	2.035E-04
50	2.838E-06	-7.727E-08	-4.398E-05	7.982E-07	1.469E-05
51	-1.573E-03	-1.037E-05	2.432E-02	1.069E-04	8.108E-03
52	-2.601E-03	-1.716E-05	4.010E-02	1.764E-04	1.337E-02
53	1.187E-05	-1.002E-07	1.838E-04	1.035E-06	6.129E-05
54	4.186E-06	-2.577E-05	1.412E-04	4.250E-05	3.960E-04
55	4.181E-06	-3.777E-06	6.096E-05	2.886E-05	5.508E-05
56	4.296E-06	-3.625E-06	6.304E-05	2.866E-05	5.326E-05
57	4.203E-06	2.606E-13	6.667E-05	2.755E-12	2.222E-05
58	4.284E-06	1.298E-07	6.874E-05	1.388E-06	2.297E-05
59	4.145E-06	9.421E-06	7.536E-05	4.195E-05	1.522E-04
60	3.221E-06	8.423E-06	6.345E-05	3.373E-05	1.388E-04
61	3.161E-06	-6.604E-09	5.417E-05	7.545E-08	1.806E-05
62	2.579E-03	-1.655E-05	3.978E-02	1.701E-04	1.326E-02
63	1.623E-03	-1.042E-05	2.497E-02	1.069E-04	8.325E-03
64	-1.761E-06	-5.565E-08	2.708E-05	5.704E-07	9.050E-06
65	1.763E-06	-1.722E-05	9.049E-05	1.796E-05	2.641E-04
66	-8.194E-07	-1.997E-05	1.018E-04	8.326E-06	3.041E-04
67	-8.158E-07	-3.671E-06	2.102E-05	8.135E-06	5.581E-05
68	-2.843E-06	-5.685E-06	4.565E-05	2.609E-05	8.478E-05
69	-2.774E-06	1.321E-07	4.373E-05	1.387E-06	1.467E-05
70	-2.624E-07	2.624E-06	1.423E-05	2.764E-06	4.160E-05
71	-2.543E-07	8.646E-06	4.732E-05	2.777E-06	1.416E-04
72	1.175E-05	2.060E-05	1.943E-04	1.122E-04	3.269E-04
73	-3.299E-05	-1.691E-07	5.089E-04	1.739E-06	1.696E-04
74	1.354E-05	-1.355E-05	1.984E-04	9.923E-05	1.985E-04
75	1.368E-05	-1.977E-05	2.031E-04	1.154E-04	2.900E-04
76	1.478E-05	-1.871E-05	2.160E-04	1.188E-04	2.725E-04
77	1.484E-05	-5.719E-06	2.224E-04	5.443E-05	1.021E-04
78	7.853E-06	-1.259E-05	1.187E-04	6.835E-05	1.857E-04
79	7.753E-06	2.674E-06	1.188E-04	2.626E-05	5.166E-05
80	8.237E-06	3.188E-06	1.265E-04	3.109E-05	5.820E-05
81	8.247E-06	1.036E-07	1.292E-04	1.081E-06	4.307E-05
82	-2.872E-03	2.134E-05	4.569E-02	2.263E-04	1.523E-02
83	1.323E-02	-1.850E-05	2.056E-01	1.917E-04	6.854E-02
84	-1.049E-05	-1.396E-07	1.625E-04	1.442E-06	5.419E-05
85	1.055E-05	-1.258E-05	1.539E-04	8.300E-05	1.833E-04
86	1.416E-05	-8.898E-06	2.096E-04	7.761E-05	1.349E-04
87	1.408E-05	3.218E-06	2.170E-04	3.250E-05	8.222E-05
88	3.071E-06	-7.745E-06	5.510E-05	2.969E-05	1.182E-04
89	4.472E-06	9.329E-08	7.046E-05	9.797E-07	2.351E-05
90	3.025E-06	9.900E-08	4.791E-05	1.045E-06	1.601E-05
91	-2.011E-06	-6.570E-08	3.146E-05	6.848E-07	1.052E-05
92	1.389E-03	-8.813E-06	2.168E-02	9.166E-05	7.226E-03
93	-9.296E-06	-1.076E-07	1.458E-04	1.125E-06	4.863E-05
94	9.434E-06	-4.212E-05	2.436E-04	9.487E-05	6.459E-04
95	-6.194E-03	1.508E-05	9.556E-02	1.551E-04	3.185E-02
96	-2.133E-05	-4.499E-08	3.338E-04	4.694E-07	1.113E-04
97	2.795E-05	9.528E-06	4.344E-04	9.505E-05	1.880E-04
98	4.590E-05	3.366E-07	7.323E-04	3.580E-06	2.441E-04
99	-7.300E-07	-7.573E-08	1.154E-05	7.954E-07	3.957E-06
100	-7.861E-06	-5.098E-08	1.250E-04	5.404E-07	4.167E-05
101	7.865E-06	-8.614E-06	1.180E-04	6.154E-05	1.292E-04

102	-1.509E-06	5.203E-07	2.375E-05	5.252E-06	1.033E-05
103	9.684E-06	-8.556E-06	1.463E-04	6.840E-05	1.294E-04

TIME STEP 1

ELAPSED TIME 30.00 DAYS

COMPUTED CONCENTRATION

NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE
1	31.2	2	30.7	3	30.5	4	34.2	5	30.0
6	31.6	7	30.2	8	31.8	9	30.3	10	32.2
11	35.7	12	33.7	13	35.1	14	34.3	15	32.9
16	32.2	17	33.0	18	34.4	19	44.2	20	31.3
21	36.0	22	39.4	23	36.1	24	44.9	25	46.4
26	39.3	27	35.7	28	40.2	29	27.7	30	41.5
31	41.9	32	40.5	33	38.2	34	41.8	35	40.1
36	21.9	37	46.0	38	41.0	39	36.9	40	30.7
41	33.1	42	36.3	43	41.5	44	30.9	45	31.3
46	42.3	47	40.8	48	41.0	49	19.7	50	19.1
51	23.0	52	41.0	53	27.0	54	25.9	55	23.7
56	21.8	57	33.6	58	41.1	59	41.0	60	23.0
61	27.9	62	24.6	63	25.4	64	38.4	65	41.0
66	28.8	67	38.4	68	31.5	69	30.8	70	25.8
71	38.6	72	35.7	73	41.0	74	33.5	75	30.3
76	37.2	77	38.0	78	33.3	79	42.2	80	33.4
81	38.9	82	33.4	83	33.3	84	33.3	85	34.0
86	37.5	87	34.1						

HYDRAULIC PARAMETERS

HYDRAULIC TIME STEP 2

ELEM	QX	QY	DXX	DXY	DYY
1	1.010E-05	7.177E-08	2.282E-04	1.081E-06	7.607E-05
2	1.114E-06	-9.532E-09	2.491E-05	1.422E-07	8.306E-06
3	-1.134E-06	-2.011E-09	2.502E-05	2.958E-08	8.339E-06
4	3.396E-06	9.827E-09	7.328E-05	1.414E-07	2.443E-05
5	1.927E-05	9.457E-08	4.047E-04	1.325E-06	1.349E-04
6	-2.206E-05	2.266E-07	4.440E-04	3.040E-06	1.480E-04
7	-8.300E-04	6.958E-06	1.615E-02	9.027E-05	5.385E-03
8	-1.433E-05	1.060E-07	2.703E-04	1.333E-06	9.012E-05
9	-3.810E-06	4.303E-05	2.641E-04	4.569E-05	7.760E-04
10	4.702E-05	2.269E-07	8.499E-04	2.734E-06	2.833E-04
11	7.876E-05	6.181E-07	1.399E-03	7.320E-06	4.665E-04
12	8.317E-06	-2.027E-07	1.459E-04	2.371E-06	4.873E-05
13	4.464E-05	-4.096E-08	7.634E-04	4.670E-07	2.545E-04
14	-6.333E-05	1.194E-07	1.093E-03	1.374E-06	3.643E-04
15	4.282E-07	-2.257E-07	7.079E-06	2.276E-06	3.959E-06
16	-4.677E-05	-4.190E-05	7.332E-04	3.455E-04	6.571E-04
17	-2.917E-05	-6.319E-05	5.243E-04	2.953E-04	1.028E-03
18	-2.994E-05	-3.013E-07	4.878E-04	3.273E-06	1.627E-04
19	-7.065E-05	5.467E-09	1.167E-03	6.018E-08	3.888E-04
20	2.198E-03	1.882E-05	3.722E-02	2.125E-04	1.241E-02
21	4.575E-04	4.223E-06	8.126E-03	5.000E-05	2.709E-03
22	1.290E-04	8.441E-07	2.284E-03	9.960E-06	7.614E-04
23	-1.373E-04	2.162E-07	2.359E-03	2.475E-06	7.862E-04
24	-1.278E-02	4.376E-05	2.269E-01	5.180E-04	7.563E-02
25	1.207E-06	2.054E-06	1.916E-05	1.106E-05	3.147E-05
26	4.283E-06	-3.374E-09	6.953E-05	3.651E-08	2.318E-05

27	-9.612E-03	-4.391E-05	1.550E-01	4.722E-04	5.168E-02
28	-2.679E-03	-2.010E-05	4.275E-02	2.139E-04	1.425E-02
29	1.837E-05	-1.115E-07	3.003E-04	1.215E-06	1.001E-04
30	-1.429E-05	4.377E-06	2.280E-04	4.515E-05	9.445E-05
31	-1.416E-05	-4.261E-05	2.930E-04	1.463E-04	6.846E-04
32	2.522E-05	-3.328E-06	4.093E-04	3.580E-05	1.427E-04
33	2.423E-05	1.882E-05	3.893E-04	1.678E-04	3.036E-04
34	5.934E-05	3.604E-05	1.015E-03	3.659E-04	6.346E-04
35	-1.774E-06	4.065E-06	3.601E-05	2.000E-05	7.310E-05
36	-1.386E-03	1.961E-06	2.314E-02	2.182E-05	7.714E-03
37	-9.346E-05	-3.315E-05	1.425E-03	3.233E-04	6.278E-04
38	2.677E-04	-1.170E-06	4.140E-03	1.206E-05	1.380E-03
39	-3.705E-05	-1.611E-07	5.742E-04	1.665E-06	1.914E-04
40	1.790E-05	5.652E-06	2.730E-04	5.563E-05	1.144E-04
41	1.753E-05	4.480E-06	2.743E-04	4.575E-05	1.070E-04
42	1.117E-05	-1.689E-06	1.785E-04	1.785E-05	6.310E-05
43	1.095E-05	-3.310E-06	1.767E-04	3.457E-05	7.284E-05
44	2.453E-05	1.058E-05	4.002E-04	1.084E-04	1.958E-04
45	1.759E-06	2.305E-07	3.053E-05	2.652E-06	1.064E-05
46	-5.985E-05	3.111E-07	1.065E-03	3.690E-06	3.550E-04
47	-1.887E-04	-9.090E-07	2.933E-03	9.419E-06	9.778E-04
48	4.967E-06	-1.414E-05	9.425E-05	4.832E-05	2.149E-04
49	3.741E-06	-1.274E-05	7.934E-05	3.702E-05	1.945E-04
50	3.738E-06	-7.683E-08	5.787E-05	7.928E-07	1.931E-05
51	-1.117E-03	-7.401E-06	1.729E-02	7.639E-05	5.766E-03
52	-3.873E-03	-2.559E-05	5.959E-02	2.625E-04	1.987E-02
53	1.259E-05	-1.460E-07	1.935E-04	1.497E-06	6.453E-05
54	7.380E-06	-3.212E-05	1.842E-04	7.310E-05	4.855E-04
55	7.346E-06	5.713E-06	1.067E-04	4.605E-05	8.332E-05
56	6.745E-07	-9.444E-07	1.001E-05	5.651E-06	1.389E-05
57	6.580E-07	-1.711E-06	1.217E-05	6.482E-06	2.652E-05
58	1.044E-06	-1.305E-06	1.583E-05	8.676E-06	1.974E-05
59	1.008E-06	1.071E-05	6.033E-05	1.106E-05	1.768E-04
60	2.361E-06	1.193E-05	7.308E-05	2.589E-05	1.988E-04
61	2.319E-06	-5.406E-08	3.958E-05	6.151E-07	1.321E-05
62	2.209E-03	-1.435E-05	3.366E-02	1.458E-04	1.122E-02
63	1.141E-03	-7.515E-06	1.739E-02	7.638E-05	5.798E-03
64	4.383E-06	1.128E-07	6.666E-05	1.143E-06	2.226E-05
65	-4.356E-06	-2.573E-05	1.405E-04	4.382E-05	3.919E-04
66	-1.516E-06	-2.316E-05	1.179E-04	1.525E-05	3.498E-04
67	-1.509E-06	-9.605E-07	2.194E-05	8.202E-06	1.427E-05
68	-5.875E-06	-5.329E-06	8.455E-05	4.012E-05	7.670E-05
69	-5.729E-06	-1.332E-06	8.883E-05	1.353E-05	3.380E-05
70	1.191E-06	5.557E-06	3.245E-05	1.222E-05	8.687E-05
71	1.150E-06	1.227E-05	6.813E-05	1.245E-05	1.997E-04
72	8.470E-06	1.952E-05	1.532E-04	8.499E-05	3.122E-04
73	-2.713E-05	-1.534E-09	4.115E-04	1.551E-08	1.372E-04
74	1.258E-05	-1.009E-05	1.835E-04	8.085E-05	1.477E-04
75	1.270E-05	-2.295E-05	1.959E-04	1.130E-04	3.375E-04
76	1.534E-05	-2.041E-05	2.229E-04	1.243E-04	2.949E-04
77	1.542E-05	-5.370E-06	2.293E-04	5.115E-05	1.002E-04
78	1.012E-05	-1.053E-05	1.454E-04	7.410E-05	1.513E-04
79	9.970E-06	5.659E-06	1.485E-04	5.073E-05	8.788E-05
80	7.488E-06	3.209E-06	1.138E-04	3.064E-05	5.544E-05
81	7.502E-06	9.287E-08	1.167E-04	9.628E-07	3.890E-05
82	-2.729E-03	2.028E-05	4.311E-02	2.135E-04	1.437E-02
83	1.442E-02	-2.017E-05	2.220E-01	2.070E-04	7.399E-02
84	-1.397E-05	-1.429E-07	2.146E-04	1.463E-06	7.155E-05
85	1.404E-05	-1.050E-05	2.039E-04	8.566E-05	1.533E-04
86	1.397E-05	-1.045E-05	2.039E-04	8.566E-05	1.533E-04

87	1.391E-05	3.241E-06	2.128E-04	3.246E-05	8.101E-05
88	-7.311E-06	-1.801E-05	1.279E-04	6.949E-05	2.708E-04
89	5.274E-06	8.672E-08	8.244E-05	9.036E-07	2.750E-05
90	-7.203E-06	1.413E-07	1.125E-04	1.471E-06	3.754E-05
91	-3.817E-06	-5.465E-08	5.932E-05	5.663E-07	1.979E-05
92	1.628E-03	-1.034E-05	2.526E-02	1.069E-04	8.420E-03
93	-1.122E-05	-1.109E-07	1.750E-04	1.154E-06	5.835E-05
94	1.159E-05	-1.117E-04	5.776E-04	1.160E-04	1.685E-03
95	-1.831E-02	4.444E-05	2.732E-01	4.421E-04	9.108E-02
96	-3.586E-05	-6.637E-08	5.507E-04	6.795E-07	1.836E-04
97	4.648E-05	1.541E-05	7.108E-04	1.515E-04	3.039E-04
98	7.526E-05	5.983E-07	1.183E-03	6.267E-06	3.943E-04
99	-1.688E-07	-7.003E-08	2.599E-06	6.798E-07	1.242E-06
100	-7.111E-06	-4.598E-08	1.125E-04	4.850E-07	3.750E-05
101	7.113E-06	-8.468E-06	1.065E-04	5.743E-05	1.267E-04
102	-1.130E-06	2.093E-07	1.790E-05	2.185E-06	6.507E-06
103	9.507E-06	-8.416E-06	1.429E-04	6.685E-05	1.265E-04

TIME STEP 2

ELAPSED TIME 60.00 DAYS
COMPUTED CONCENTRATION

NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE	NODE	VALUE
1	32.0	2	31.4	3	31.1	4	35.4	5	29.9
6	32.9	7	30.9	8	32.6	9	31.0	10	33.8
11	37.3	12	34.8	13	37.8	14	36.1	15	33.8
16	31.2	17	33.6	18	35.2	19	49.6	20	32.1
21	41.7	22	40.6	23	36.2	24	46.4	25	49.0
26	40.3	27	36.6	28	43.3	29	28.2	30	42.6
31	43.2	32	41.6	33	39.0	34	43.1	35	40.1
36	30.8	37	58.6	38	41.9	39	39.2	40	19.9
41	34.5	42	37.6	43	43.2	44	33.2	45	29.7
46	44.0	47	41.9	48	41.9	49	21.6	50	19.6
51	23.3	52	42.1	53	28.0	54	26.8	55	24.2
56	21.6	57	34.4	58	42.3	59	42.1	60	23.8
61	28.4	62	26.4	63	26.3	64	39.3	65	41.9
66	30.0	67	39.2	68	32.3	69	31.5	70	26.7
71	39.7	72	36.6	73	42.1	74	34.4	75	30.9
76	37.3	77	38.2	78	34.2	79	45.3	80	34.2
81	40.8	82	34.3	83	34.1	84	34.2	85	36.2
86	45.4	87	36.1						

7-6-30-2