Process-based modelling of river flow and nitrate loadings in the Ythan catchment, Scotland

Thesis
submitted in fulfillment of the
requirement of the degree of Doctor of Philosophy at the
Department of Environmental Science
University of Stirling

by
Noraini Jaafar

May 1998

DECLARATION

I declare that this thesis has been composed by me and that the work which it embodies has been done by me and has not been included in another thesis. Where data from secondary sources have been used, they have all been duly ackowledged.

Signed: ----------------------

Date: 16/5/98

Acknowledgements

In the name of God, the Most Merciful, the Most Gracious. All praise be to the Almighty who has granted His blessings to me in pursuing this study. I pray to God that the efforts spent in this pursuit will not be of waste and be put to good use in many years ahead. I take this opportunity to express my most sincere gratitude to all parties who have made this work possible. First and foremost, I would like to acknowledge my gratitude to the Universiti Teknologi Malaysia and the Department of Public Services, Malaysia, for providing the financial support necessary to undertake this study. This study would not be possible without the technical and academic support of the Department of Environmental Science, University of Stirling; the support of the North East River Purification Board, and the Macaulay Land Use Research Institute. A special acknowledgement must go to my two supervisors, Dr. Ian Moffat and Dr. David Gilvear who have provided continuous support throughout the study period. I wish to express a special thank you to Dr. David Gilvear who has generously spend his time and effort in critically evaluating my work. His systematic and professional ways have expedited my progress in many ways. I also wish to express my most sincere gratitude to Dr. Paul Quinn, who has provided his unconditional support in the beginning years of my modelling study. His unassuming ways and enthusiasm helped me tremendously. Throughout the research period he made great effort to facilitate my work and gave great thoughts to my research. For that I am ever debtful to him. I am also indebted to Dr. Anthony Edwards from the Macaulay Land Use Research Institute for his generosity and expediency in dealing with my request for information. Many more people has contributed towards my research. A special note of thanks must go to the Malaysian community in Stirling and my family, to whom I trusted the care of my

children on so many occasions when the intensity of the efforts needed to complete this dissertation has demanded so much of my time away from them. A special tribute must go to my four children who showed great perseverence in coping with a new culture and for being very independent and cooperative in many ways. Last, but not least, a special thanks to all the doctorate students for their warmth and comraderie throughout my stay at the University of Stirling.

DEDICATION

This work is dedicated to the memory of my late father Jaafar Muda, and my four children Sumayyah, Muhammad, Halimah and Ismail.

TABLE OF CONTENTS

CHAPTER 1

Introduction:

Problem Description and Research Objectives

CHAPTER 2

The Study Area

CHAPTER 3

Nitrate Cycling and Transport in Agricultural Catchments

CHAPTER 4

Review of Models for Estimating Flow and Nitrate Emissions from Agricultural Lands

CHAPTER 5

Modelling the Ythan River Using TOPMODEL

CHAPTER 6

Simulating Catchment-Scale Hydrochemical Response of the Ythan River Using SWRRBWQ

CHAPTER 7

List of Tables

1

List of Figures

List of plates

List of Appendices

ABSTRACT

The Ythan catchment has been undergoing a steady increase in nitrate concentration over the years with a significant increase after 1990. Nitrogen transformations in soil and its transport through the catchment is a very complex process. Modelling can help in explaining this complexity. In this study, TOPMODEL and SWRRBWQ models are applied to the Ythan catchment. TOPMODEL performance in simulating catchment hydrological responses is assessed to test the ability of the model structure to simulate basic transport processes in the Ythan catchment. The result of TOPMODEL simulation shows the ability of the model to simulate total runoff with an accuracy of 95 % while the efficiency of the model in simulating runoff pattern is between 74 % and 54 %. SWRRBWQ is a process based hydrological and water quality model which allows the impact of changing agricultural management practices to be simulated. In this study the performance of SWRRBWQ in simulating catchment hydrological responses and nitrate loadings is assessed. Modelling result shows a good performance in modelling monthly runoff pattern with high correlation of 0.92 for calibration period (1991), 0.87 for 1990, and 0.74 for 1993; nevertheless the model underpredicts total runoff quantity throughout the three years under scrutiny. SWRRBWQ is found to be useful as a tool to evaluate the sensitivity of soil parameters on nitrate leaching and to study the impact of changing agricultural management patterns on nitrate loadings. The model results show a high tendency for nitrate leaching in soil with high conductivity. Modelling of rate of fertilisation and cropping pattern shows that nitrate loadings increase with increasing nitrate fertiliser use; 13, 20, and 78 $kgha^{-1}$ for application rates of 78, 100, and 200

$kgha^{-1}$ respectively. The model also simulated the order of increasing nitrate loadings according to crop in the following manner:

grass; winter wheat > winter barley > spring barley.

Chapter 1

Problem Description and Research Objectives

1.1 Introduction

Water pollution originating from non-point sources constitutes a major problem in agricultural watersheds. Nitrate nitrogen, primarily used as fertiliser, is one of the prime concerns because it is highly soluble and very weakly held in the soil (Giorgini and Zingales, 1986). Nitrate pollution has raised three main concerns: first the alleged detrimental effects on human health caused by nitrates in drinking water; second, the impact of eutrophication (profuse growth of aquatic organisms in water) on the commercial and ecological value of the river as a wildlife and leisure resource; and third, the reduction in the ecological diversity of grassland (Allanson *et al.*, 1993). Although nitrates can be a health hazard in concentrations above 10 parts per million, a more common problem is accelerated eutrophication (Haan *et al.*, 1982). High levels of nitrogen in rivers and streams act as nutrients causing eutrophication and rapid increase in the growth of weeds. This in turn can alter their ecological balance and as a consequence their recreational values.

The EEC Drinking Water Directive (EEC, 1980) sets the guidelines for Maximum recommended level at 11.3 mgl^{-1} NO_3-N (50 mgl^{-1} NO_3); and Maximum acceptable level at 22.6 mgl^{-1} NO_3-N (100 mgl^{-1} NO_3). The main form of current legislation for controlling nitrate discharge is through land use controls such as the designation of Nitrate Sensitive Areas (MAFF/DOE, 1990). Action plans for the control of nitrate is required to protect areas experiencing high nitrate turnover and mathematical models provide a means of assessing this problem in a systematic manner (Ferrier *et al.*, 1995).

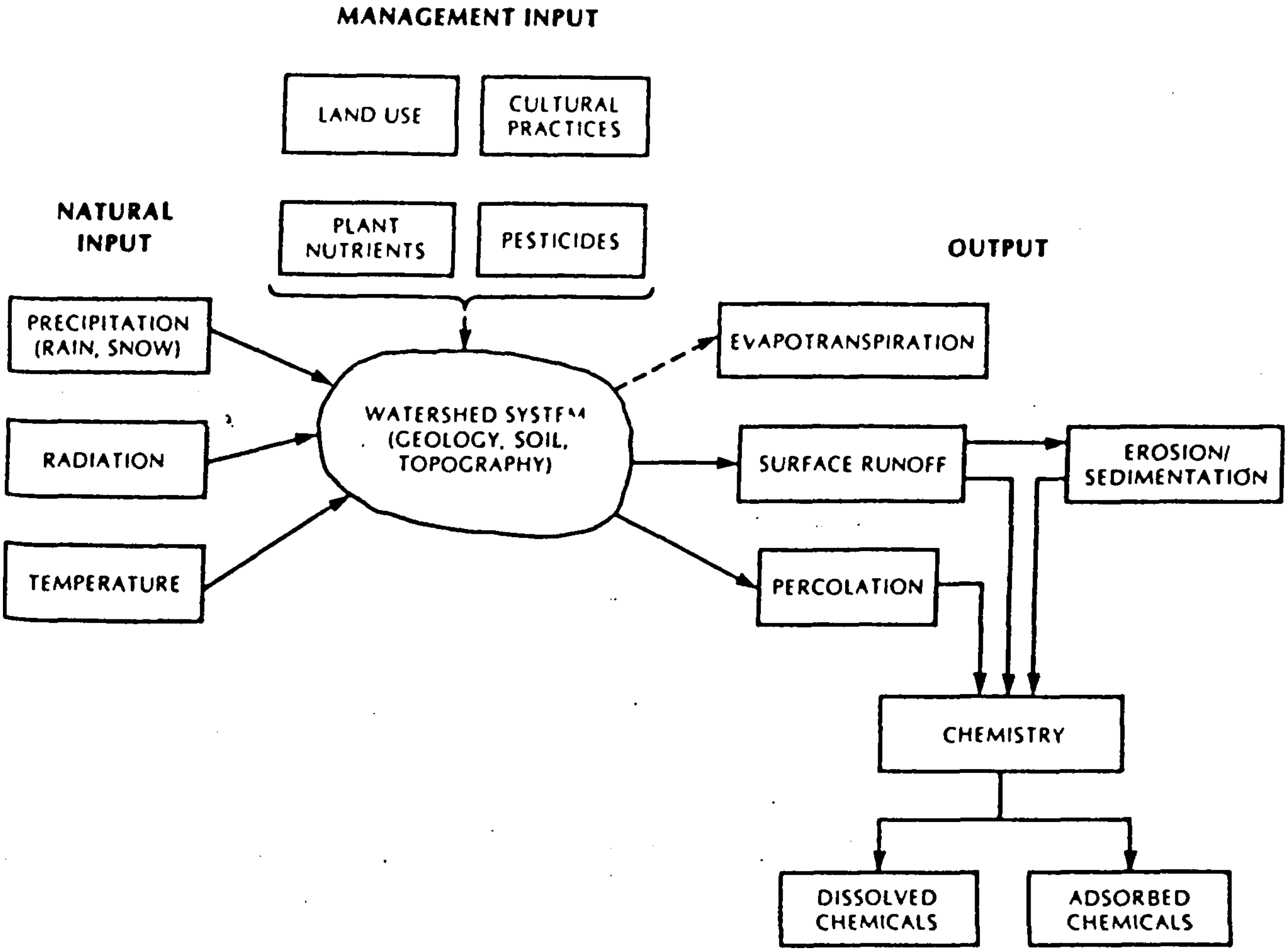
Water pollution as a result of nitrate is typically a function of the use and management of land, of the physical properties of the land, and of the hydrological and meteorological properties of the area (Gilliland and Potter, 1987). The complex effects of land use, climate change, and their potential interaction on hydrochemical response makes understanding and predicting nitrogen responses very difficult. This problem can be tackled as a whole by the adoption of some kind of systems approach. Figure 1.1 shows the diagram of the interaction between different parameters affecting chemical transport in a catchment system.

1.2 Research Problem

Several reports have indicated the rising trends in nitrate concentration over time in the Ythan River (exp. Wright et al., 1991; MacDonald et al., 1995; and Raffaelli *et al.*, 1989). Most of the nitrate modelling studies carried out in the Ythan catchment were based on statistical correlations between the rate of fertiliser application and other agricultural farming practices on nitrate loadings to surface water. A few statistical correlation models have been proposed. One study applied GIS models to explain the spatial parameters governing nitrate discharge. However, there is no previous study carried out on the use of a physical or process based model in simulating nitrate transport in the Ythan catchment. This dissertation will explore the application of process-based hydrological models to the hydrological regime of the Ythan catchment

Figure 1.1

A systems approach to modelling nutrient transport in a catchment



(Source: Knisel, 1980)

and the interactions between the physical and management parameters that affect nitrate loadings to surface water.

Delivery and movement of soluble pollutants occurs by both surface and subsurface pathways, with the subsurface pathway being the more dominant pathway (Burt and Haycock, 1992). Therefore it is crucial that the models chosen represent the subsurface flow process sufficiently. TOPMODEL and SWRRBWQ are two process-based hydrological model which have been chosen to understand catchment responses. These two models are continuous time simulation models which allow the use of readily available hydrological and meteorological data. The rainfall-runoff response in TOPMODEL can be used as a tool for explaining the hydrochemical response. SWRRBWQ also has a built-in soil nitrate cycling submodel which takes into account differences in soil parameters and agricultural management parameters.

1.3 Aim and Objectives of Study

The aim of this study is evaluate the performance of two process-based hydrological models (TOPMODEL and SWRRBWQ) in modelling river flow and nitrate loadings to the Ythan River. This research is mainly concerned with understanding continuous, large scale (i.e. whole catchment) catchment responses in rainfall-runoff processes and its use in understanding nitrate transport to surface water. The SWRRBWQ model will be used to assess catchment hydrological and chemical response specifically nitrate loadings to surface water. The TOPMODEL will only be used as a tool to understand catchment hydrological response and its potential to be used as a transport model for nitrate loadings.

The objectives of this study are as follows:

1. Describe nitrate behaviour in the Ythan river using existing data.
2. Describe ancillary variables affecting nitrate cycling.
3. Examine various types of mathematical models used to simulate flow, nitrate cycling and loadings.
4. Perform sensitivity analyses of model parameters.
5. Model calibration, testing, and evaluation.

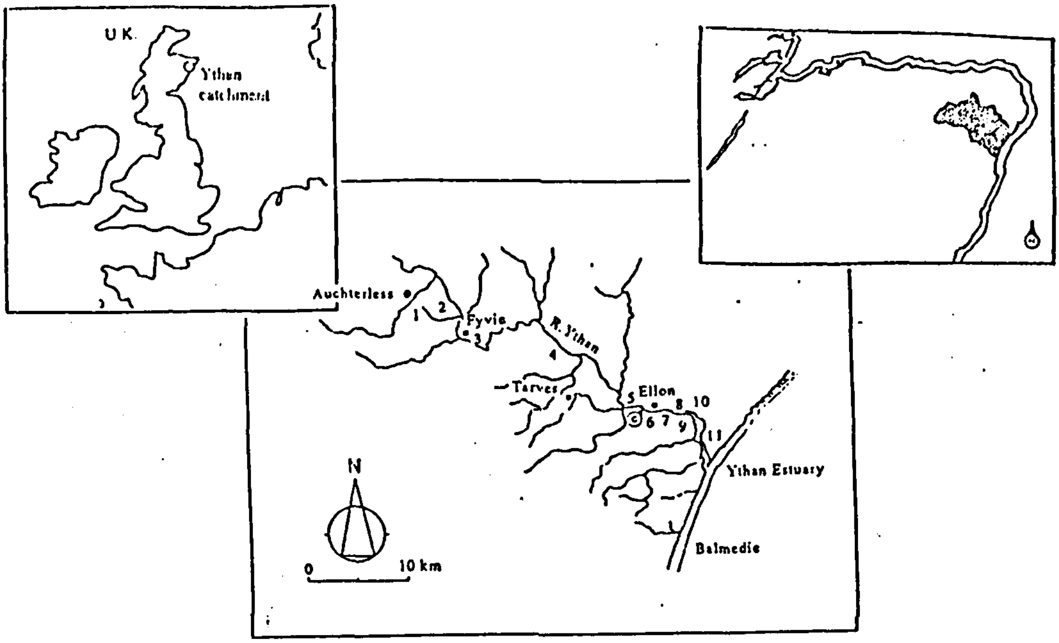
This thesis is a contribution to the field of hydrological and water quality modelling specifically; the application of hydrological models in understanding hydrochemical catchment response at a watershed scale.

1.4 The Study Area

The Ythan catchment is located in Aberdeenshire in the North East of Scotland (Figure 1.2). The Ythan river is approximately 63 km long, with a catchment area of 689 km^2 (68390 ha). The Ythan river enters the North Sea via an 8 km long estuary close to the town of Ellon (NJ 955 305). The river runs in a south-easterly direction from Methlick and passes through Ellon to enter the sea at Newburgh. The river rises to the west at Ythan wells in the Foudland Hills (Glentworth and Muir, 1963). The catchment is

Figure 1.2

Location of the Ythan Catchment, gauging station (G) and nitrate sampling points



(MacDonald *et al.*, 1995)

characterised throughout by fertile gently rolling lowland mostly under 260 metres high (Figure 1.3). The catchment is almost entirely overlain by glacial deposits of silt and clay interspersed with large deposits of sand and gravel. Agriculture is the largest single land use in the area with arable cropping and livestock production carried out throughout the catchment.

The Ythan estuary together with the adjacent Sands of Forvie is a Site of Special Scientific Interest and a National Nature Reserve with an estimated 185 hectares of intertidal mud flats providing a rich habitat for many species of birds (Gormon and Raffaelli, 1993). Bird populations are the most important feature of its natural history and it has been suggested that increased Enteromorpha sp. weed mat growth is leading to serious feeding problems for a number of sea birds (Raffaelli *et al*, 1989). The river also supports a good salmonid fishery.

The largest town in the catchment is Ellon with a population of approximately 10,000 persons. The town is served by an efficient modern sewage treatment works with a treatment capacity for 15,000 persons. Newburgh is a much smaller village located near the mouth of the estuary. Plates 1 - 4 show the typical view of the Ythan catchment.

The Ythan river has been experiencing a rising trend in nitrate concentrations in recent years (MacDonald *et al.*, 1994; Wright *et al.*, 1991) and this phenomenon has caused some ecological problem such as eutrophication (Raffaelli *et al.*, 1989). This study will

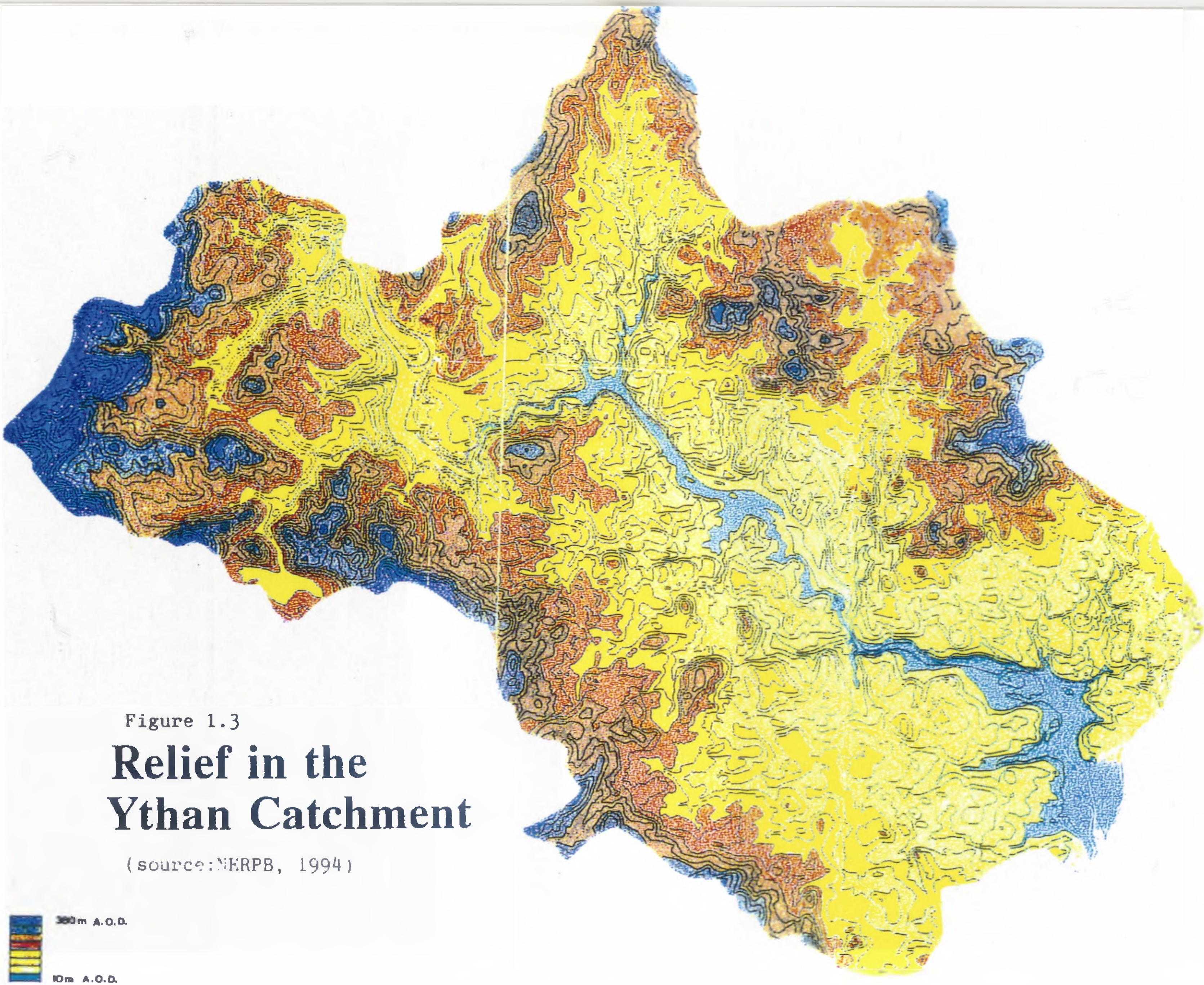


Figure 1.3

Relief in the Ythan Catchment

(source:NERPB, 1994)

Plate 1. The Ythan river and its bank indicating the lack of buffer zone to absorb the incoming nutrient into the river.

Plate 2. The Ythan estuary and the prolific growth of algae indicating eutrophication of the estuary.

Plate 3. One of the typical land use in the catchment (grassland)

Plate 4. Another land use (arable crop).

describe the nature of the nitrate problem in the Ythan catchment and explore the performance of process-based hydrological models in simulating catchment responses.

1.5 Thesis Structure

This thesis is divided into seven chapters. This chapter is the introductory chapter which describes the research problem and research aim and objectives, and the study area briefly. Chapter 2 describes the study area in detail, which includes the hydrogeological characteristics of the catchment, the soil classification, and the climatic and hydrological regime of the Ythan river. Trends and behaviour of nitrate concentrations and loadings to the Ythan river will be assessed and previous studies on nitrate in the Ythan river will be reviewed. Chapters 3 and 4 review the background theory and relevant works that has been undertaken; Chapter 3 focuses on nitrate cycling and the processes affecting its tranformation and transport while Chapter 4 examines the use of models in simulating hydrological response and nitrate behaviour in rivers. Chapter 5 describes TOPMODEL theory and its application in modelling runoff of the Ythan river. The performance of the model in simulating runoff will be assessed. Chapter 6 presents the SWRRBWQ theory and its performance in simulating water yield and nitrate loadings to surface water. The sensitivity of model parameters will be discussed and catchment response to different agricultural management scenarios will be discussed. The final chapter, Chapter 7, summarizes the research findings and concludes with recommendations for further work.

CHAPTER 2

The Study Area

2.1 Introduction

The Ythan catchment is a critical area in Scotland with respect to water quality, and its management over the next decade may have far reaching consequences for the ecology of the Ythan estuary. The main threat to the estuary is eutrophication, which is manifested by the increasing extent of Enteromorpha spp. in the estuary (Raffaelli *et al.*, 1989) and was designated as a "Nitrate Vulnerable Zone" (North East River Purification Board, 1994).

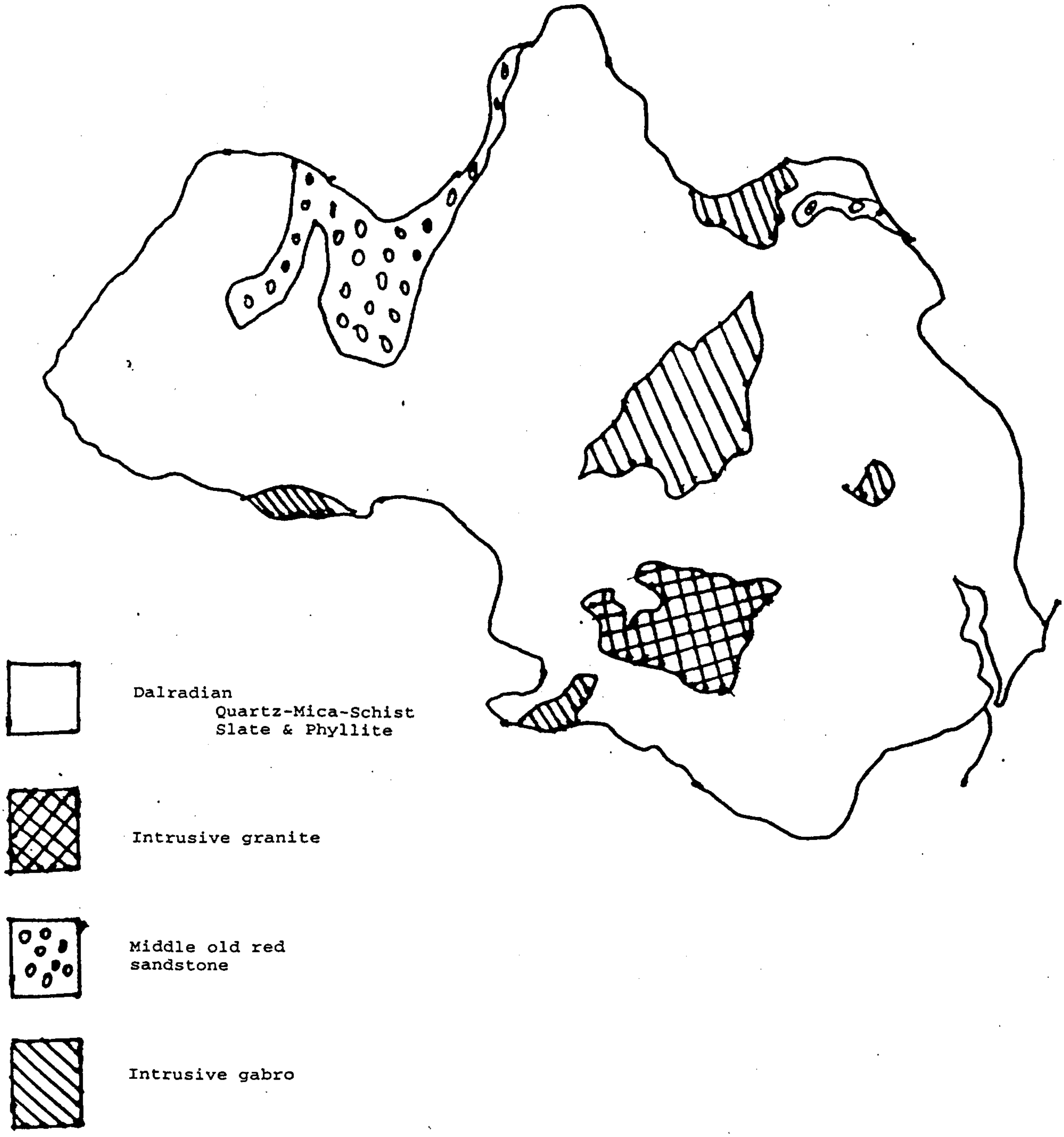
In this chapter, the physical attributes of the catchment and the agricultural management practices will be described. Then the nitrate variation in the Ythan river and previous works on nitrate studies in the Ythan catchment will be discussed.

2.2 Solid and Drift Geology

The geological structure of the Ythan catchment consists of the Lower Dalradian metamorphic rock which is penetrated by both acid and basic igneous intrusions and in one area overlain by sedimentary rock (Figure 2.1). Much of the bedrock which underlies the Ythan catchment is impermeable and, as a consequence, the area is generally lacking in exploitable groundwater resources. Following the retreat of the glaciers in the Quaternary the whole of the north east of Scotland was covered by

Figure 2.1

The geology of the Ythan catchment



(Source: NERPB, 1994)

boulder clay and glacial drift. The clays give a poorly draining soil and the number of boulders present is indicated by the massive stone dykes around the fields. From Methlick down to Ythanbank and in the area north west of Newburgh are areas of sand and gravel of fluvoglacial origin which offer better drainage characteristics. Alluviums are deposited along the river channels.

2.3 Soil

The distribution of soil series in the Ythan catchment and the explanation of the symbols and colours are shown in Figure 2.2 (NERPB, 1994). The soils of the catchment comprise freely drained humus iron podzols in the upper reaches with both free and imperfectly drained brown forest soils in the middle and lower reaches. The dominant soil in the Ythan catchment are (1) Foudland - Foudland Series (USDA Equivalent: Cryic Fragiorthod); (2) Foudland-Ettenbreck series; (3) Tarves - Pitmedden Series (USDA equivalent: Typic Fragiochrept) and (4) Tarves - Tarves soil series. The particle size distribution and texture of the Foudland-Ettenbreck series and Tarves-Pitmedden series are described in Table 2.1 (a) and (b); and Table 2.2 (a) and (b) respectively. The Tarves - Tarves soil series is freely drained brown forest soil while the Tarves Pitmedden series is a poorly drained non-calcareous and calcareous gleys. The Foudland series represents freely drained iron podzols. The soils are predominantly class 3 according to the Land Capability for Agriculture classification guidelines and therefore suitable for agriculture.

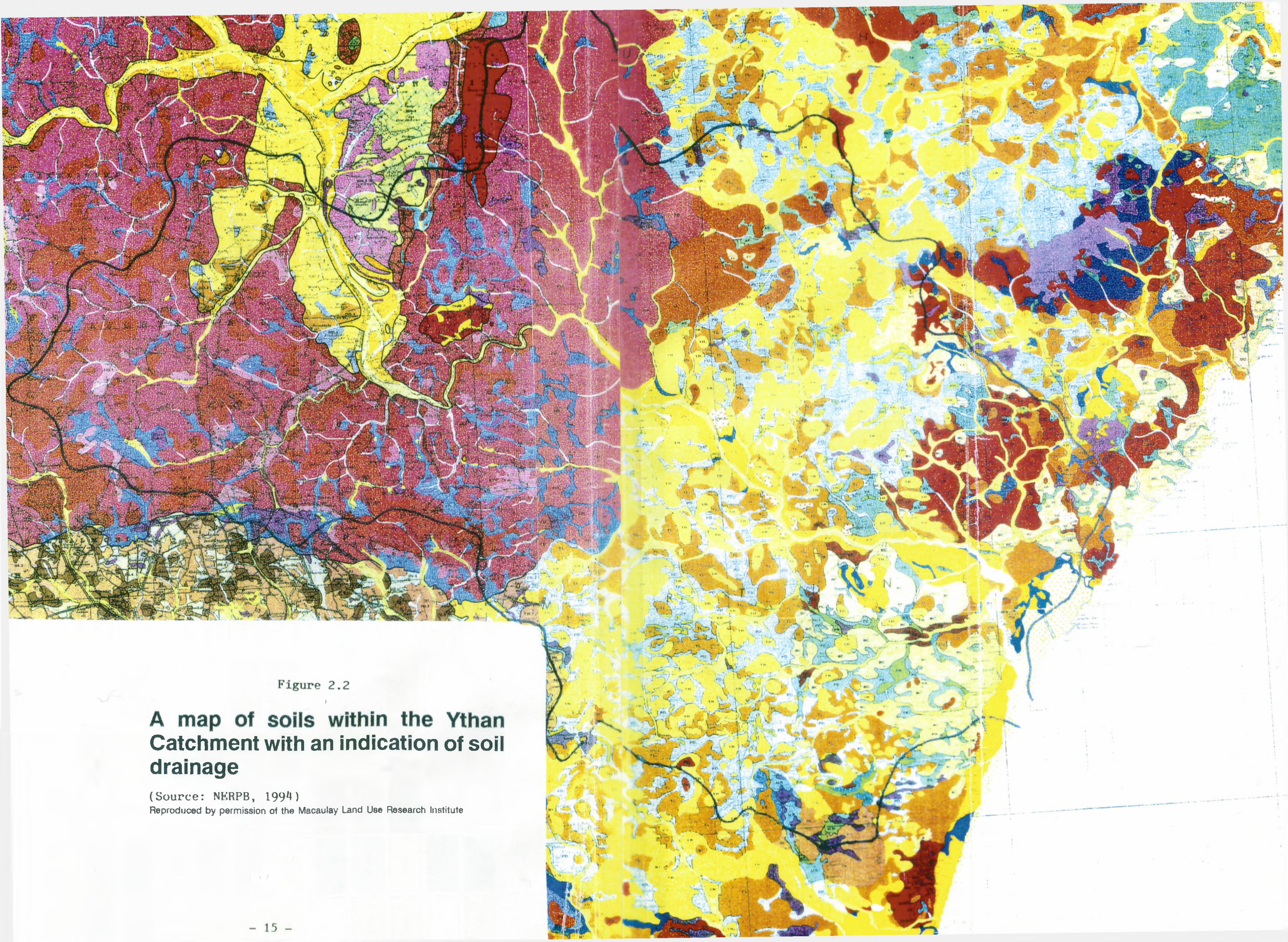


Figure 2.2

A map of soils within the Ythan Catchment with an indication of soil drainage

(Source: NERPB, 1994)

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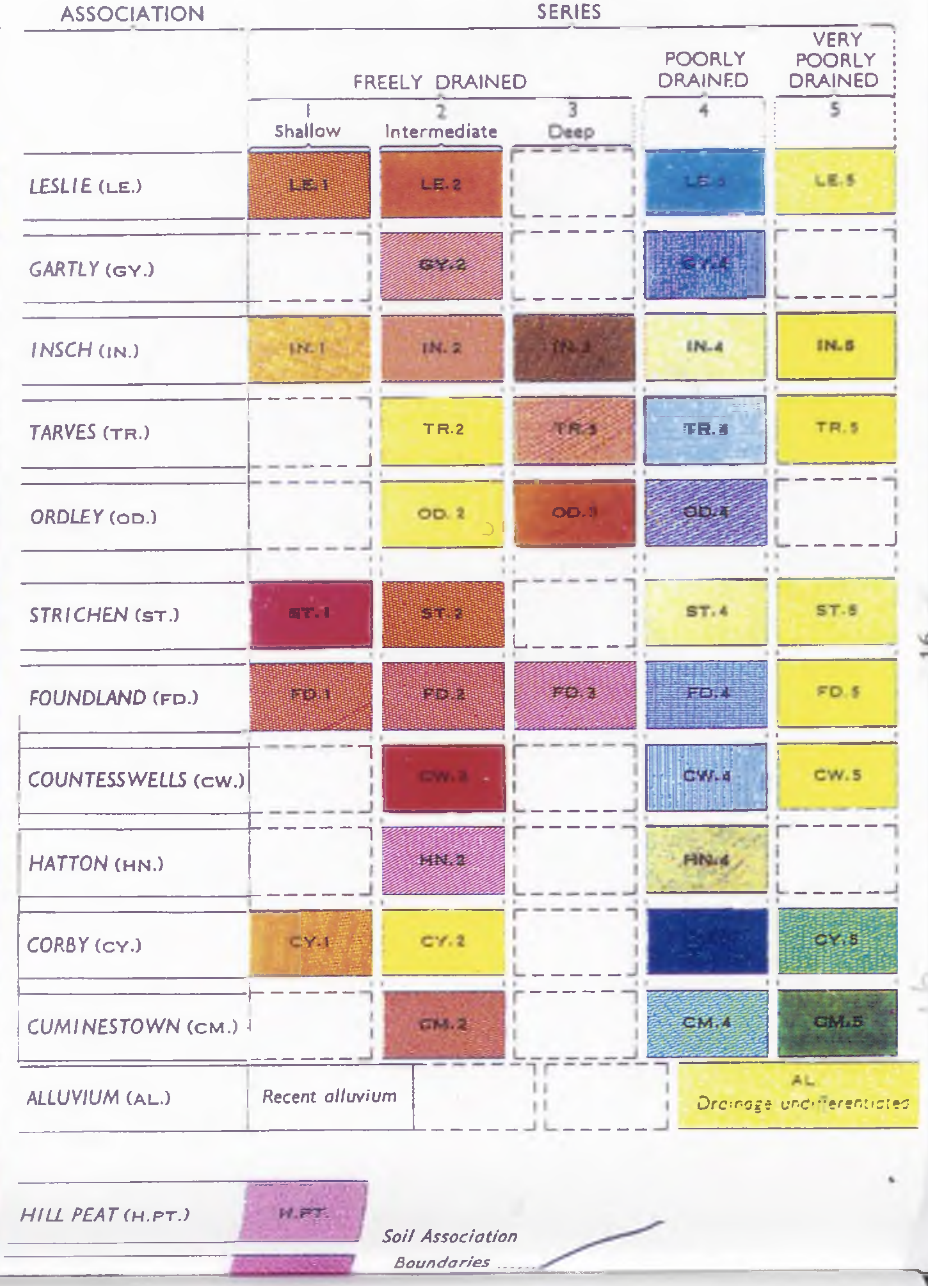
EXPLANATION OF SOIL SYMBOLS AND COLOURS

ASSOCIATION	SERIES							
	Brown Forest Soils		Iron Podzols		Peaty Podzols	Non-Calcareous and Calcareous* Gleys		Peaty Gleys
	Freely Drained	Imperfectly Drained	Freely Drained	Imperfectly Drained	Freely Drained Below BI	Poorly Drained	Very Poorly Drained	Very Poorly Drained
TARVES (TR.)	TR. Tarves	TL. Thistlyhill	TN. [illegible]			PD. Pitmedden		PK. Pettymuick
PETERHEAD (PE.)		BC. Blackhouse				PE. Peterhead	PR. Pitourn	
COLLIESTON (CN.)	CO. Cairnrobin	CN. Collieston				MX. [illegible]		
TIPPERTY (TP.)		TP. Tipperty				BX. Birness	DQ. Dorbs	
CUMINESTOWN (CM.)			CM. Cuminestown			CJ. Culbyth		WS. Woodside
COUNTESSWELLS (CW.)			CW. Countesswells	DS. Dess	CR. Charr	TV. Terryvale		DM. Drumlosie
FOUDLAND (FD.)			FD. Foudland			FH. Fisherford		SQ. Shargunner
STRICHEN (ST.)		BI. [illegible]	ST. Strichen		GR. Gaerlie	AE. Anniegatnel		HY. Hythie
DURNHILL (DH.)				FF. Fernybrae	DH. [illegible]	KY. [illegible]		BD. [illegible]
SKELMUIR (SK.)					SK. Skelmuir	BG. Bogenjoggie		SV. Savock
BOGTOWN (BT.)						BT. [illegible]		
AUCHINBLAE (AB.)			AB. [illegible]			CG. Candy		
BOYNDIE (BY.)			BY. Boyndie	AN. [illegible]		DA. [illegible]		BA. Balindarg
CORBY (CY.)			CY.	LS.				MO. [illegible]



ASSOCIATION	SERIES				
	FREELY DRAINED			POORLY DRAINED	VERY POORLY DRAINED
	1 Shallow	2 Intermediate	3 Deep	4	5
LESLIE (LE.)	LE.1	LE.2		LE.4	LE.5
GARTLY (GY.)		GY.2		GY.4	
INSCH (IN.)	IN.1	IN.2	IN.3	IN.4	IN.5
TARVES (TR.)		TR.2	TR.3	TR.4	TR.5
ORDLEY (OD.)		OD.2	OD.3	OD.4	
STRICHEN (ST.)	ST.1	ST.2		ST.4	ST.5
FOUNDLAND (FD.)	FD.1	FD.2	FD.3	FD.4	FD.5
COUNTESSWELLS (CW.)		CW.2		CW.4	CW.5
HATTON (HN.)		HN.2		HN.4	
CORBY (CY.)	CY.1	CY.2			CY.5
CUMINESTOWN (CM.)		CM.2		CM.4	CM.5
ALLUVIUM (AL.)	Recent alluvium			AL. Drainage undifferentiated	
HILL PEAT (H.PT.)	H.PT.				

Soil Association Boundaries

Table 2.1

Soil texture and particle size distribution of the Foudland - Ettenbreck Soil Series

Depth	Texture
4-0	Black well decomposed humus
0-6	Loamy fine sand
6-9	Fine sandy loam
9-34	Fine sandy loam
4-66	Sandy Loam
34-66	Sandy Loam
66-118	Loamy sand to loamy fine sand

(a) Soil texture

Note: Parent Material: Coarse loamy drift from mica-schist and phyllite
(USDA Equivalent: Cryic Fragiorthod).

Depth	% Silt	% Clay	% Organic Carbon
4-0			49.1
0-6	20	7	11.7
6-9	29	7	9.0
14-24	31	9	3.6
40-50	34	7	1.3
80-90	27	4	0.4
110-118	2		

(b) Particle size distribution.

Table 2.2

Soil texture and particle size distribution of the Tarves-Pitmedden soil Series

Depth	Texture
3-0	Dark brown turfy layer
0-18	Dark brown to brown sandy loam
18-35	Sandy loam
25-55	Sandy loam
55-95	Gritty sandy loam

(a) Soil texture

Note : Parent material: Coarse loamy till from mixed acid and basic igneous and metamorphic rocks overlying weathered gneiss.
(USDA equivalent: Typic Fragiochrept)

Depth	% Silt	% Clay	% Organic Carbon
3-12	16	10	7.2
20-33	27	12	1.6
35-50	25	17	
58-70	25	12	
85-95	27	6	

(b) Particle size distribution

2.4 Temperature

The area is subject to moderate winters without prolonged frost. The average summer temperature is about 12 C. The monthly mean temperature from 1983-1993 is shown in Figure 2.3. The average growing season is about 241 days from early April to early November. Annual average hours of bright sunshine is over 1300 and summer months have an average of 170 hours.

2.5 Rainfall

Most of the rainfall is derived from the westerly airstream (Wright *et al.*, 1991). The Ythan Catchment averaged 780 mm of rain per year over the period of interest (1983-1993) and received most of its rain in the Autumn (Figure 2.4). Figure 2.5 shows the average annual rainfall distribution for the whole catchment over a period of thirty years (1941-1970). Over the long run, annual rainfall in the Ythan catchment varies from 700 mm on the coast to just over 900 mm on the highest parts of the catchment. Long term (1941-1970) monthly rainfall averages for Haddo House is shown in Figure 2.6. October, November, and December, and January are typically wet with November being the wettest month of the year (NERPB, 1994). Over the year 1941-1970, only 33 % of the annual rainfall at Haddo House fell in the months of February to June inclusive. July and August recorded in excess of 80 mm.

2.6 River Flow

The main rivers in the Ythan Catchment is shown in Figure 2.7. Four main tributaries enter the river from the south side (Burn of Keithfield, Bronie Burn, Tarty Burn, and

Figure 2.3
Temperature Variation (1983-1993)

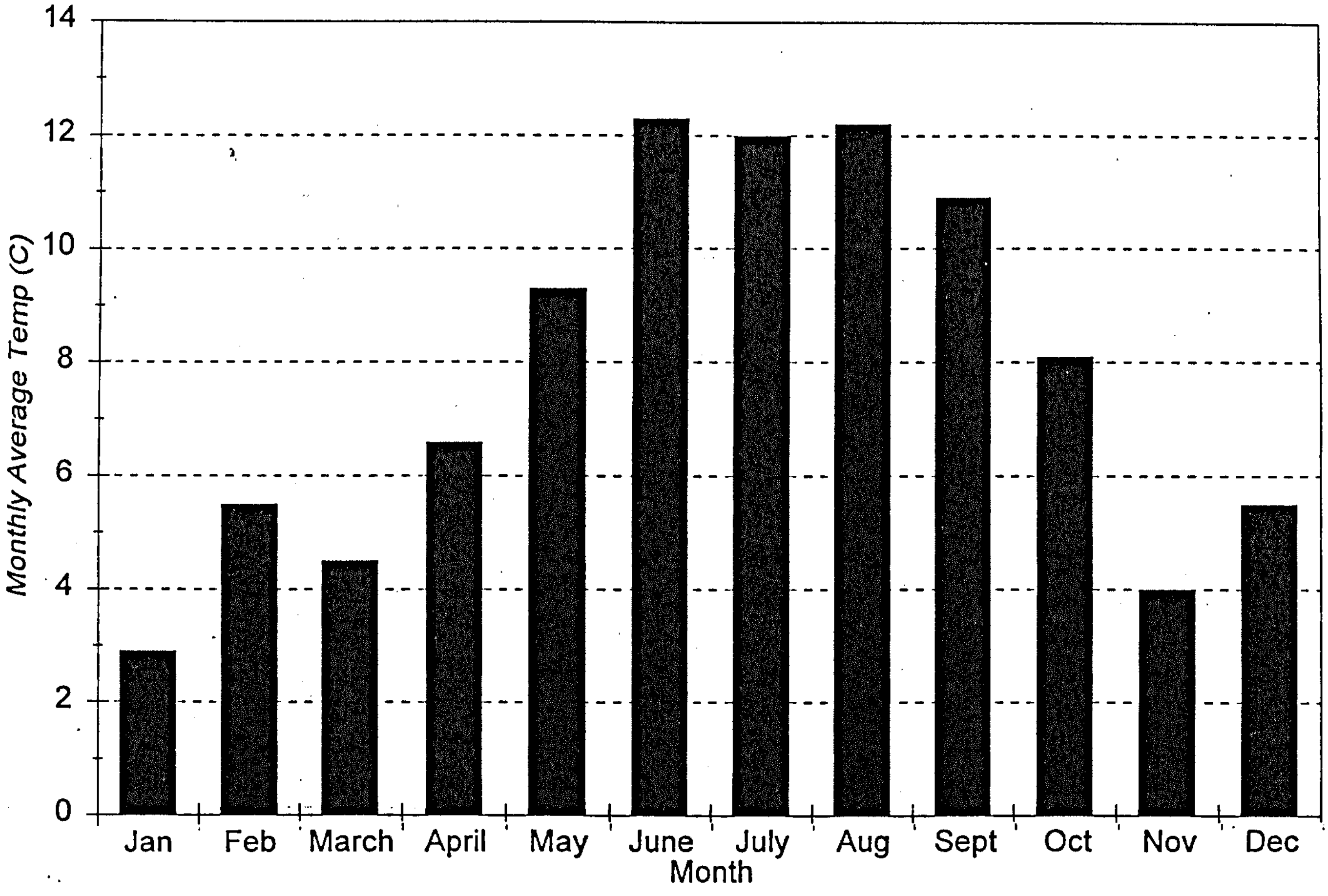


Figure 2.4
Rainfall Distribution (1983-1993)

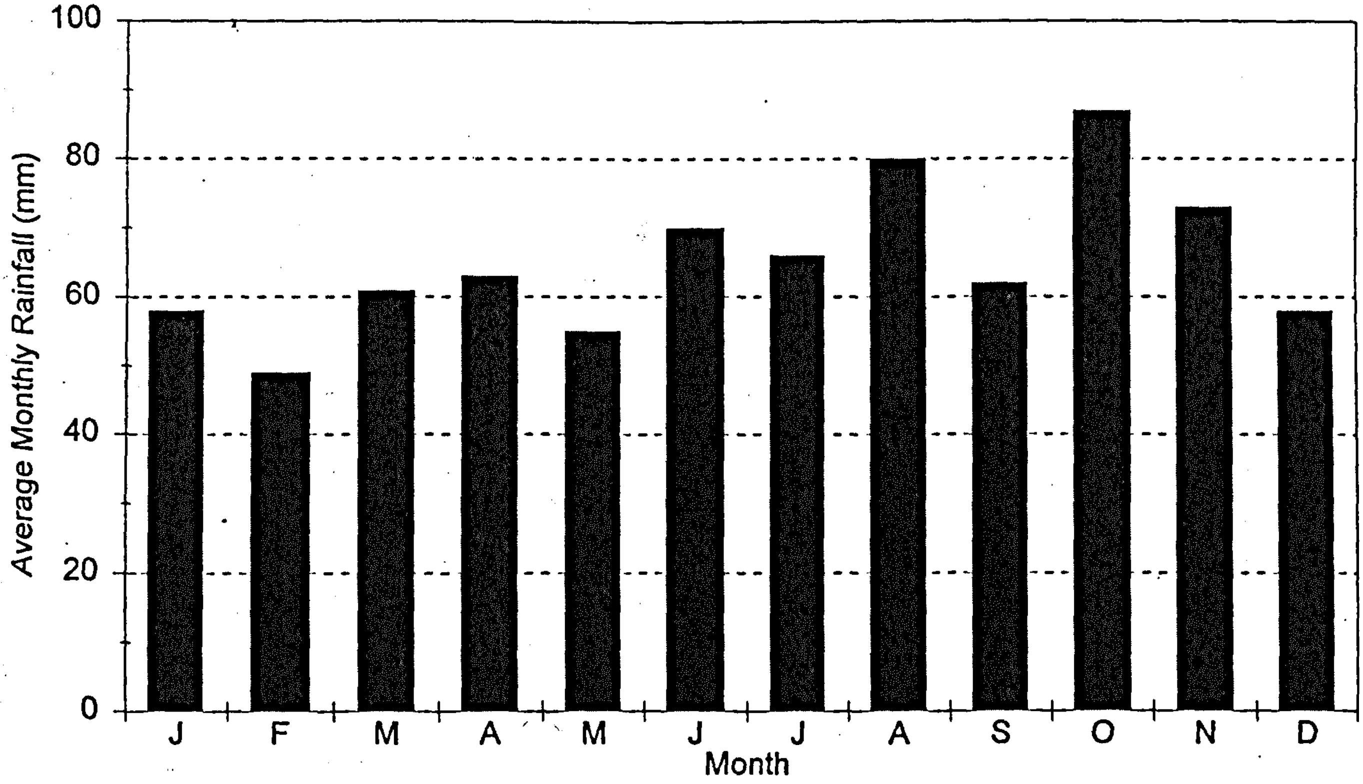


Figure 2.5

Annual Rainfall Distribution in the Ythan Catchment

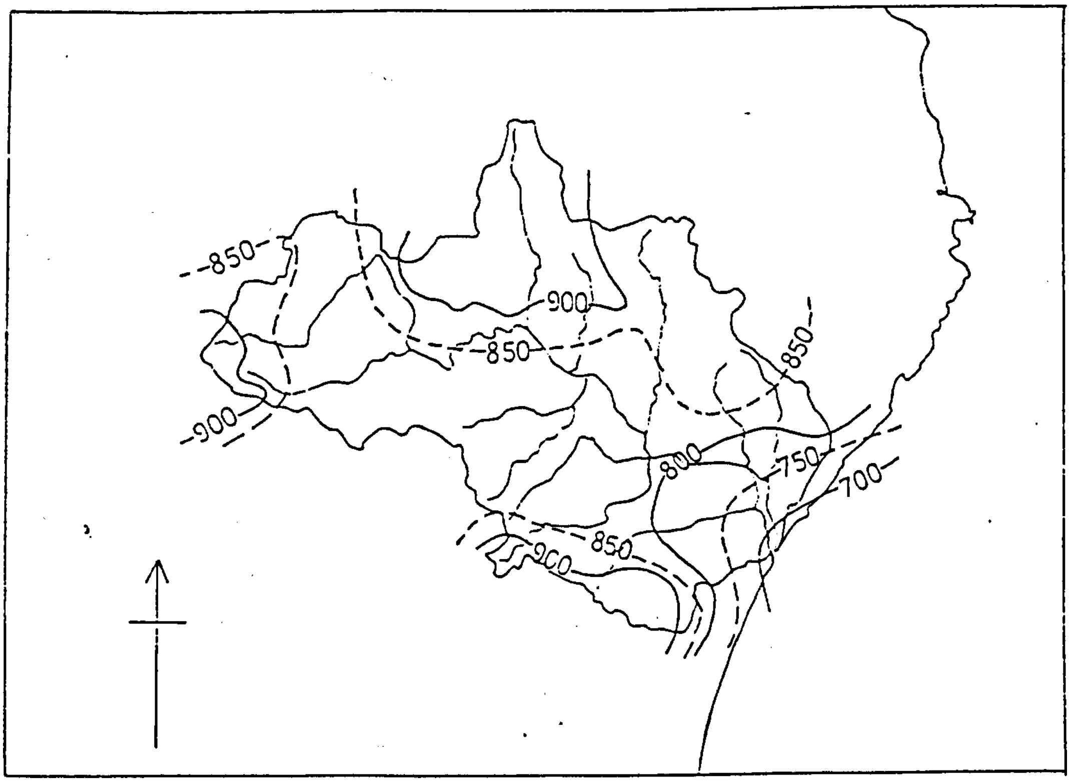


Figure 2.6

Average Monthly Rainfall at Ythan Catchment

(1941-1970)

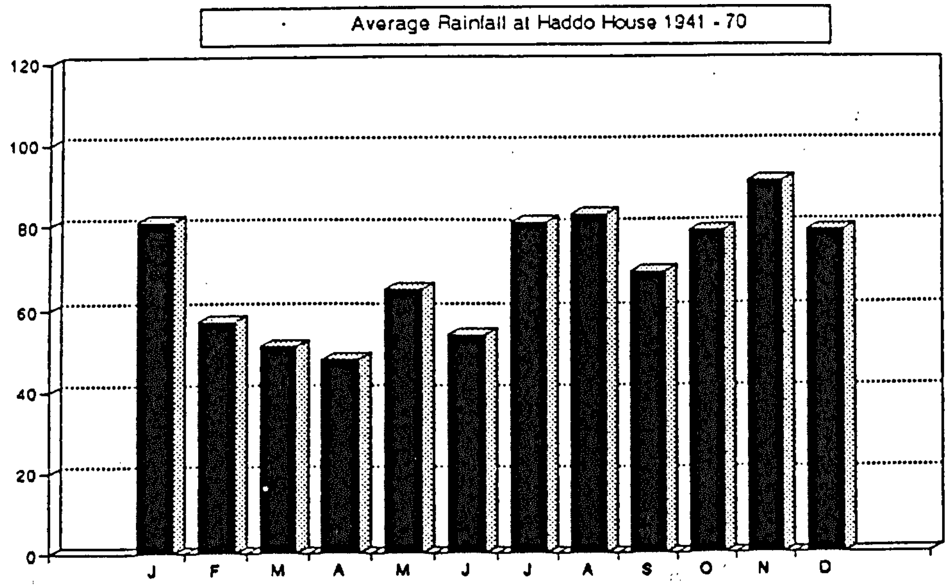
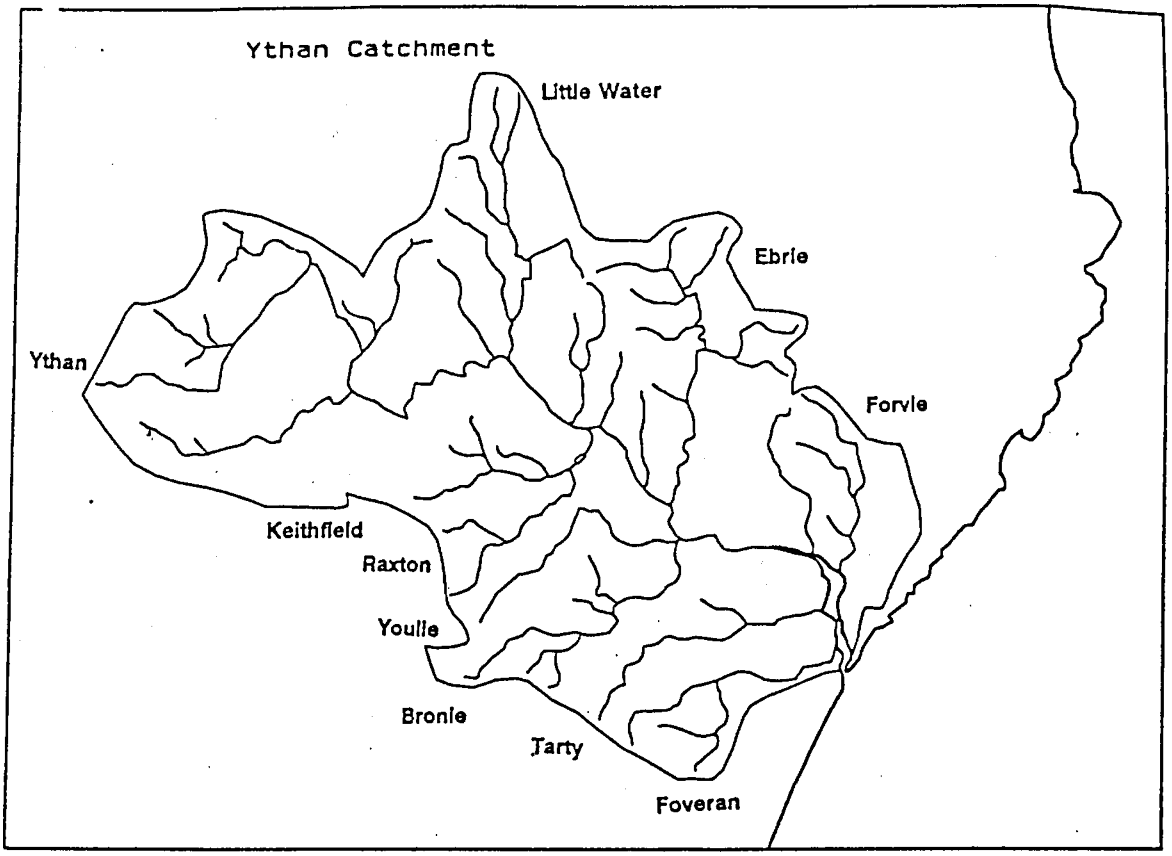


Figure 2.7

The Ythan River and Its Tributaries



(Source: North East River Purification Board)

Foveran Burn) and three (Little Water, Ebrie Burn, and Forvie Burn) enter from the north side.

Flow was monitored by the NERPB at the gauging station Ardlethen (NJ 925 309) over the time period 1980-1983; and afterwards at Ellon (NJ 957 303) which drained an area of 540 km^2 or 83 % of the catchment. The monthly flow characteristics of the Ythan river in shown in Figure 2.8. The average flow at Ellon during the study period (1983-1993) was 7.04 m^{3}s^{-1}, with a seasonal average of; winter (10.07 m^{3}s^{-1}), spring (7.77 m^{3}s^{-1}), summer (3.62 m^{3}s^{-1}) and autumn (6.69 m^{3}s^{-1}) as shown in Figure 2.9. The flow was highest in winter and lowest in the summer. As a comparison, the mean flow reported by Benzie for the period 1981-1983 was 6.3 m^{3}s^{-1} (14.1 l s^{-1} km^{-2}) with mean winter flow of 7.5 m^{3}s^{-1} (16.8 ls^{-1} km^{-2}) and 1.8 m^{3}s^{-1} (4.0 l s^{-1} km^{-2}) in the summer (Benzie *et al.*, 1991).

The annual rainfall and runoff pattern for the Ythan catchment for the period 1985-1993 is shown in Table 2.3. The table shows the high variation in yearly rainfall and runoff in the catchment indicating a comparatively dry period between 1989-1990.

2.7 Potential Evapotranspiration

The annual mean potential evapotranspiration (PE) for 1961-1990 is 510.2 mm with 346.9 mm of effective precipitation (Meteorological Office, 1994) which indicates that about 60 percent of the catchment precipitation is lost through evapotranspiration. Monthly total evapotranspiration are at the highest in the summer months of June, July,

Figure 2.8

Monthly Mean Flow

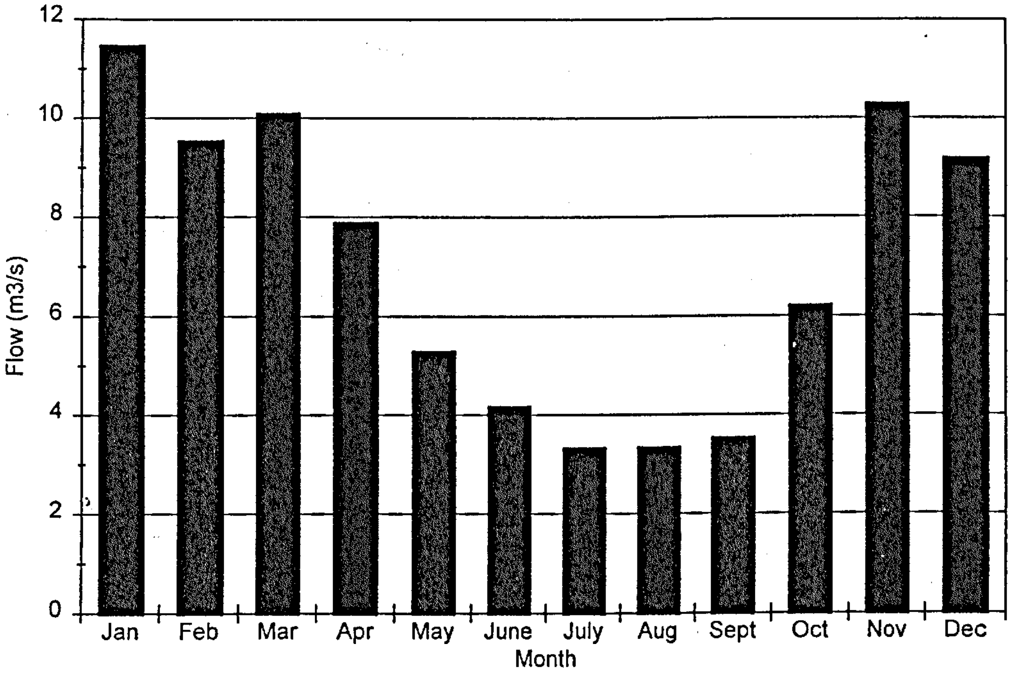


Figure 2.9

Seasonal Variation in Flow

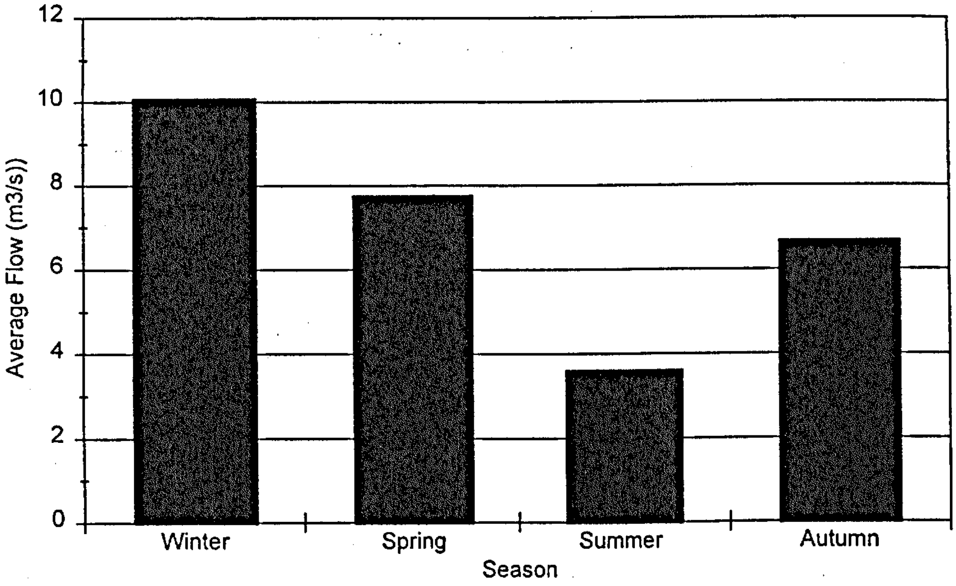


Table 2.3

Annual rainfall and runoff patterns in the Ythan catchment

(1985-1994)

Year	Rainfall (mm)	Runoff (mm)
1985	1031	636
1986	718	1024
1987	838	505
1988	859	532
1989	493	170
1990	767	262
1991	703	398
1992	825	398
1993	787	434
Average	780	484

and August with a resultant low effective precipitation and high soil moisture deficit (Table 2.4).

2.8 Land Use and Agricultural Management System

About 65320 ha (95%) of the catchment is classified as agricultural with the remaining 5 % divided between hill/upland, forestry or urban (Wright *et al.*, 1991), with the highest percentage of land use in arable crops and improved pasture (Table 2.5). Figure 2.10 shows the distribution of land cover in the catchment. Over 85 % of the area is used for arable crops and about 5.5 % for improved pasture. The distribution of crop types in the Ythan catchment is 36 % for spring crops, 22 % for winter crops, and 42 % for grass (MacDonald *et al.*, 1995).

Typical agricultural management practice in the Ythan catchment is described in Table 2.6. The exact amount of commercial fertilizers and farmyard manures applied to each field are not known, but estimates can be made using recommended rate. Typical application rates for spring crops, winter crops and grass are 95, 205 and 125 kg N ha^{-1} respectively. A estimate of nitrogen fertiliser applied in the Ythan catchment based on the survey of fertiliser practice for 1991 is as follows: arable crops: 5360 tonnes yr^{-1}; and grass:3348 tonnes yr^{-1}; with the total value of 8707 tonnes yr^{-1} or an average application rate of 12.6 tonnes km^{-2} or 127 kg ha^{-1}. The amounts and timing for winter crops show considerable differences, with double the amount of N for winter crops than for spring crops. Fertiliser timing may also have important consequences for N leaching with respect to both soil moisture status and crop uptake. Spring barley would

Table 2.4

Ythan catchment

Average monthly potential evaporation (PE), soil moisture deficit, and effective precipitation

(1961-1990)

Month	Monthly Total Potential Evapotranspiration	End of Month Soil Moisture Deficit	Monthly Total Effective Precipitation
Jan	12.7	0.8	68.1
Feb	15.4	1.6	40.1
Mar	33.5	7.0	32.5
Apr	49.8	16.8	16.0
May	72.5	40.0	14.6
June	76.0	56.9	2.9
July	78.1	61.4	3.1
Aug	65.1	51.2	12.5
Sep	47.4	33.2	8.8
Oct	29.5	16.2	34.3
Nov	17.3	6.1	51.8
Dec	12.9	3.9	62.2
Total/ Mean	510.2		346.9

(Source: Meteorological office, 1994)

Table 2.5

Percentage of Land cover in the Ythan catchment

Land Cover Group	Area In sq km	% cover
Arable	590.39	86.5
Improved Pasture	37.23	5.5
Coniferous Plantation	15.75	2.3
Smooth Grassland	12.85	1.9
Blanket Bog	5.15	0.8
Built up Land	5.96	0.9
Broadleaved Woodland	3.36	0.5
Dunelands	2.72	0.4
Estuary	2.61	0.4
Mixed Woodland	2.09	0.3
Woodland Recently Felled	1.98	0.3
Low Scrub	1.00	0.1
Heather Moor	0.39	0.1
Salt Marsh	0.32	Not Significant
Recently Ploughed Land for Forestry	0.27	Not Significant
Inland Water	0.25	Not Significant
Wetlands	0.25	Not Significant
TOTAL	682.57	100.00

Source: Macaulay Land Use Research Institute (Crown Copyright 1992)

Table 2.6

Typical Agricultural Management Practices in the Ythan Catchment

Crop / Nitrogenous fertilizer application	1st	2nd	Other	Total	Other details
Winter wheat	40kg/ha early March	149 kg/ha early April		189 kg/ha	Planting : late Septembe Harvest: September - October
Winter barley	40 kg/ha early March	106 kg/ha early April		176 kg/ha	Planting: late Septembe Harvest: September - October
Spring barley	40 kg/ha mid April/ May	38 kg/ha		78 kg/ha	Planting: Late March Harvest: September - October
Oilseed rape		104 kg/ha early March	100 kg/ha early April	204 kg/ha	Planting: late August Harvest: August - September
Temporary grass	30 kg/ha mid March	90 kg/ha early April	31 kg/ha mid May 31 kg/ha mid June	182 kg/ha	One cut of silage- mid May Grazing: June - Octob
Permanent grass	30 kg/ha mid March	88 kg/ha early April		118 kg/ha	Grazing March October

Source: Adapted from Allanson, 1990 and personal communication with the Macaulay Land Use Research Institute) receive all its applied N during late March/early May compared to winter barley where 15 kg ha^{-1} would be applied in September, 65 kg ha^{-1} late February/early March and the remainder in March/early April (Edwards *et al.*, 1990).

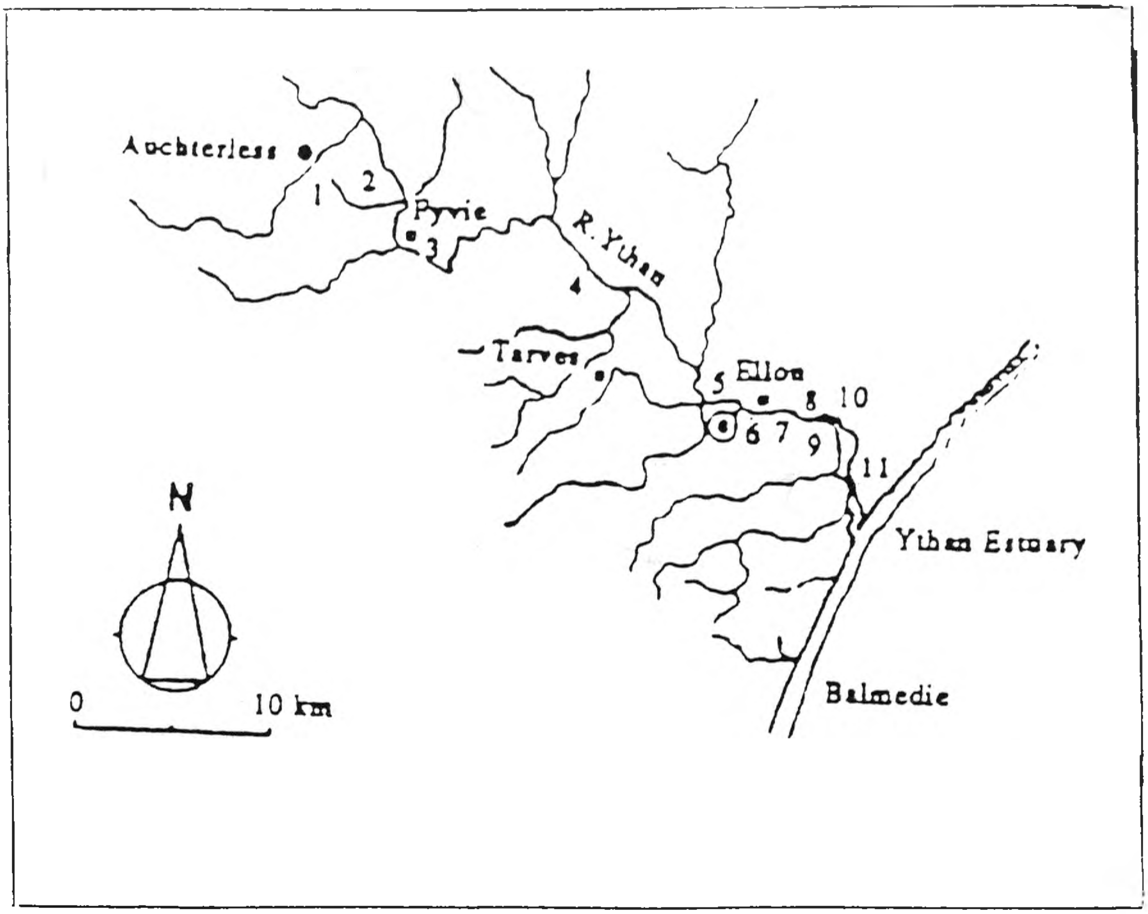
2.9 Nitrate Concentrations in the Ythan river

Nitrate concentrations in the River Ythan are monitored at ten sampling sites along the entire length of the river at a frequency of every other month except at Ellon where these were sampled once a month. Water samples were analysed for NO_3-N using automated colorimetric procedures. Total oxidised nitrogen (TON), the sum of NO_3-N and NO_2-N, was determined by the automated cadmium reduction method and expressed as mg l^{-1}. Values for NO_3 concentration were obtained by subtracting NO_2 values, determined separately from the total oxidised nitrogen values.

Characteristics of nitrate variation at Ellon is assessed in great detail since it is also the gauging station used in this study and represents the catchment outlet to the Ythan estuary. Figure 2.11 shows the location of the nitrate sampling sites as well as the gauging station. The database containing nitrate, temperature, and runoff variation in the period of study (1983-1994) is given in Appendix 1. Long term nitrate concentration was 6.7 mg l^{-1} with seasonal average of 7.2 mgl^{-1} for winter, 6.7 mgl^{-1} for spring, 5.4 mgl^{-1} for summer and 6.1 mgl^{-1} for autumn (Figure 2.12). The seasonal distribution of nitrate concentrations showed the peak in winter and decreased progressively with the lowest concentration in summer, which displays a typical pattern similar to other British rivers (Johnes and Burt, 1990).

Figure 2.11

Nitrate sampling points along the main river



1. Auchterless
2. Tifty
3. Fyvie
4. Methlick
5. Ardlethen
6. Ellon Car Park
7. Ellon STW
8. [illegible] Rock
9. Logie Buchan
10. Bridge Newburgh

The annual mean nitrate concentration in River Ythan has been increasing from 1983-1993 (Figure 2.13). The increase is very significant after 1990 (5.95 mgl^{-1}) onwards where there was a 25 % increase between 1990 and 1991.

The data showed limited spatial variation in nitrate pollution along the length of the river except at the upstream stations of Auchterless and Fyvie, which were slightly higher than the average concentration, and at the lowest monitoring station at Bridge Buchan which showed a significantly lower average nitrate concentrations. The average nitrate concentration levels at Auchterless, Tifty, Fyvie, Methlick, Ardlethen, Ellon Car Park, Ellon WWTP, Doocot Rock, Logie Buchan, and Bridge Newburgh (from 1983 to 1993) were as follows: 7.1 mgl^{-1}, 7.2 mgl^{-1}, 6.5 mgl^{-1}, 6.5 mgl^{-1}, 6.5 mgl^{-1}, 6.5 mgl^{-1}, 6.5 mgl^{-1}, 6.5 mgl^{-1}, 6.2 mgl^{-1}, and 2.9 mgl^{-1} respectively (Figure 2.14). This pattern has also been shown by other researchers (example, MacDonald *et al.*, 1995; Wright *et al.*, 1991).

2.10 Nitrate Loadings from the Ythan Catchment

Nitrate loadings to the surface water has been calculated by multiplying the concentration with instantaneous flow. Annual nitrate loads (Figure 2.15) to the Ythan river does not show the increase seen in the average annual concentration; rather annual load shows a high correlation to annual runoff (Figure 2.16). Given that concentration and discharge increase during the winter months, it is not surprising that nitrate load peaks in winter; a clear seasonal regime is also evident for nitrate load where most of the load is exported in winter.

Figure 2.12

Seasonal Variation In Nitrate Concent.

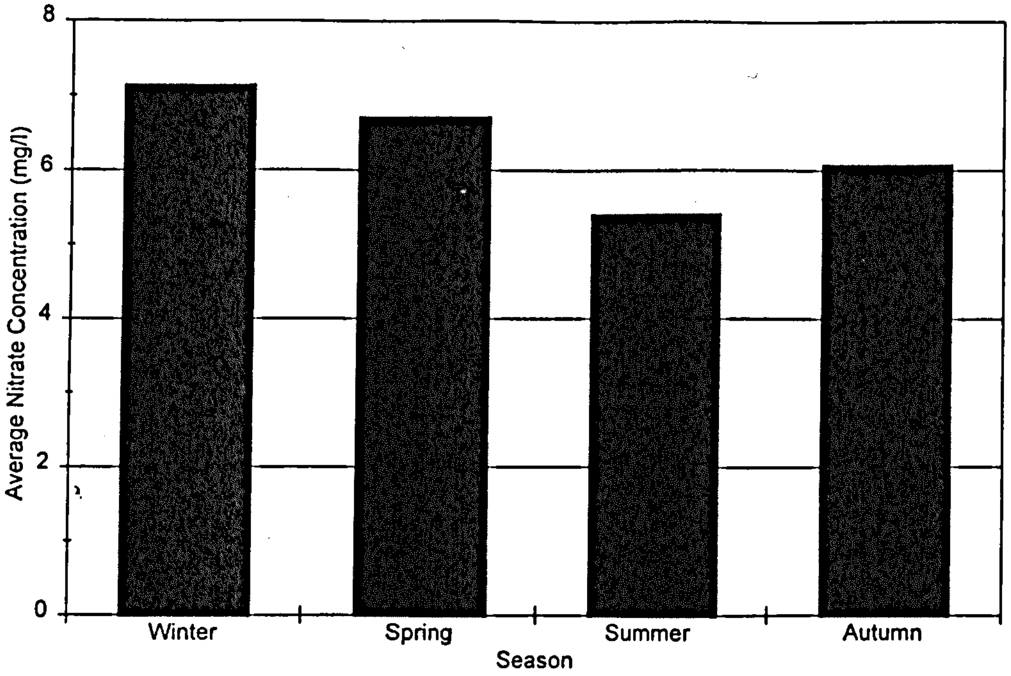


Figure 2.13

Annual Mean Nitrate Concentrations

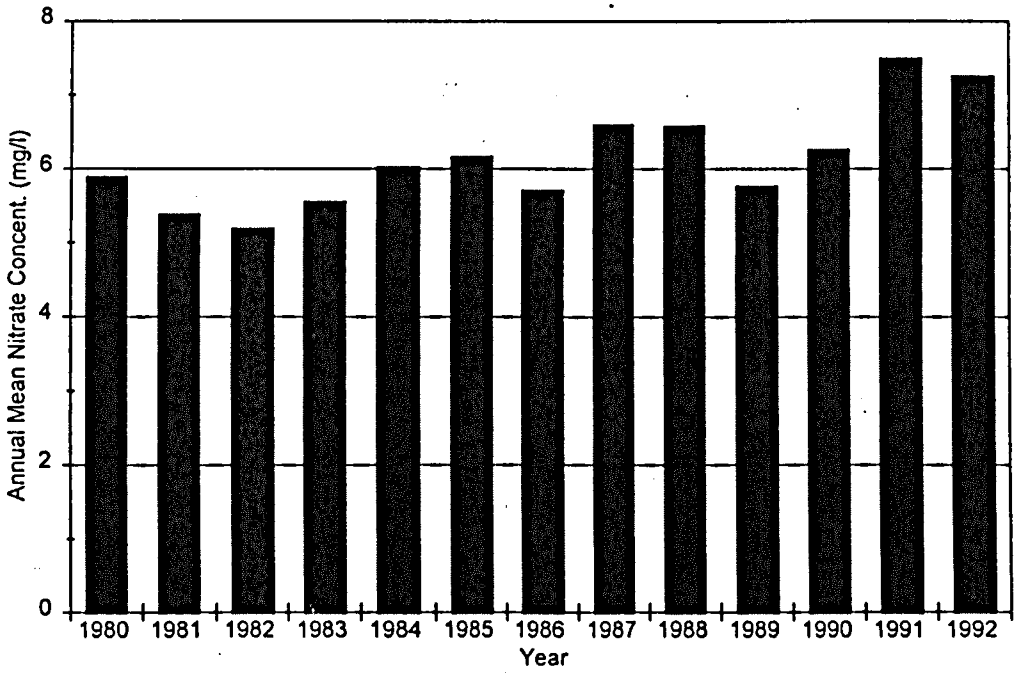


Figure 2.14
Spatial Distribution of Nitrate

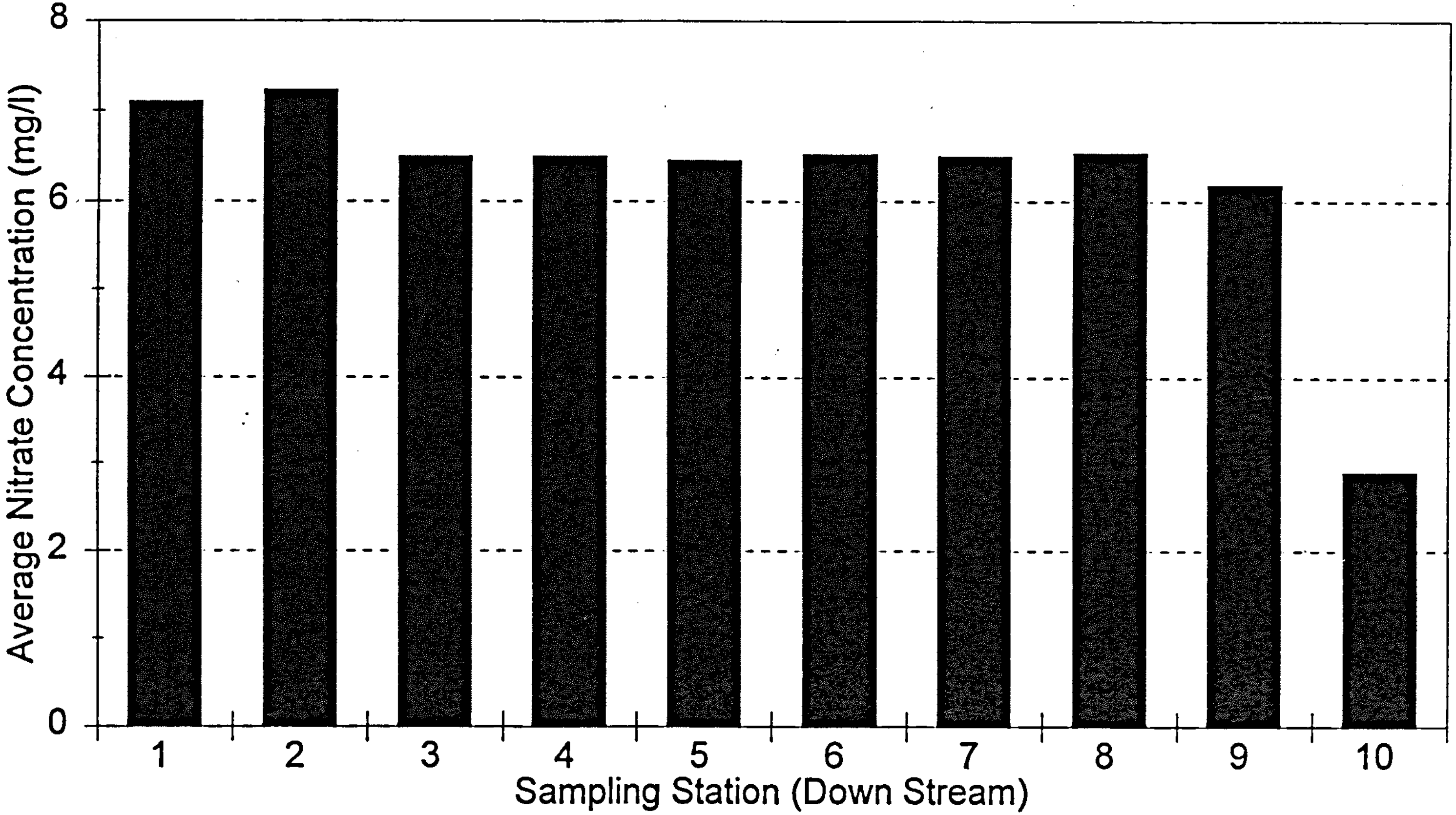


Figure 2.15
Annual Nitrate Loadings

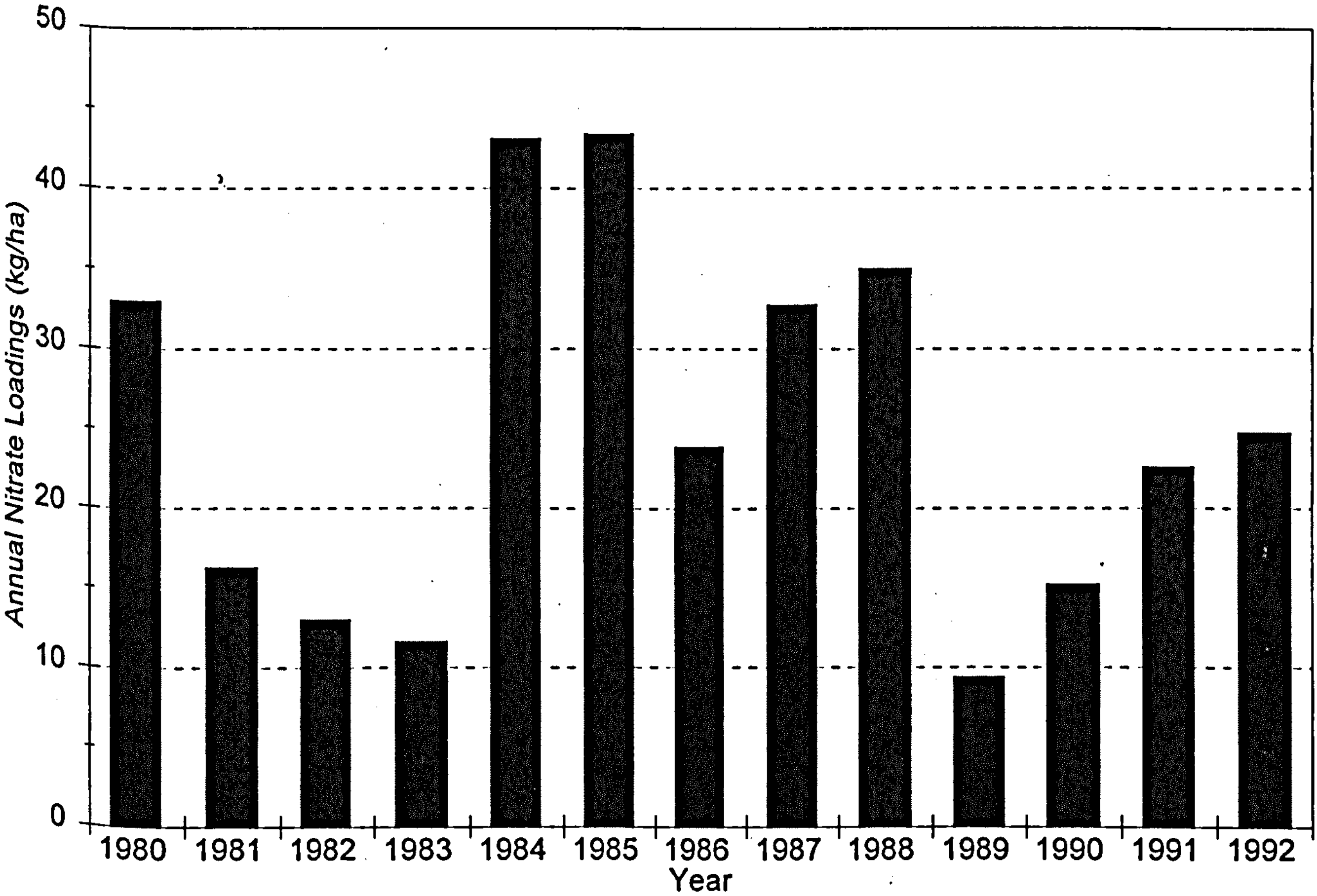
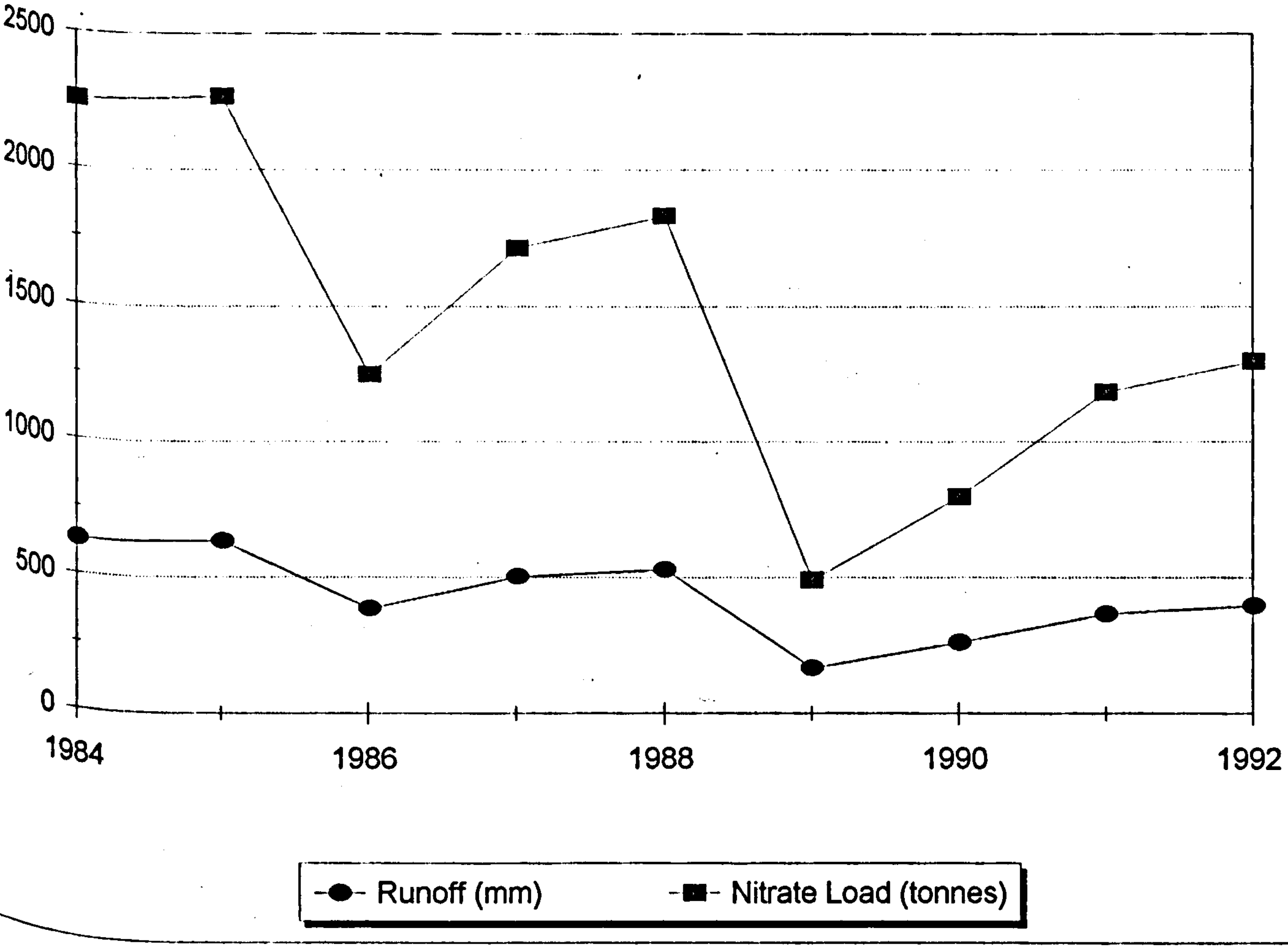


Figure 2.16
Annual Runoff and Nitrate Loadings



2.11 Correlation Analysis

The result of the correlation analysis between nitrate and several variables is shown in Table 2.7. The correlations were significant at 0.001 level. The results of correlation analysis showed negative correlation between nitrate concentration and temperature (-0.57), and a very slightly positive correlation (.08) with rainfall. The correlation between nitrate concentrations and flow was 0.4, but the correlation increased to 0.56 when the logarithm of flow was taken into account. There was a very high correlation between nitrate load and flow (0.97); this is not surprising since flow is a component of nitrate loading calculation. The high correlation reflects the link between water fluxes (which is the transport mechanism for nitrate) and nitrate loadings to the surface water (Foster, 1981).

Regression between nitrate concentration and flow showed an R^2 of 0.12 (Figure 2.17a) and increased to 0.315 when the logarithm of flow is taken into account (Figure 2.17b). The low correlation coefficient is also observed by other researchers who found that nitrate concentrations are very difficult to predict using flow records. However, the R^2 value is very high when the nitrate loads is regressed against flow yielding R^2 of 0.95 (Figure 2.18). The relationship between load and log flow shows a non-linear relationship (Figure 2.19).

Although flow is the transport mechanism for nitrate, other soil processes affecting nitrate variability such as mineralisation, denitrification, and agricultural management

Table 2.7

Pearsons Correlation

	Nitrate	Flow	Load	Temp
Flow	0.347			
Load	0.507	0.973		
Temp	-0.620	-0.446	-0.509	
Log Flow	0.562	0.887	0.903	-0.614

(All correlations were significant at 0.001 level).

Figure 2.17 (a)

Regression of Nitrate Conc vs Flow

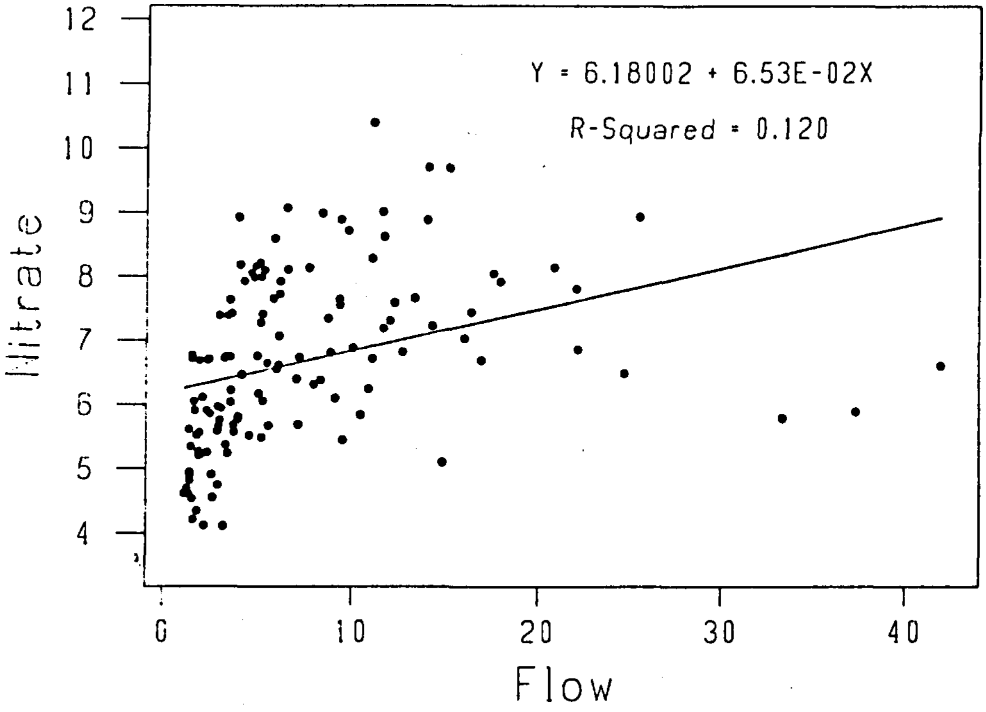


Figure 2.17 (b)

Regression of Nitrate Conc. vs Log Flow

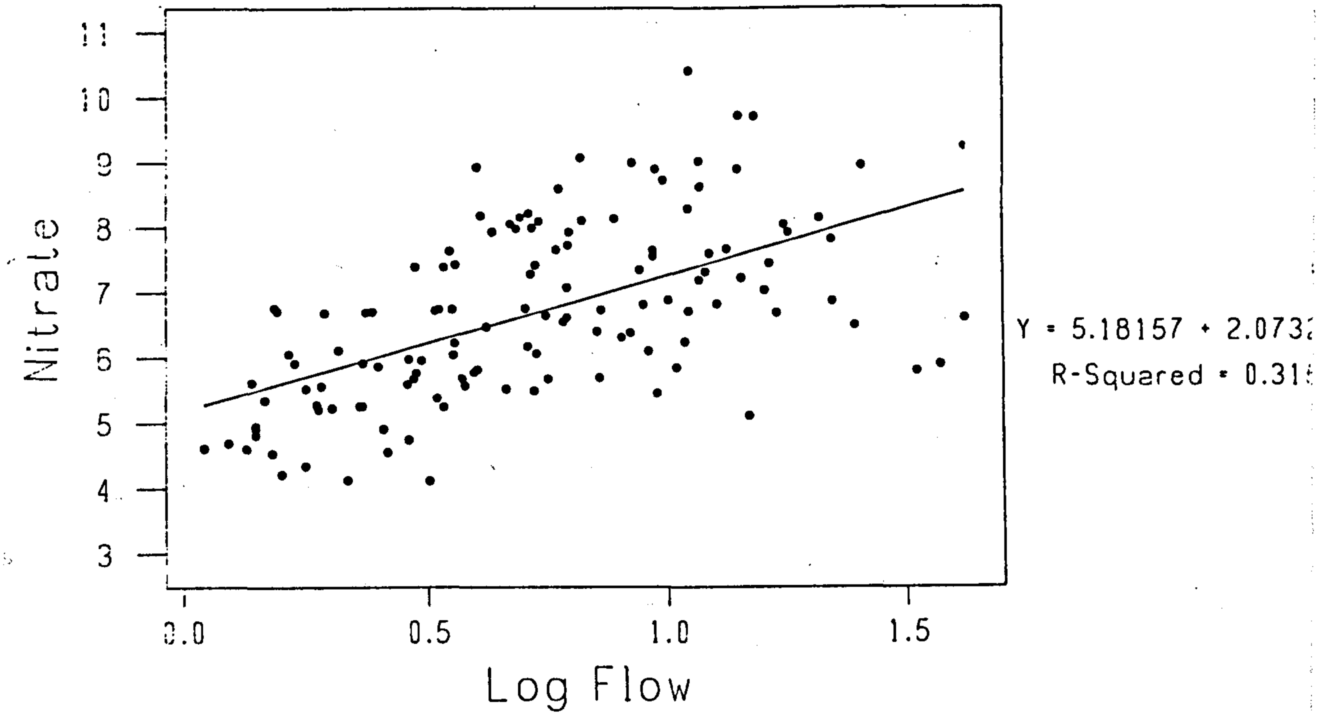


Figure 2.18

Regression of Nitrate Load vs Flow

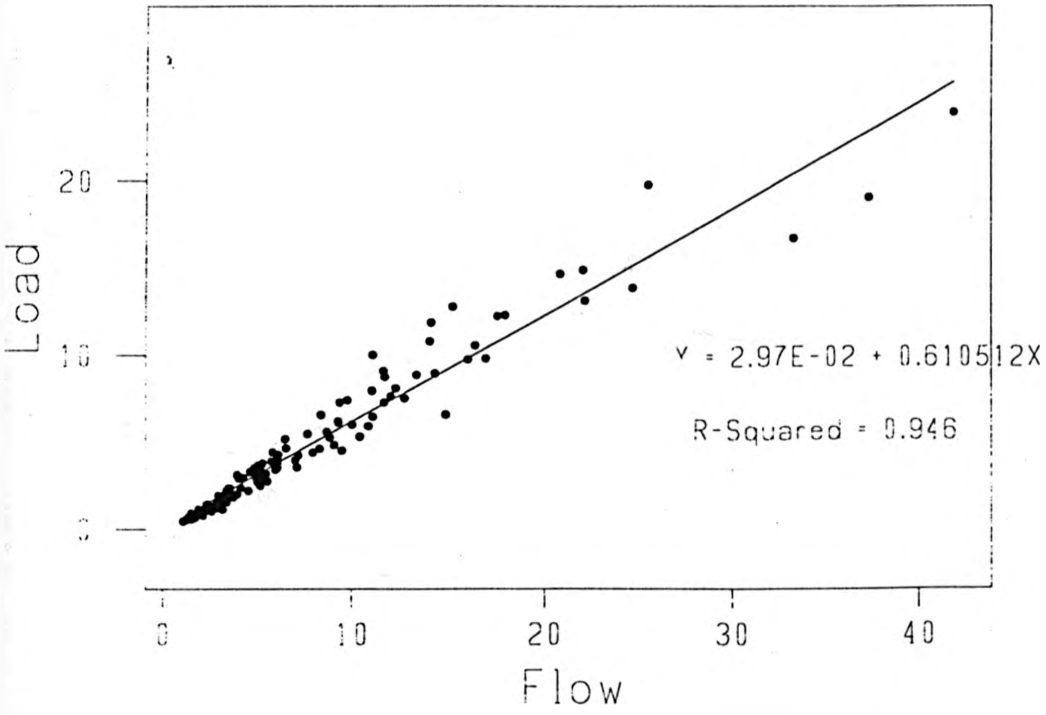
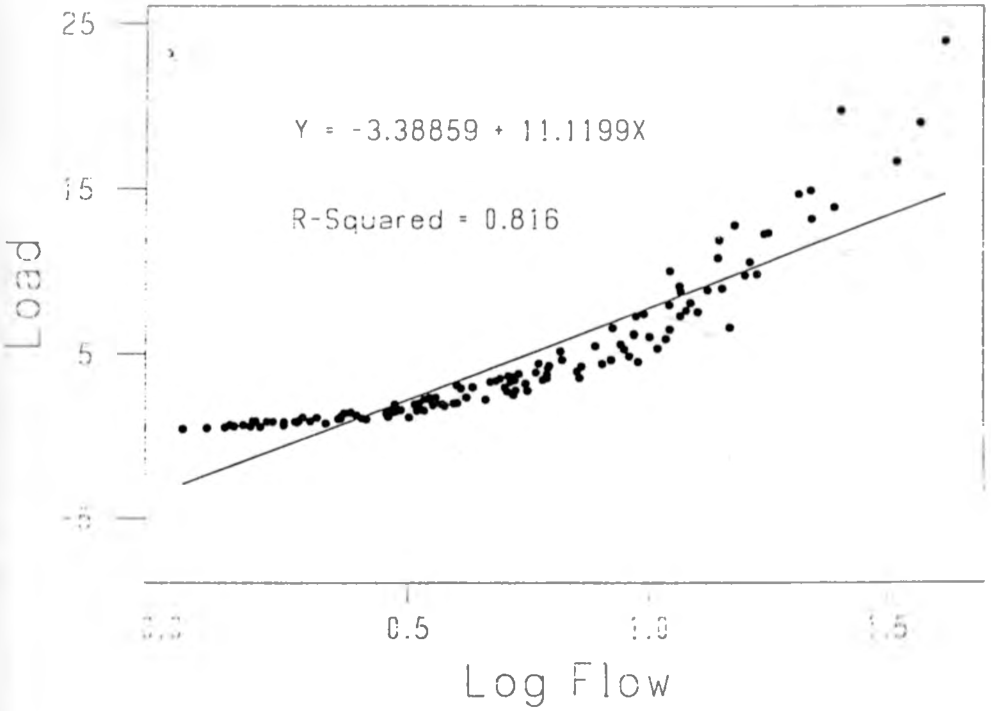


Figure 2.19

Regression of Nitrate Load vs Log Flow



practices do not necessarily affect the catchment water balance. Therefore, although log flow shows a high correlation to nitrate concentrations, the correlation varies greatly from season to season and cannot be used to predict nitrate concentrations under a different agricultural practices.

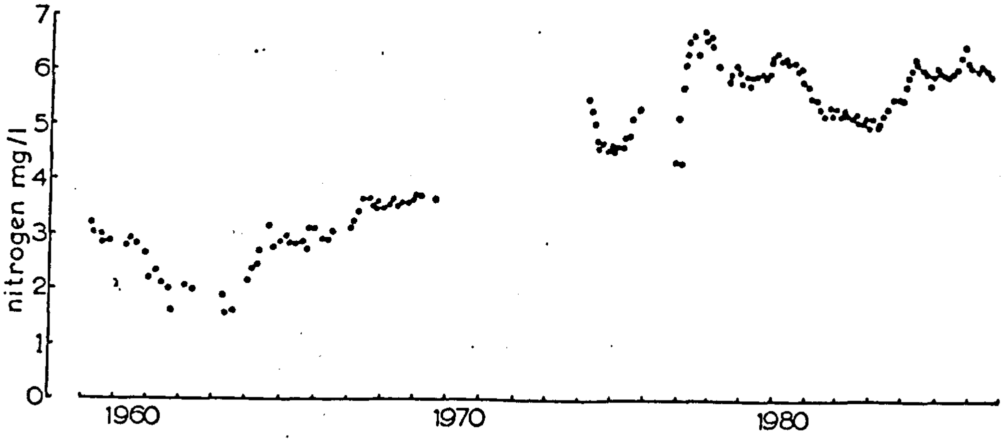
2.12 Previous Studies on Nitrate Pollution in the Ythan Catchment

Concentrations of NO_3-N in the River Ythan were high in comparison with other rivers within Scotland (Benzie *et al.*, 1991; Lyons *et al.*, 1993; and Wright *et al.*, 1991) and relatively high within the U.K. (Betton *et al.*, 1991).

Several studies have documented increasing trend in mean NO_3-N concentration. Figure 2.20 shows the long term variation in nitrate concentration in the Ythan river. Nitrate concentration showed an increase from about 2.5 to 6 mgl^{-1} in the late 60s to 70s. In the same period the biomass of the green seaweed, Enteromorpha, also increased which now form dense mats in the estuary (Raffaelli *et al.*, 1989). The long term changes in the peak summer biomass of the green seaweed, *Enteromorpha*, on Newburgh South Quay mudflat is shown in Table 2.8. Another study on nitrate concentrations between 1980-1992 showed variation between 3.98 mgl^{-1} and 10.38 mgl^{-1} depending on season with a long term mean of 6.14 mgl^{-1} measured at Ellon with the increase most evident in spring when ploughing is carried out and fertiliser is commonly applied. The significant increase in mean spring NO_3-N concentrations reported in the River Ythan from 1980-1992 was not observed in the River Don or the River Dee over the same time period although the two rivers are situated in the north-east of Scotland. Over the same

Figure 2.20

Long term variation in nitrate concentration in the Ythan catchment (1959-1986)



(Source: Raffaelli et al., 1989)

Table 2.8

Long term changes in the peak summer biomass of Enteromorpha on Newburgh Quay mudflat

(1963-1986)

	mean wet weight g/m^2
1963	1240
1964	169
1965	477
1966	634
1967	904
1968	1058
1969	1337
1973	1255
1974	607
1985	2087
1986	2314

(Source: Raffaelli et al., 1989)

period, inputs of fertiliser N into the catchment also increased by 24 % and the catchment also experienced an increase in the practice of winter rather than spring cropping. It was therefore concluded that the increase is due to management practice rather than climate (MacDonald *et al.*, 1995).

NO_3-N concentrations measured at Ellon showed a clear seasonal pattern typical of many British Rivers (Johnes and Burt, 1993). Mean seasonal concentrations (1980-1992) were 6.5 mgl^{-1}, 5.2 mgl^{-1}, 5.8 mgl^{-1}, and 7.0 mgl^{-1} for spring, summer, autumn, and winter respectively. Mean NO_3-N concentrations measured at Ellon, on a seasonal basis, showed a significant trend during the period 1980 to 1992. The significance of the trends, however, were seasonally dependent and did not conform to the overall apparent increasing trend in every year. The increase in spring (March, April, May) NO_3-N concentrations over time was highly significant with the remaining seasons also showing significant increase ($P > 0.05$). These trends were reflected at all sampling points throughout the catchment (MacDonald *et al.*, 1995).

Annual agricultural census figures (SOAFD) indicate a distinct move away from spring cropping towards the use of winter cropping in the Ythan catchment. In 1980, approximately 5 % of agricultural land use was used for winter cereals, by 1992 this figure had increased to around 33 %. The shift in cropping practice has resulted in changes in the timing of cultivation and fertiliser application. The amount of N fertiliser applied to winter crops is approximately 200 $kgha^{-1}$ compared with about 80 $kgha^{-1}$ for spring crops. Over this period, inputs of fertiliser N into the catchment increased by 24 % from 6600 tonnes in 1980 to 8200 in 1992. By 1992, approximately 1/3 of the Ythan catchment was receiving over double the quantity of fertiliser N used in 1980 (MacDonald *et al.*, 1995). Winter cropping has the advantage that the soil is not left fallow over winter and may reduce NO_3 losses particularly from surface runoff and utilising available N. Uptake values of 35-40 kg ha^{-1} by winter wheat crops by February have been reported. The change in cropping practice from spring to winter cereals within the catchment has coincided with an increase in spring NO_3-N concentrations in the River Ythan over the same time period (MacDonald et al., 1995).

Annual loss of NO_3-N from the Ythan catchment equates to 16 % of N applied annually as inorganic fertiliser, even-though the complexity of soil N cycle makes it difficult to quantify the specific contributions of inorganic nitrogen relative to organic and atmospheric inputs (MacDonald *et al.*, 1995).

Whilst nutrient concentrations in the River Ythan are relatively high by UK standards, the loads of nutrients transported by the Ythan are low because of the low river base flow. Mean annual discharges were 7, 25, and 38 m^3s^{-1} for the Ythan, Don, and Dee respectively. Total annual loads were 1369, 2010, and 623 t a^{-1} for the Ythan, Don, and Dee respectively for the period of 1980-1992. Whilst eutrophication problems have been reported in connection with the River Ythan, no such problems have been encountered in the River Don despite the high nutrient loads. This may be due to the fact that although load is a useful measure in nutrient balance, it is not necessarily important in determining vulnerability to eutrophication and in some cases the concentration of nutrient is the critical factor (MacDonald *et al.*, 1995).

Mean annual loads of N were calculated as 1305 tonnes which is equivalent to catchment losses of 19 kg N ha^{-1}. There was no indication of increasing NO_3-N loads over time. This is attributed to the large annual variability in flow (MacDonald *et al.*, 1995).

The relationship between nitrate loading and agricultural intensity of river catchments in the North East of Scotland, which covers a total of 11 river catchments and subcatchments, over the period of 1980-1986, was examined. The study showed River Ythan to have the highest nitrate concentration (5.31 mgl^{-1}) compared to other catchments in North East Scotland; which was attributed to the high percentage of the catchment being used for agriculture (Wright *et al.*, 1991).

Simple regression analysis against primary land cover suggests that agriculture is responsible for the majority (91 %, CV ± 31.6 %) of the annual losses of nitrate in North East Scotland river catchments. Since rainfall variation across this region is small and discharge tends to be related to catchment area, this correlation indicates a direct relationship between agricultural intensity and catchment mean NO_3-N concentration in river waters. There are however significant differences between catchments of similar agricultural intensity. Further multi-variable linear regression analysis, using GIS data and agriculture census returns indicates that most of the outstanding variation can be accounted for if agricultural variable is related to arable and grass crops or fertilizer N applied to spring, grass and winter crops (Wright *et al.*, 1991).

Using data collected between 1980-1992, the seasonal relationship between flow and nitrate concentration in the Ythan river was explained using regression equations (Table 2.9) which showed that flow accounted for a small variation in NO_3-N during each season (notably winter, with R^2 of only 6 %). The result therefore indicates that continuous flow could not be used to reliably predict NO_3-N concentrations (MacDonald *et al.*, 1995).

NO_3-N concentration in River Ythan showed very little variation along the length of the river indicating constant inputs into the water course throughout the catchment. This relatively constant NO_3-N concentrations along the river also reflects the uniform land use and soil types within the catchment.

The amounts and timing of fertilizer nitrogen additions for winter crop are double (205 $kgha^{-1}$) the amounts applied to spring crops (95 $kgha^{-1}$) and managed grass (125 $kgha^{-1}$). Wright estimated average agricultural losses of 1998.7 tonnes yr^{-1} or 30 kg ha^{-1} between 1980-1987 (Wright *et al.*, 1991). Load calculations are estimate and make use of the best available data and as such the estimate varies from one report to another. For the study period between 1980-1992 MacDonald reported annual loadings of 1305 tonnes or 19 kg $ha^{-1}a^{-1}$. Annual loss of NO_3-N is calculated at 16 % of N applied annually as inorganic fertiliser (MacDonald *et al.*, 1995).

Table 2.9

Regression equations developed to model nitrate concentrations in the Ythan river

Spring	NO_3-N concentration = 0.713 + 0.121 flow; R^2 = 34 %
Summer	NO_3-N concentration = 0.654 + 0.126 flow; R^2 = 41 %
Autumn	NO_3-N concentration = 0.679 + 0.116 flow; R^2 = 22 %
Winter	NO_3-N concentration = 0.814 + 0.041 flow; R^2 = 6 %

(Source: MacDonald, et al., 1995).

CHAPTER 3

Nitrogen Cycling and its Transport in Agricultural Catchments

3.1 Introduction

There is considerable worldwide concern about increasing levels of nitrate nitrogen in both river systems and groundwater sources. High levels of nitrate in drinking water are becoming a problem in some regions such as Western Europe. The greatest increases in nitrate concentrations in surface waters seem to be occuring in Western Europe and North America. Nitrate concentations in the UK waters are also rising, with the highest levels occuring in the south and east of England, particularly in Lincolnshire, Cambridgeshire and East Anglia (Croll and Hayes, 1988). This chapter reviews previous works on nitrate transformations and transport in agricultural catchments.

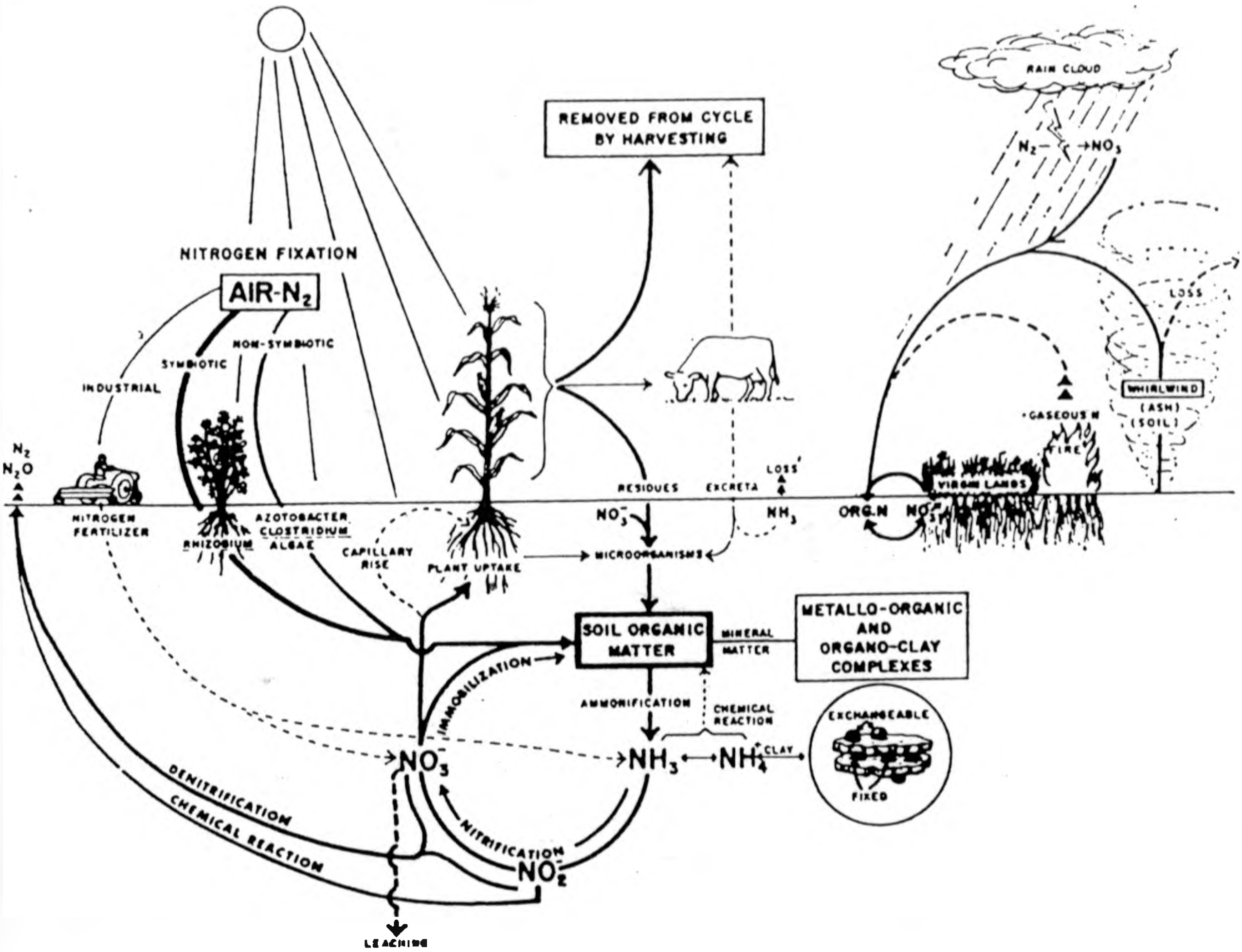
3.2 Nitrogen Cycling in Agricultural Land

Nitrogen is an essential element for plant and animal growth. It is cycled in soils, plants and animals in a complex series of biological and chemical processes. In excess of 90 % of the nitrogen is present in organic forms. This organic form is made up of a vast range of compounds, derived from biological materials and from humification processes. However, the relatively small amount of nitrogen present in inorganic form, such as ammonium, NH_4^+, and nitrate, NO_3^-, is significantly greater in agricultural soils, especially those under intensive management, than in other ecosystems. Nitrogen inputs to the soil occurs by a number of pathways including rainfall, mineralisation of soil organic matter, dry fall of dust and dirt, biological fixation of atmospheric nitrogen, and direct application of fertiliser nitrogen. Among the important processes occuring in the nitrogen cycle in agricultural landa are mineralisation, denitrification, and crop uptake. A study on nitrogen cyling in upland pastures has suggested that 20-60 kgN ha^{-1} is mineralized annually with a further 5-10 kg N ha^{-1} a^{-1} supplied by biological fixation. Atmospheric input (14 kg ha^{-1}yr^{-1}) makes a substantial contribution to the overall nitrogen budget of these pastures and becomes relatively more important to moorland where biological fixation is low (Burt *et al.*, 1993).

The numerous transformations of nitrogen in the soil-water-air-plant environment, collectively called the nitrogen cycle is shown in Figure 3.1. One of the most important processes in the nitrogen cycle in agriculture is mineralisation - the production of nitrate from soil organic matter. Mineralisation is the process by which organic compounds in the soil break down to release ammonium ion, NH_4^+, with the concurrent release of carbon as CO_2. This process is called ammonification. The ammonium ion is then oxidised to nitrate by soil bacteria in a process called nitrification. The extent, and the rate, of the processes are affected by many factors, including the composition of the decomposing substrate(s), soil temperature, moisture content and pH. Immobilisation is the reverse process, by which there is a net incorporation of mineral nitrogen, usually NH_4^+, into organic forms (Burt *et al.*, 1993). Only a small proportion of the total nitrogen in the soil is mineralised each year - up to about 150 kgha^{-1}. Because both mineralisation and nitrification are biological processes, they are affected by soil and weather conditions, especially temperature. Both processes are slowed down by shortage of oxygen (due for example to soil compaction or waterlogging) by drying out

Figure 3.1

The nitrogen cycle in soil



(Source: Haan et al., 1982)

of the soil, and by soil acidity. Mineralisation is stimulated by soil disturbance. It is increased when easily degraded material is added to the soil as organic manures or leafy plant residues. These materials go through a period of rapid decomposition in the first year, followed by a much slower breakdown of the more resistant material in subsequent years. Ploughing of old grassland leads to the mineralisation of large amounts of nitrogen (Burt *et al.*, 1993).

Supply of mineral nitrogen in the soil increases as soil temperature rises. The supply of mineral nitrogen from the soil does not keep pace with the requirement of most arable crops, which increases very sharply with rapid growth in the April-June period. It is at this stage that addition of fertiliser nitrogen is most important for the growing crop (Burt *et al.*, 1993).

Conditions remain favourable for mineralisation into the late summer and early autumn. After harvesting of arable crops, which all mature in this period, the nitrogen released by mineralisation continues to accumulate in the soil. Even if crops are sown in the autumn, the soil mineral N supply will usually exceed the uptake by such crops, because of relatively slow uptake during this stage of growth. It is the mineral N formed in the soil in autumn which contributes most of the loss of N by leaching during the winter. Some of this mineral N will be derived from the fertiliser nitrogen applied to the previous crop (mainly via organic debris from that crop) but a larger part will be derived from the mineralisation of older organic matter (DOE, 1986).

Denitrification is the microbial reduction of nitrate to NO, N_2O and N_2. This is a biological process which returns the fixed nitrogen to the atmosphere. Estimates of the quantities of nitrogen lost by denitrification from agricultural land differ widely. One estimate puts a figure of 0 - 20 % of the applied nitrogen from arable lands and 0 - 7 % from grasslands (Burt *et al.*, 1993).

Another important process in nitrogen cycle is nitrogen uptake by plants. Generally, plants remove from 40 to 80 percent of the nitrate and ammonium supplied by fertiliser or mineralisation. The uptake process varies with the plant species and with growth as controlled by the environment (Haan *et al.*, 1982).

3.3 Factors affecting nitrate transport and emission

Nitrate is highly soluble in water and as such it is almost always carried in solution although a small part might be transported as suspended particulate. Nitrate tends to move down the soil profile with the initial infiltrating rain and thus away from the surface. Consequently, nitrate in surface runoff is seldom closely related with antecedent nitrate contents in surface soil. Exceptions may be when an intense rainstorm occurs shortly after surface application of nitrate fertiliser, or when a soil horizon barrier in the profile results in interflow which reappears as surface runoff (Frere *et al.*, 1975).

Water that infiltrates into the soil, moves laterally above an impeding horizon, and then reappears on the soil surface or joins the surface runoff downslope, has a high potential for transporting soil chemicals in solution into runoff. This type of flow is commonly known as interflow or subsurface runoff. This shallow subsurface flow may be significant in sloping soil with surface horizons of high permeability underlain by a horizon of much lower permeability (Ahuja and Ross, 1982). Shallow subsurface flow was the main pathway for soluble nitrate transported to runoff from claypan soils of the Midwestern United States. A similar result was obtained from Olinthic Coastal Plain soils, where 79 % of the total runoff was subsurface flow, which contained 99 % of the total N in runoff (Jackson *et al.*, 1973).

Water movement within a soil profile can be subdivided into three simple portions: saturated flow, unsaturated flow, and by-pass flow. In saturated condition beneath the water table, water flows in response to the hydraulic gradient, following Darcy's law. In unsaturated flow, water and solute also follow a similar relationship where their movement is in response to a potential gradient. By-pass flows occurs whenever there is preferential movement of water along specific pathways (Linsley *et al.*, 1982).

Conceptually, the amount of nitrate leached from the soil is dependent on three main factors: first, water balance between rainfall received at a site, water lost in evapotranspiration from vegetation cover and the water holding capacity of the soil. Second, the quantity of nitrogen present in the soil either from natural sources or fertiliser input; and finally the degree to which nitrogen is removed by the vegetation cover present at the site (DOE, 1986).

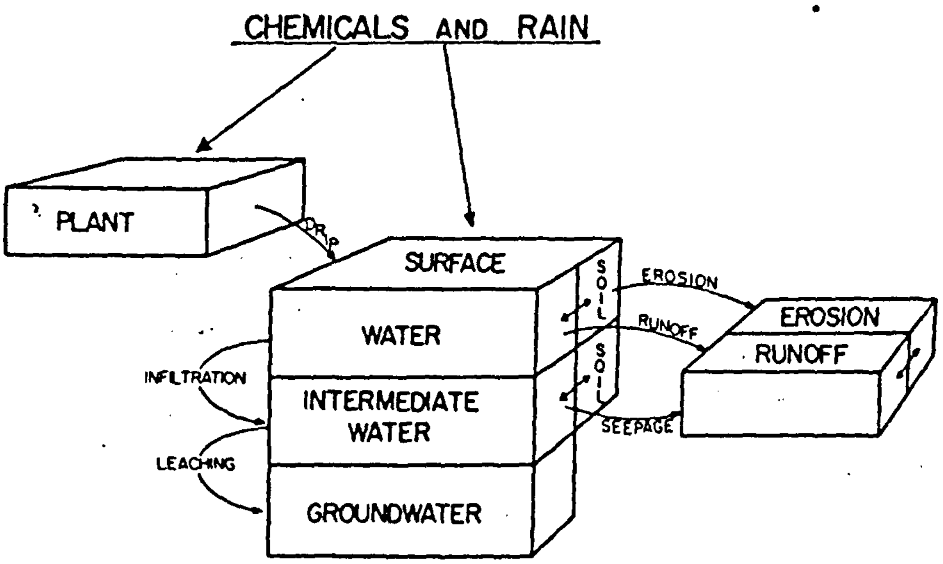
The three major routes for nitrate movement out of a soil profile are:

1) upwards, crop uptake and gaseous loss
2) sidewards, via surface/subsurface flow
3) downwards, as profile leaching.

The transport mechanism for chemical movement in a catchment is shown in Figure 3.2. In terms of nitrate, most of it would be carried by water instead of through erosion. Part of the nitrate remaining in the soil would be leached into the groundwater and part of it would be carried in surface and subsurface flow. The balance between vertical and lateral flow on a site depends on its hydrology, and in particular on the nature of the soil. In free-draining soils, movement is predominantly in the vertical direction, and nitrate studies are typically concerned with the downward movement of solute through the base of the profile. However, on impermeable soils there is effectively no downward movement below the base of profile, and losses are predominantly horizontal. Many soils occupy a position intermediate between the two extremes of being free-draining or impermeable, and experience a mixture of both vertical and lateral movement, the balance between the two varying with the time of the year. Many soils experience periods of lateral flow during winter due to water logging, but can be considered to have simple vertical flows during the summer period. Nitrate emission at a given site therefore depends on the interaction of environmental and management factors. The emission will vary seasonally with soil type, climate, crop cover and crop husbandry (Bartholomew and Clarke, 1965).

Figure 3.2

Mechanisms for chemical movement in a catchment



(Source: Knisel, 1980)

Jackson conducted a research to determine the amount of nitrate-nitrogen that was transported by surface and subsurface drainage from a small watershed cropped with corn for 3 years. The soil is generally loamy sandy with high infiltration rates. The author found that about 99.1 % of the NO_3-N lost in runoff was in subsurface flow. Except where considerable runoff occurs, nitrate is usually low in surface runoff (Jackson *et al.*, 1973).

Among the physical attributes that influences leaching of nitrate from farming systems are fertilisation rate, soil texture, land use and cropping patterns. Trends in fertiliser N application to the most widely grown crops in England and Wales showed that applications have increased substantially and they are particularly high on potatoes. A 10 year study on an arable clay soil in Sweden indicated that leaching of nitrate was moderate up to a rate of application of 100 kg N ha^{-1} a^{-1}, but increased rapidly thereafter, reaching 91 kg NO_3-N ha^{-1} a^{-1} for the application rate of 200 kg ha^{-1} a^{-1}. Another study carried out on the rate of leaching of nitrogen from sandy loam and clay soil using lysimeters found that 74 and 41 kg ha^{-1} a^{-1} were leached from sandy loam and clay soils respectively (Burt *et al.*, 1993).

The relationship between leached nitrate and nitrogen applied is not straight forward because, in addition to the applied nitrogen, soils also contain substantial amounts of organically bound nitrogen. Additional inputs of nitrogen from atmospheric deposition and biological N fixation can also make significant contributions to the overall N budgets of natural ecosystems. Factors which affect the rate of release of nitrate from these organic sources include soil type, temperature, moisture and management practices (Burt *et al.*, 1993).

On arable soils the greatest leaching losses occur during late autumn, winter, and early spring following periods of reduced plant uptake, increased tillage and incomplete ground cover to intercept the nitrate released by mineralisation or fertiliser application. During this time rainfall exceeds moisture losses by evaporation and transpiration. Arable land loses one third and grassland one tenth of the amount of nitrogen lost by fallow land into the drainage system (Wright *et al.*, 1991).

Fertiliser timing and the amount used may have important consequences for N leaching with respect to both soil moisture status and crop uptake (Edwards *et al.*, 1990). The amount and timing of fertiliser N additions for winter sown crops are double (205 $kgha^{-1}$) the amounts applied to spring crops (95 $kgha^{-1}$) and managed grass (125 $kgha^{-1}$). Spring barley would receive all its applied N (80-100 $kgha^{-1}$) during the late March/early May compared to winter barley where 15 $kgha^{-1}$ would be applied in September, 65 $kg\ ha^{-1}$ late February/early March and the remainder in late March/early April (Wright *et al.*, 1991). Nitrate loss from agriculture area is calculated to be about 21 $kgha^{-1}a^{-1}$ for the North East Scotland rivers, Don and Dee (Edwards, 1990). These values were consistent with those reported for other British catchments with an average of 24 $kgha^{-1}\ a^{-1}$ (Webb and Walling, 1985).

3.4 Nitrate behaviour in streamflow draining agricultural catchments.

3.4.1 Temporal and spatial variation

The release of nitrate nitrogen from soils in the United Kingdom characteristically shows two distinct flushes, in the months of May and June and in October, which are thought to be related to the mineralisation of organically held nitrogen in warm wet conditions (Willcox and Townsend, 1964).

An intra-annual cycle of nitrate concentration is evident for many rivers; since the highest nitrate concentrations occur in winter, also the time of maximum discharge, nitrate loads peak strongly in winter too. The variation can be characterised by the fitting of simple harmonic curves to data collected over several years at a sampling station. The amplitude of the fitted first-order harmonic ranged from 0.1 to 7.2 mg l^{-1} NO_3-N. It was also noted that second-order harmonic often fits the data better, showing that assymmetrical nitrate regime is most common: peak concentration between December and March followed by slow decline through the summer with a rapid rise during the autumn. Nitrate loads also showed a dominant peak in December-March period; earlier in the west and later in the east because of the strong dependence of load on flow regime (Burt and Haycock, 1992).

Upland UK nitrate concentrations were generally found to be below 2.5 mg NO_3-N L^{-1} compared to lowland regions where concentrations are higher. The highest nitrate levels tend to be found in the east. Nitrate loads of 15 - 30 kg ha^{-1} a^{-1} are typical of large parts of central England and loads are found to be much lower in Wales and Scotland . Figure 3.3 shows the spatial variation of nitrate concentrations and loadings in the UK (Burt *et al.*, 1993).

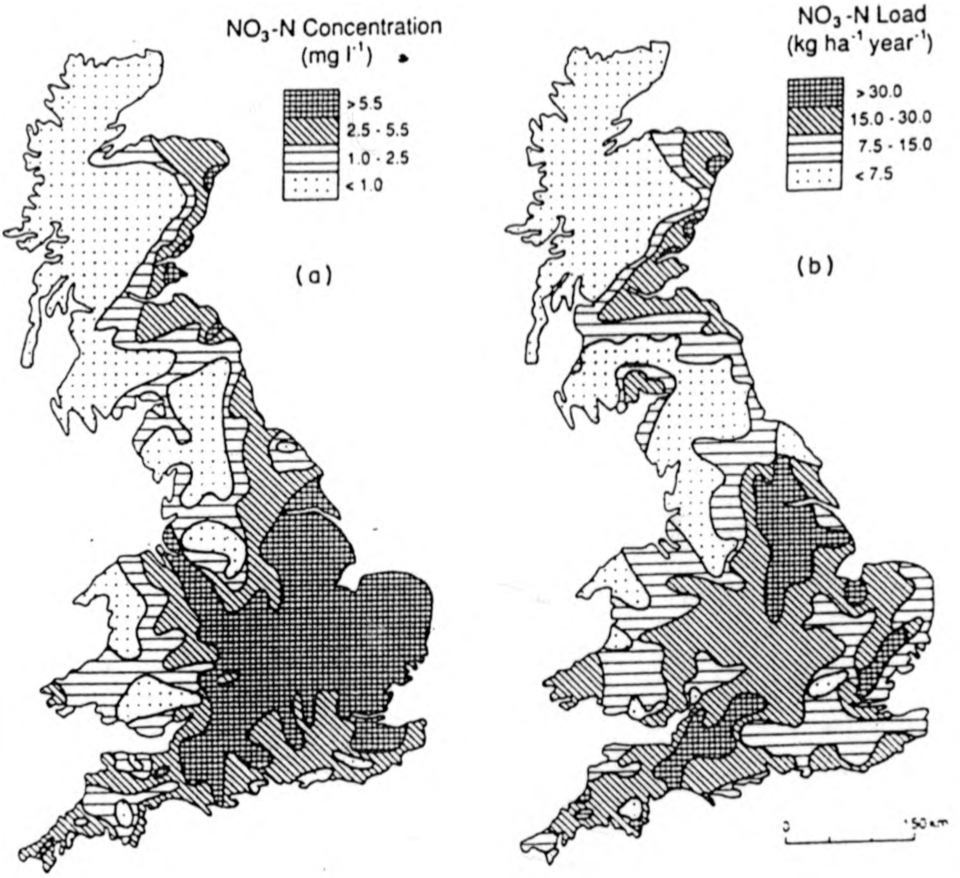
A number of studies examined nitrate losses in small drainage basins of less than 10 $km^{2.}$ At this scale it may be possible to aggregate the results of plot studies, to relate them to patterns of nitrate transport at the catchment outlet, and to ascribe the pattern of nitrate loss within the basin to the distribution of land use and topography . In a study of the spatial pattern of runoff and nitrate loss within the 94 ha Slapton Wood catchment, it was found that the largest nitrate losses and the highest concentrations were found in mainly arable headwaters. The results at Slapton Wood suggested that in terms of nitrate leaching, it is not just near-stream land which may be sensitive, valley sides slopes and even more distant fields beyond, particularly those which drain through hillslope hollow, may also require careful management (Burt *et al.*, 1993)

3.4.2 Concentration-Flow Relationships

Solutes generally respond in one of two ways to an increase in stream discharge during individual storm events. The majority of ions, for example Ca^{2+}, Mg^{2+} and Cl^{-}, decrease in concentration with increasing discharge, whereas others, for example K^{+}, increase in concentration with increasing discharge . Direct relationships between discharge and solute concentration are frequently complicated by hysteresis effects, which in large streams may be related to differences between water and flood wave movement downstream, or channel routing and in small catchment may be reacted to antecendent

Figure 3.3

Spatial patterns in (a) nitrate concentrations, and (b) nitrate loads in British rivers.



(Source: Burt et. al., 1993)

catchment conditions and seasonal effects. Storm period NO_3-N behaviour at the main gauging stations exhibited a complex pattern of response which varied throughout the year (Foster, 1981).

Generally, concentrations were found to increase significantly with increased water flow, but for at least part of the survey period, high flows were associated with reduced nitrate concentrations. Detailed examination of 600 storm events between 1975 and 1983 revealed that contrary to the general positive relationship between concentration and flow, dilution responses were typical behaviour in some storm events. Dilution responses accounted for 75 % of the events monitored and there was a clear seasonal distribution in the two contrasting types of storm period nitrate behaviour, with the majority of dilution responses in the months of October-April while concentration effects were more typical from May-September. This is directly related to soil moisture content which is saturated in winter and deficient in summer (DOE, 1986).

NO_3-N levels in River Dart were associated with a positive rating relationship which generally reflects the occurence of high concentrations at times of greater discharge during the winter period. The occurence of statistically significant concentration-flow ratings for NO_3-N does not necessarily indicate a causal relationship, since nitrogen losses in drainage are a complex function of hydrological, pedological, and biological processes, and NO_3-N concentrations may exhibit correlations with other variables, including soil moisture and temperature, which are as strong as those found with discharge. The relationship could be taken to indicate the importance of water movement through the soil to NO_3-N leaching. All three major storm hydrographs in the winter of 1989/90 were associated with increases in nitrate concentration, especially on the falling limbs. This strongly suggests that shallow groundwater is able to make a rapid contribution to the stream. Given high discharge and concentrations at these times, it is not surprising that storm events have been identified as the dominant periods for nitrate transport (Webb and Walling, 1985).

CHAPTER 4

Review of Models for Estimating Flow and Nitrate Emissions from Agricultural Lands

4.1 Introduction

In the mathematical sense the word model describes a system of assumptions, equations, and procedures intended to describe the performance of a prototype system (Linsley *et al.*, 1982) while simulating is the process of making a model of a real world and then performing experiments on the model. The purpose of simulation is to understand the behaviour of the system, in which one may wish simply to predict its future behaviour or to evaluate alternate means of operating or controlling the system.

A simulation involves a description of the way in which a system changes over some period of time. A quantitative representation of the system at some instant of time is called the state of the system. Thus, the heart of any simulation model is a description of the way in which values of state variables of the system change with time. Continuous models examine the rate of change of state variables with time. The rules governing the change of state may be either deterministic or probablistic. In a deterministic model, the new state may be completely deduced from the old state by applying well-defined rules. In a probabilistic model, a variety of new state are all possible, the one which actually occurs is subject to some predetermined laws of chance.

Mathematical and simulation modelling may have quite diverse objectives: testing existing or new concepts and hypothesis, obtaining greater conceptual understanding of complex problems, obtaining quantitative evaluation or prediction of observed phenomena, identifying research need, and helping develop guidelines for best management practices (Tanji, 1982).

Models can assist in explaining natural phenomena and under some conditions can assist in making predictions in a deterministic or probabilistic sense. In water quality, they can assist in predicting the influence of one or a combination of factors on nutrient loadings. Another advantage of modelling is the possibility of determining the sensitivity of different parameters to the end result. It may be that high accuracy of some data is not needed because the end results are not sensitive to the precise value of one variable. This helps in deciding whether better data collection is needed or not (Haan *et al.*, 1982).

This chapter reviews existing models with respect to nitrate transport and runoff in agricultural catchments.

4.2 Types of Models

Several different criteria have been used to develop a classification system for models. Anderson and Burt (1985) classified models into three general classes:(1) Black-box or empirical models (2) conceptual models, and (3) deterministic models. Ward and Elliot (1995), on the other hand, classifies model as empirical, deterministic, or stochatic.

Empirical or black box models are developed by analyzing a large set of data, and developing statistical relationships between the inputs and the outputs. These models contain no physically based transfer function to relate input to output. Such models depend upon establishing a statistical correspondence between input and output. Within the range of data analysed, black-box models may be highly successful. Statistical models, for example, may provide insight into the dynamics of the system, such as the dependence, or independence, of the levels of nitrate on flow and temperature in the river (Anderson and Burt, 1985).

Nevertheless, statistical or black-box models have a few drawbacks. These models can be applied only under strictly controlled conditions, suffer from a number of deficiencies, and are most profitably employed only when the 'laws' determining system form and process are poorly understood (Hugget, 1993). Empirical models are also not easily transferable between geographic regions (Ward and Elliot, 1995). The conventional models are unable to handle events producing random shock to the system such as that caused by fertiliser application and extreme hydrological conditions. Furthermore statistical analysis of the output data reveals little of physical significance for understanding the process mechanisms resulting in the generation of these outputs (Foster, 1981).

Conceptual models occupy an intermediate between the deterministic approach and empirical black-box analysis. These models employ a series of functions which are considered to describe the catchment processes involved. The algorithms are usually simplified by use of empirical relations. Such models are formulated on the basis of a simple arrangement of a relatively small number of components, each of which is a simplification of one process element in the system being modelled. The general form of this type of model is $S = K.Q^n$ where K and n represent constants. The non-linear form of such models reflects the thresholds present in hydrological systems which cannot be adequately incorporated within a linear model (Anderson and Burt, 1985).

Deterministic models, sometimes described as theoretical or process-based models, mathematically describe the processes (biological, chemical or physical) involved. As the processes are independent of geographic variations, deterministic models can be applied to a wider range of conditions. For the purpose of this thesis, conceptual models are discussed as a subset of deterministic models. Stochastic models seek to identify statistical preobabilities of a certain event, like rainfall, and to predict the probability of a given outcome. This type of model will not be explored further in this dissertation.

Further to the above classification, hydrological modelling is also differentiated by the manner in which parameters or input values are handled. Lumping replaces a spatially distributed process by one that is parameterized at a larger scale as a watershed. By spatially averaging certain parameters, a lumped process model results. Lumped models treat a whole catchment as if it were homogeneous in character and subject to the same environmental conditions. Distributed models divided the catchment into a large number of small subareas, simulate each separately, and combine them to obtain catchment response. Distributed proces model treat the individual input parameters directly without lumping except at the computational element level. Such models avoid the errors caused by spatial averaging or lumping processes which may misrepresent the physical process (Vieux ,1991).

Another classification criteria for models is the role of the time factor, models can also be classed as dynamic (continuous) or static (storm event model). Dynamic models require differential equations with time as an independent variable and thus can show the time variability of outputs. In hydrology, dynamic models are use to generate outflow hydrographs over long periods of time (Haan *et al.*, 1982). These models are useful for simulation of long flow records for use in design and evaluating the impact of changes in a catchment on stream flow (Linsley *et al.*, 1982). This thesis will explore this type of model in understanding catchment responses. Static models include various empirical equations in which time is not an independent variable. Event models designed to simulate a single event such as the hydrograph of a single storm is an example of a static model.

4.3 A review of models used for simulating runoff and nitrate transport in catchments.

The use of models in understanding hydrological and nitrate transport processes are discussed below.

4.3.1 Empirical Models

Most modelling studies on nitrate pollution in surface water fall into this group. One group of models aims to determine the underlying trend with some models incorporating information on current and previous flow. A model which relates nitrate concentration on a given day to functions of current and historical flow, seasonality and long term trend explains approximately 80 % of the variance when fitted to data for the Nene and Welland for 1968-1982 and to data for the Stour for 1965 - 1980. The study indicated that nitrate concentrations in the Nene, Welland and Stour have been increasing at 1.11, 1.24 and 1.15 mg l^{-1} a^{-1} respectively (DOE, 1986)

The relationship between nitrate concentrations and flow is also examined for the River Dart using hourly concentrations for 1975-1983. Statistical analysis identified strong positive correlation between nitrate concentrations and instantaneous flow using these hourly values, and 60 % of the variance could be explained by a relationship between these values. Of the total nitrate load transported in the study period, 90 % was accounted for in only 37 % of the period (DOE, 1986).

One of the concentration-flow models used the general equation:

$$\log C = a + b\log F \qquad \text{Eqn. 1}$$

where C = concentration (mgl^{-1}), and F = instantaneous flow (m^3s^{-1}) and a and b are constants. This equation provided the best model for concentration-flow relationships and allowed direct comparison with relationships established by other workers in England and Wales. The relationship between NO_3-N and flow varied from site to site but generally concentrations increased significantly with increased flow although diluting effects were detected in some stations (Foster, 1981).

Another form of linear regression model frequently used to describe solute response is the bivariate model which relates ionic concentrations to stream discharge and generally takes the form

$$C_i = aQ^{-b} \qquad \text{Eqn. 2}$$

where C_i is the concentration of an individual ion (i), Q is discharge and a and b are empirically derived constants. This equation plots as a straight line on double logarithmic paper. The model was applied to data collected at intervals of six hours from the main gauging station in East Devon, Exeter, from September 1974 to January 1976. The model explained in excess of 40% of the variance in nitrate. Nevertheless, this model was much poorer when applied to nitrate as compared to Mg^{++}. An improved fit was obtained by modifying equation 2 to produce a polynomial relationship at the cubic level where $C = aQ^b + Q^{2c} + Q^{3d}$ where C is concentration and Q is discharge. Levels of explained variance for the cubic model reached 54.1 %, an increase of 12.6 % over the linear relationship (Table 4.1).

The nitrate model demonstrates a complex response compared to magnesium, where the highest NO_3 concentrations appear to be associated with discharges of between 10 and

Table 4.1

Polynomial rating curve characteristics

Solute	Model	a	b	c	d	R^2
Mg^{2+}	Linear	1.203	-0.210	-	-	87.7
	Cubic	1.151	-0.014	-0.134	0.014	94.0
NO_3-N	Linear	0.534	0.159	-	-	41.5
	Cubic	0.469	0.364	-0.089	-0.015	54.1

(Source: Foster, 1981)

100 ls^{-1} (Figure 4.1). This association suggests that high nitrate levels may be associated with the throughflow component of storm runoff (Foster, 1981).

Storm period response is also modelled using Equation 2. Storm period NO_3-N behaviour exhibited at the main gauging station in East Devon exhibited a complex pattern of response which varied throughout the year. Results of the Student's t test analysis indicated that NO_3-N behaviour were divided into summer and winter response since the responses were significantly different. The exponent was positive in summer and negative in winter, indicating a reversal of response to increasing discharge. The value for a and b are 0.5720 and 0.1068 with R^2 of 4.42 for summer and 0.776 and -0.0812 with R^2 of 8.42 for the winter season. Levels of explained variance for both models were below 10 %, which emphasises the indeterminate nature of NO_3-N levels during storm events (Foster, 1981).

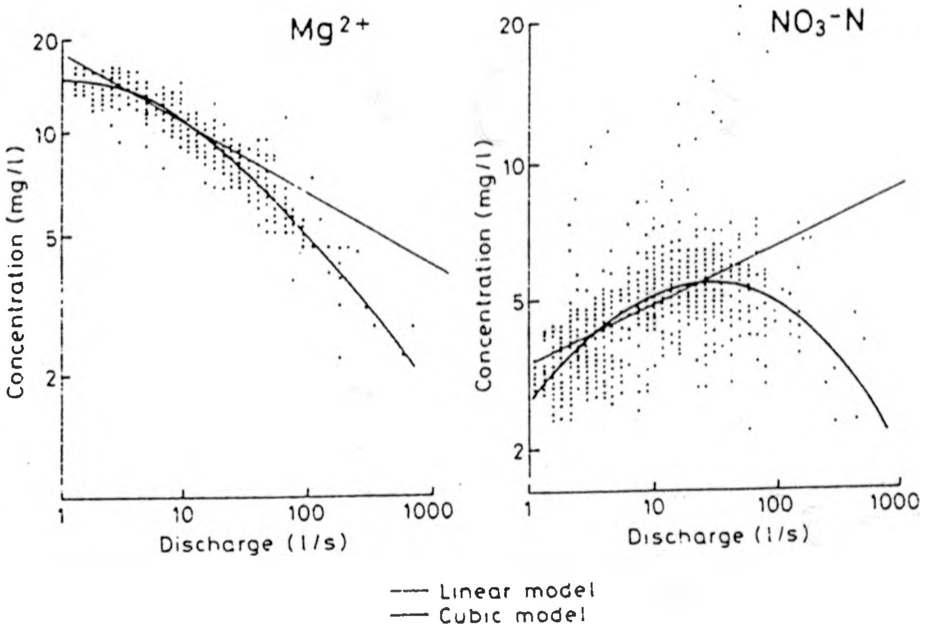
Another form of regression model used to model nitrate is the multivariate models. One study uses SMD (Soil Moisture Deficit), API (Antecedent Precipitation Index), and the Sine Index in addition to discharge as variables to simulate nitrate response. The sine index takes the form of;

$$\text{Sine Index (radians)} = \text{Sine } 2\ D/365 \qquad \text{Eqn. 3}$$

where D = day of year from January 1 st. The multivariate model explained less than 30 % of the nitrate variation at the woodland stream in East Devon. Results of multivariate models for storm period response indicated that levels of explained variance were

Figure 4.1

Solute versus discharge relationship



(Source: Foster, 1981)

higher for summer (74.1 %) than winter (24.0 %) data sets. A time series approach also carried out on nitrate in the East Devon catchment explained less than 55 % of the nitrate variability (Foster, 1981).

Another black box model frequently used is the screening model or export coefficient models. These models are simple tools used to identify problem areas in a large basin. These models usually rely on assignment of unit loads of pollution to the various lands within the watershed,sometimes referred to as loading functions. A unit loading is a simple value or function expressing pollution generation per unit area and unit time for each typical land use. The loads are typically expressed in kilograms per hectare-year. Here, nutrient losses from catchments were predicted, first by compiling a detail enumeration of all possible sources, and then, by using appropriate coefficients, based on literature values, calculating losses of nutrients to surface waters. The model is then normally calibrated by direct monitoring for a limited period, or validated by other means such as comparison with data from similar areas (Johnes and O'Sullivan, 1989). Despite its questionable accuracy, the concept of relating pollution loading to land use categories have found wide application in area wide pollution abatement efforts and planning. The concept provides a simple mechanism and quick answers to pollution problems of large areas where more complicated efforts would fail because of the enormous amounts of information required. The land use/pollutant loading is also compatible with so called "overview modelling", whereby unit loadings are combined with information on land use, soil distribution, and other characteristics to yield watershed loadings, or to identify areas producing or causing the highest amount of nonpoint pollution. The loading concept is applicable in most cases to long term estimates such as average annual loading figures (Giorgini and Zingales, 1986). The export coefficient approach used for predicting nitrate losses from Slapton catchment is;

$$L = A \times E + I + a \qquad \text{Eqn. 4}$$

where L = loss of element (kg ha^{-1} a^{-1})

A = area of watershed (ha)

I = input from precipitation (kg ha^{-1} a^{-1})

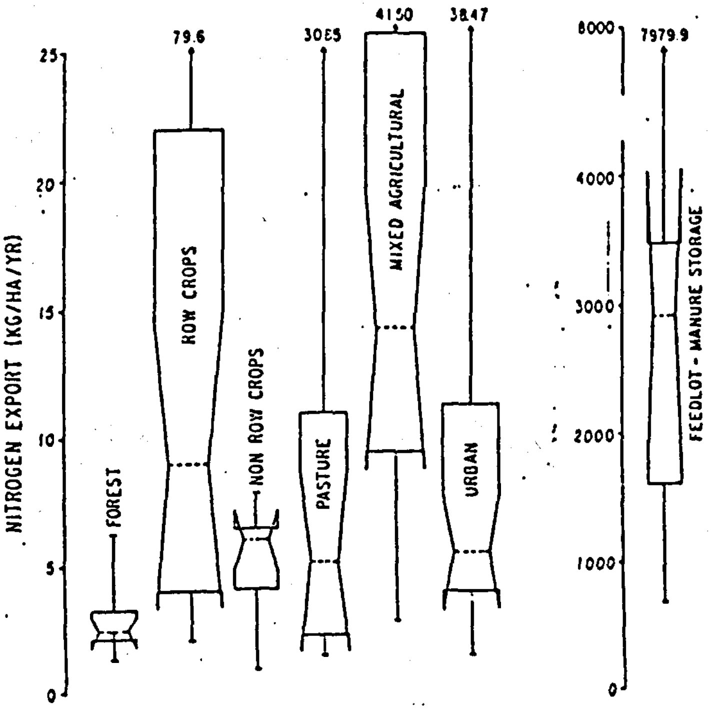
a = artificial inputs such as sewage treatment works (kg a^{-1}).

The predicted nitrate loss of 12.3 kg ha^{-1} a^{-1} (Johnes and O'Sullivan, 1989) is low compared to 26.17 kg$ha^{-1}a^{-1}$ reported by Troake and Walling (1973) and 33.75 kg ha^{-1} a^{-1} by Burt and Arkell (1987).

Beaulac and Reckhow (1982) examined the use of land use - nutrient export relationships in comparing nutrient from forest, agricultural, and urban land use. Land use dominated by agricultural activities demonstrated significantly higher total nitrogen export than undisturbed forested watershed. Nevertheless, nutrient ouput from pasture and grazing activities is not significantly different than output from undisturbed forests (Figure 4.2).

Figure 4.2

Box plots of nitrogen export coefficients from various land uses



(Source: Beaulac and Reckhow, 1982)

Nitrate loading coefficients also varies between soil type, management practices, and crop type. It was indicated that sandy/gravel soils generally demonstate low nutrient export via runoff because it generally cause downward flow of water to the ground water. Conversely, clay soils (clay loams, silt loams) commonly displays high nutrient export via runoff because of its low infiltration capacity. Organic soils also displays high nutrient export capability because of its low infiltration capacity and high nutrient content. Nevertheless, for water resources management purposes, the use of nutrient loading estimates for predicting present and future water quality conditions with changing land use is highly subjective. To reduce application uncertainty, the user or analyst of these coefficients must be familiar with the biogeochemical process which influences nutrient flux (Beaulac and Reckhow, 1982).

Another model used to estimate nitrate losses is the input-output model which look at nutrient output through different routes.

$$\begin{array}{ccc} \text{Input} & & \text{Output} \\ N_p + N_f + N_m & = & N_{pl} + N_g + N_i + N_l + N_r + dN \end{array} \qquad \text{Eqn. 5}$$

where the subscripts for N indicate:

p: precipitation; f:fertiliser and manure; m: mineralisation; pl: plant uptake; g: gaseous loss by denitrification; i: immobilisation; l: leaching loss; r: runoff, and d: increase in the soil (Wild and Cameron, 1980).

4.3.2. Conceptual models

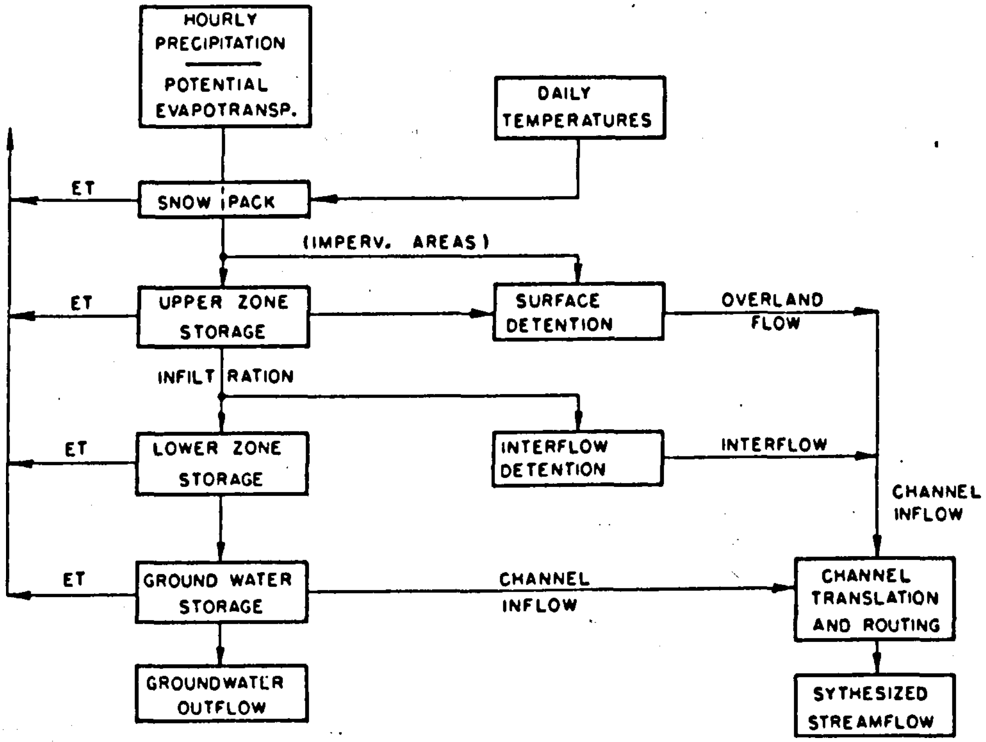
A number of conceptual models are available for the simulation of catchment processes. One of the earlier one is the Stanford Watershed Model (Crawford and Linsley, 1966). In the Stanford Model, the various hydrological processees are represented mathematically as flows and storages (Figure 4.3). In general, each flow is an outflow rom a storage, usually expressed as a function of the current storage amount and the physical characteristics of the subsystem. Thus, the overall model is physically based, although many of the flows and storages are represented in a simplified or conceptual manner (Haan *et al.*, 1982). Another conceptual model that has been use is the TOPMODEL. If the parameters of a conceptual model are physically based, as in TOPMODEL, the model is capable of coping with changes in catchment characteristic. Such changes cannot be accomodated into a black-box model with any confidence. In Chapter 5 a full description of TOPMODEL is presented and its capability in predicting water flow and its potential as a framework for modelling nitrate will be assessed.

4.3.3 Deterministic or Process-Based Models

Deterministic or process-based models are formed on complex physical theory. By offering a totally physically based approach, such models offer the ability to predict the effect of catchment changes. This is very useful where resource management is involved. An important contribution of deterministic models is their value in helping to improve our understanding of hydrological systems, regardless of the predictive success of such models relative to simpler models (Anderson and Burt, 1985).

Figure 4.3

General Structure of Stanford Watershed Model IV



(Source: Haan et al., 1982)

Process-based models vary widely in scope. Some were designed to simulate N losses from larger-scale systems, such as watersheds and irrigation projects (Frere *et al.*, 1975; Donigian & Crawford, 1976). Most of these models, however, simulate N and water fluxes in small scale systems such as field plot and lysimeters (such as Addiscott and Whitmore, 1987; and Bergstrom and Jarvis, 1991). FORTRAN language is the most prevalent programming language used. The physical processes usually modelled in the soil-plant-water system are infiltration, redistribution, evaporation, transpiration, and seepage of soil water. Tanji (1982) provides a complete listing of the development of dynamic soil nitrogen simulation since 1972. Since this study focuses on large scale modelling, the individual plot scale processes will not be described in detail.

Conceptually, the nitrate concentration in the soil profile will depend on the amount of nitrate in the soil as a result of input by mineralisation of soil organic matter, fertiliser, animal and plant residue, and nitrate contribution from the rainfall. Nitrate is lost from the root zone by plant uptake, leaching, and denitrification (Kolenbrander, 1981). The amount of nitrate leached is a function of the amount of water percolated out of the root zone estimated by the hydrology component and the concentration of nitrate in the soil water. Large scale process based models usually use the hydrological model as the basic foundation. Several efforts have been made toward mathematically modeling the processes of chemical transport from land surfaces, in conjuction with existing models for water and sediment transport. Amongst them are Crawford and Donigian, 1973; Frere *et al.*, 1975; Donigian and Crawford, 1976; Knisel, 1980; Beasley *et al.*, 1980; Young *et al.*, 1989; and Arnold *et al.*, 1990. Some of these models will be discussed further in this chapter.

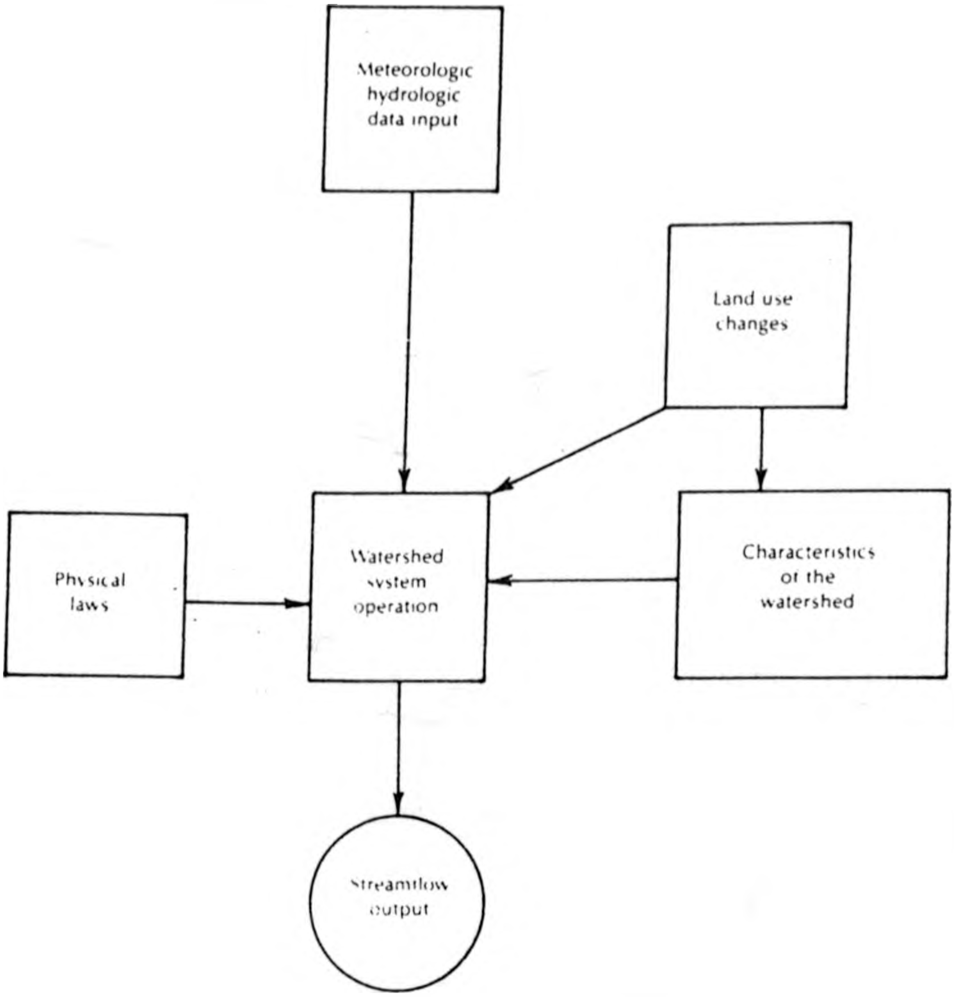
The understanding of the hydrological cycle and water movement is crucial to understanding nitrate movement (Shen, 1979). The systems approach for modelling the hydrologic response of watersheds is shown in Figure 4.4 which shows the basic components of all hydrological models. Model structure relates to what part or parts of the hydrological cycle are included and their level of abstraction in the model. Four levels of abstraction can be identified: (a) individual processes, (b) component models, (c) integrated watershed models, and (d) global watershed models. These levels of abstraction are described schematically in Figure 4.5. An individual process model is a mathematical description of one of the physical processes involved in the hydrological cycle, for example, models of evaporation from a free water surface. Component models as illustrated in Figure 4.5 (b) include linked models of individual processes with a component operator that apportions the flow of water in the proper order. As illustrated in Figure 4.5 (c), an integrated model consists of a set of linked computer models along with an operator that apportions the flow of water to the individual components in the proper order (Haan *et al.*, 1991).

The Agricultural Research Service, USA, developed the Agricultural Chemical Transport Model (ACTMO) for storm events in agricultural watersheds. The model consists of hydrological, sediment, and chemical transport simulation. The nitrogen simulation considers mineralisation of organic nitrogen to nitrate, plant uptake of nitrate, and nitrate removal by overland flow and leaching (Frere *et al.*, 1975).

Among the nitrate processes modelled in ACTMO is mineralisation and plant uptake. Mineralisation is modelled by a first-order rate equation:

Figure 4.4

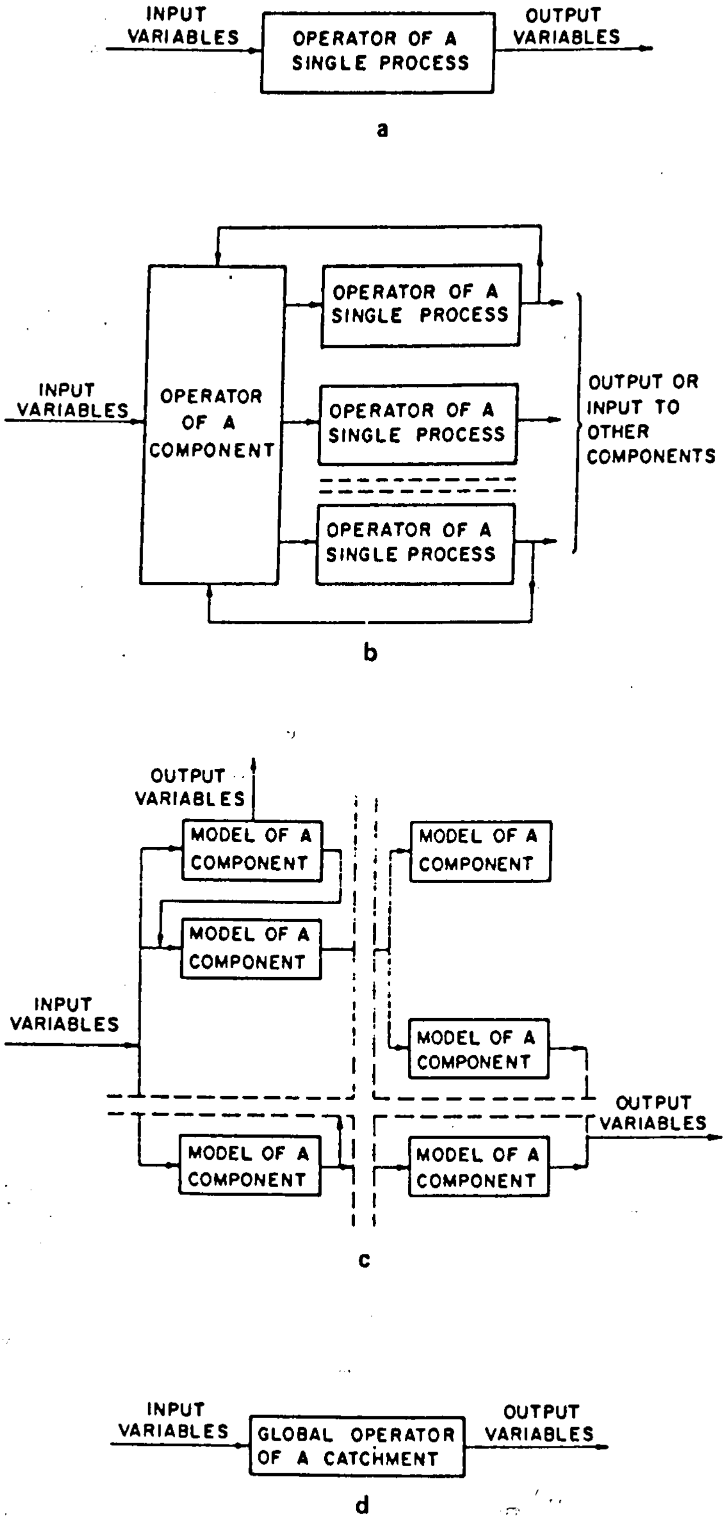
Systems approach for modelling the hydrologic response of watersheds.



(Source:Brooks et al., 1991)

Figure 4.5

Structural diagrams of hydrological models



(Source: Haan et al., 1982)

$$N = N_o[1 - \exp(MC \times t)] \qquad \text{Eqn.6}$$

where N is the amount of nitrate produced from the potential mineralisable nitrogen, N_o, in time, t. The rate constant, MC, is sensitive to temperature and moisture (Frere *et al.*, 1975).

The uptake of nitrate by the crop is the mechanism of greatest nitrate loss during the time when plants are actively growing. Nitrate uptake increases with the increasing concentration of nitrate in solution. Mass flow is the predominant mechanism for moving nitrate through the soil to the plant root. Evapotranspiration is also related to the amount of adsorbing root surface and reflects the growth rates of the plant. There is little growth, ET, or nitrate uptake under cold or drought conditions. Based on these considerations ACTMO modelled nitrate taken up by plant with the following relationship:

$$UP = AU \times ET\ (SW\ X\ WD) \qquad \text{Eqn. 7}$$

where AU is the pounds of nitrate per acre available for uptake (the initial content plus half the mineralised amount); ET is the evapotranspiration from each soil layer weighted for the distribution of nitrate within layers and the product of SW and WD gives the soil layer in inches (Knisel *et al.*, 1975). Generally, plants remove 40 to 80 percent of the nitrate and ammonium supplied by fertiliser or mineralisation. The uptake varies with plant species and with growth as controlled by the environment.

ACTMO is an event scale model and has since been upgraded and incorporated into a field scale hydrological and agricultural runoff model called CREAMS (Chemical, Runoff, and Erosion from Agricultural Management System; Knisel, 1980). CREAMS has been widely used for evaluating runoff, sediment, pesticide, and nutrient losses in runoff for different management practices. CREAMS is composed of three components: hydrology, erosion, and chemistry. CREAMS was applied to a field-sized watershed planted to cotton in the Limestone Valley region of northern Alabama, USA. The nutrient submodel based on the simulated runoff and sediment underpredicted N loss by about 60-70 % (Yoon *et al.*, 1992). CREAMS nutrient submodel was tested with measured concentrations of N and P in subsurface drain flow on a potato field and the results indicated that the model overpredicted N concentration by 32 % (Kenneth *et al.*, 1990). Since CREAMS is a field scale model and estimates nitrate mainly in surface runoff and leaching; it is thus inadequate to model catchment scale processes.

One of the simpler hydrological models available to estimate nitrate yield is the SPNM (Soil, Phosphorus, and Nitrogen Model), for predicting sediment, phosphorus, and nitrogen yields from agricultural basins. In this model NO_3 yield in surface layer is predicted by mixing total storm runoff with the water in the top 25 mm of soil. Thus nitrate concentration in the surface runoff is estimated using the equation

$$c_{QS} = \frac{(R)(c_R) + (ST)(c_{ST})}{R + ST} \qquad \text{Eqn. 8}$$

where R is the amount of rainfall in a storm, ST is the amount of water in the top 25 mm of soil, c is the NO_3 concentration , and subscripts QS, R and ST indicate surface ruonff, rainfall, and storage, respectively. The surface runoff NO_3 yield is the product of runoff and concentration.

$$YNO3_S = (c_{QS})(Q_S) \qquad \text{Eqn. 9}$$

where $YNO3_S$ is the NO_3 yield in surface runoff and Q_S is the volume of surface runoff. Subsurface NO_3 yield is predicted with a similar approach. However, the concentration is determined by considering the entire root zone rather than the top 25 mm. The concentration equation is

$$c_{QSS} = \frac{(R-Q_S)(c_R) + (SR)(c_{SR})}{R - Q_S + SR} \qquad \text{Eqn. 10}$$

where SR is the amount of water in the root zone and subscripts QSS and SR refer to subsurface flow and root zone storage, respectively. Subsurface NO_3 yield is the product of c_{QSS} and Q_{SS}, and total NO_3 yield is the sum of the surface and subsurface components. Once NO_3 enters a stream it is considered a conservative material for the duration of n individual runoff event. Thus, NO_3 routing is simply a matter of adding the yields from all sources in a routing reach. Input requirements are storage location number, concentration of organic nitrogen in the soil, NO_3 concentrations in the top 25 mm of soil and in the root zone, water content of the top 25 mm of soil and the root zone in mm mm^{-1}, root zone depth in mm, and the subsurface flow volume in mm.

SPNM was tested on Little Elm Creek basin near Aubrey, Texas. The model is shown to give realistic results when tested for average annual nitrate yields although the nutrient data was insufficient to determine the effectiveness of the model (Williams, 1980). This model has since been updated and modified into the SWRRBWQ model.

AGNPS (Young *et al.*, 1989) is a single-storm event based distributed model developed simulating non-point source pollution in agricultural watersheds. It simulates runoff, sediment, and nutrient yields in surface runoff from primarily agricultural watersheds. This model uses a distributed parameter approach to quantify a watershed by dividing the area into square grid data units within geographic areas. Runoff characteristics and transport processes of sediment and nutrients are simulated for each cell and routed to the outlet. Thus, flow, erosion, and chemical movement at any point in the watershed may be examined or nutrient loadings for the entire watershed can be estimated. Upland sources contributing to a potential problem, can be identified and locations can be prioritized for remedial action to improve water quality most efficiently. AGNPS also calculates nitrate as a surface runoff phenomenon which would have underestimated nitrate transport through subsurface route.

EPIC (Erosion Productivity Impact Calculator), is a crop growth model developed by the United States Department of Agriculture (USDA) in the early 1980s (Williams *et al.*, 1983). In this model crop growth is modelled as potential growth constrained by stress factors with phenological development determined as a function of accumulated heat units. Nutrient and water uptake are accounted for explicitly and are linked with soil and hydrological components. EPIC has been used to estimate nitrate emissions in the Tyne catchment, northern England, by crop and land class. EPIC was run for each climate-soil combination over the seasons 1985/1986 to 1988/1989 for the major crops within the Tyne catchment. Estimated annual average nitrate emissions through leaching and runoff were produced for each land class. The result of the study showed that leaching is typically higher in wetter areas and on better drained soils, while runoff and subsurface flow increase as soil permeability decreases. Of the arable crop types, winter wheat consistently yields the highest emissions and oilseed rape the lowest. However the study did not compare the estimated nitrate emissions with observed values for the study area due to inadequate storm response data (Allanson *et al.*, 1993)

A model called SWRRBWQ (Simulator for Water Resources in Rural Basins) is a continuous, distributed parameter model developed for simulating hydrological and related processes in rural basins (Arnold *et al.*, 1992). SWRRBWQ uses the daily rainfall hydrology model of CREAMS and the EPIC crop growth model and modified them for application to large, complex, rural basins. The major changes include the addition of these components: (a) simultaneous computations on several sub-basins to predict basin water yield; (b) return flow; (c) reservoir storage added (d) weather simulation (rainfall, solar radiation, and temperatures), and (e) crop growth. Recently SWRRBWQ has been expanded to allow simulation of nutrient loadings to rivers. In this thesis the performance of SWRRBWQ model in predicting water yield and nitrate loadings using data from the Ythan Catchment will be evaluated. The full detail of the model will be described in Chapter 6.

4.3.4 Spatially distributed models

Models which represent systems as a set of interacting components and which take explicit account of the spatial variations in state variables, may be called spatial models. They are so called because they take on board the location and spatial configuration of one or several variables among system components. Spatial models use the location and configuration of system components in projecting change, and predict values of state variables at various points within a system. In general, the space occupied by environmental systems may be studied in one, two, or three dimensions (Huggett, 1993).

Geographic Information System (GIS) technology is recognized to be an efficient tool for spatial modelisation and visualization in order to manage nonpoint agricultural source pollution. In recent years GIS have played a major role in natural resources modelling and proved to be an effective tool in simulating non-point source pollution. A GIS has four primary functions: data input; data storage in a structured, relational data base; analysis and manipulation of the data; and data display. Therefore, a GIS is capable of manipulating both spatially-referenced input and output parameters of a transport model simulating solute loading of non-point source pollutants to groundwater (Burrough, 1992).

GIS were successfully linked to distributed parameter single event non-point source pollution models like AGNPS and ANSWERS. Such links proved effective and efficient to collect, visualize and analyse input and output data of pollution models. Some of the linked models are described below.

GRASS is a multipurpose GIS model that have been frequently used in resource management. The link between GRASS and AGNPS were used to assess phosphorus loadings from an agricultural watersheds (Srinivasan and Arnold, 1994). Integration of AGNPS and GRASS was applied to the Cass River watershed to evaluate the effects of agricultural management practices on water quality. The study demonstrated the integration of GIS and a water quality model for agricultural non-point source pollution management. Eventhough the simulated results were not verified, it proved that the integration of GIS and water quality model could be used to identify critical areas which will then be used as a target area for pollution control (He *et al.*, 1993).
Another GIS model called VirGis is coupled with a phosphorus yield model and tested on the Nomini Creek watershed, USA to identify critical nonpoint pollution source areas. The watershed was divided into discrete land cells having hydrologically homogeneous properties. Phosphorus transport was calculated on the basis of average P content in the surface layer, the sediment yield, and the P enrichment ratio. Predicted P loadings in the Nomini Creek watershed were displayed on a cell-by-cell basis for delineation of critical areas of NPS pollution from the water quality perspective. In the case of phosphorus critical areas were defined as those land areas exceeding 1.12 kg $ha^{-1}yr^{-1}$. In recent years GIS have played a major role in natural resources modeling and proved to be an effective tool in using NPS models. The predicted loading was 1.25 kg $ha^{-1}yr^{-1}$ which is higher than the established average value for agricultural lands (Tim *et al.*, 1992).

Although spatial models have become very popular in modelling environmental systems, this approach is not adopted here due to limited spatial information for model input specifically flow data which is only monitored at one station for the whole catchment.

CHAPTER 5

Modelling the Ythan River Flow Using TOPMODEL

5.1 Introduction

TOPMODEL (Beven and Kirkby, 1979) is a semi distributed, physical-based, variable contributing area model developed for use in predicting and understanding rainfall-runoff mechanisms. It provides a compromise between the complexity of fully distributed models and the relative crudity of lumped models. Heterogeneity in catchment topography is incorporated into TOPMODEL by means of a topographic index, ln (a/tan β), where a is the area draining a given grid square and β is the average value of the outflow slopes. The model was first described by Beven and Kirkby (1979) and has become an increasingly popular modelling approach (for example, Hornberger *et al.*, 1985; Wood *et al.*, 1988; Quinn and Beven, 1993; and Robson *et al.*, 1992).

In this chapter the theory and application of TOPMODEL to the Ythan catchment is described. To create a digital terrain model (DTM), a small area in the catchment is digitised and analysed for the distribution of ln (a/tan β) index, which is then formatted for TOPMODEL. TOPMODEL is then calibrated for the Ythan river using rainfall and runoff data for October 1990 - October 1991 and verified with the 1993 hydrological data. Hydrological year 1990-1991 and 1993 are chosen as the calibration period because it is the period of most interest as far as nitrate concentrations are concerned and these years also received average amount of rainfall as is evident in Table 2.4. The performance of TOPMODEL in simulating hydrological response of the Ythan river will be assessed.

5.2 TOPMODEL THEORY

A summary of the concepts and the basic equations upon which TOPMODEL is founded is given below. Full details of the derivaton of the equations and the rationale behind the model can be found in several papers (Beven and Kirkby, 1979; Beven and Wood, 1983). The full listings of TOPMODEL is given in Appendix 2.

The theory underlying TOPMODEL relates hydrological behaviour to the topography derived variable ln (a/tan β) where a is the area drained per unit contour, β is the local slope angle and ln ( ) is the Naperian logarithm. The model calculations are semi-distributed in the sense that they are carried out for increments of ln (a/tan β) for the catchment.

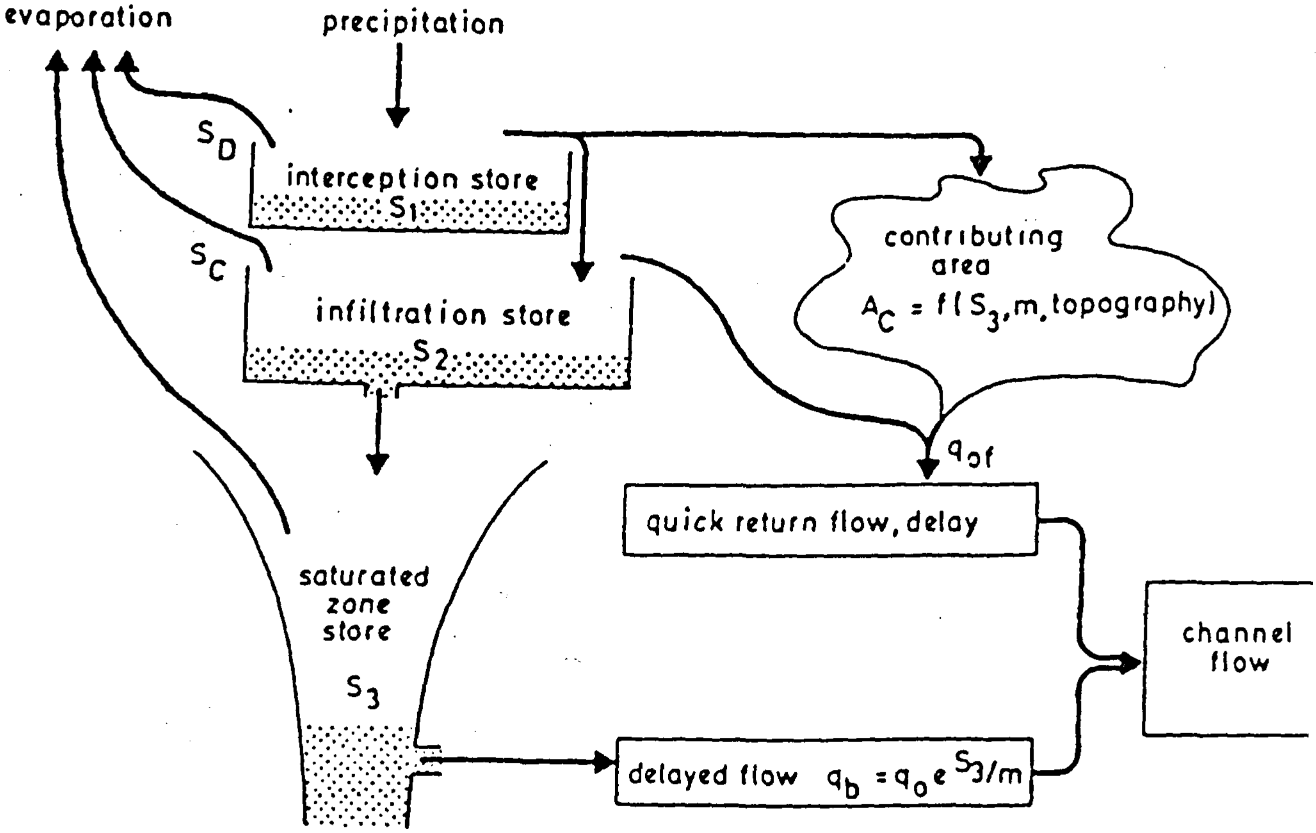
TOPMODEL conceptualizes the soil water storage as a sequence of storages with different properties. Figure 5.1 shows the schematic representations of TOPMODEL storage components. The components of TOPMODEL can be summarised as follows:

(a) A variable contributing area component related to subsurface soil water storage. Rain falling on the contributing area, A_c, will immediately become overland flow.

(b) A surface interception and depression store, S_I, with a maximum value S_D, which must be filled before infiltration from it can take place. Evaporation is allowed from this store at the estimated potential rate until it is empty.

Figure 5.1

A schematic representation of TOPMODEL storage elements



(Source: Beven and Kirkby, 1979)

(c) A near surface infiltration store S_2. A storage-based approach to infiltration is adopted, with a constant leakage rate allowed from this store to the exponential subsurface store S_3, in the area that is not considered saturated. Input to the store S_2 takes place (once the interception store S_1 is filled) at the rainfall rate i unless:

$$i > i_{max} = i_0 + b/S_2$$

In this case excess rainfall ($i-i_{max}$) is considered to reach the basin outlet by a surface route (infiltration excess overland flow). If under extreme conditions a maximum value of near surface storage, S_c, is exceeded, then again excess water is considered to reach the sub-basin outlet by a surface route (saturation excess overland flow). Further losses due to evaporation are allowed from the store at a decreasing rate depending on the level of S_2. Thus

$$e_a = e_r\, S_2/S_c$$

where e_r is the potential evapotranspiration remaining once the interception store S_1 is depleted, and e_a is the actual loss from the infiltration store.

(d) A non-linear subsurface saturated soil water store, which provides the delayed flow of Figure 5.1. The simplest form of the nonlinear storage is an exponential store for which

$$q_b = q_o \exp(S_3/m)$$

where q_b is the flow reaching the channel from the store, qo is the flow when $S_3=0$ and m is a constant. In the present model formulation this relationship is used such that S_3

is zero when the average soil water store (over the sub-basin) is just saturated. Positive values of S_3 therefore represent a moisture surplus and negative values a deficit (below average profile saturation).

The sequence of storage elements is assumed to represent the average response of the soil water in a homogeneous sub-basin unit. In this respect therefore, each subbasin is treated as a lumped system. It is further assumed that the dominant source of quick return or surface flow is an area of surface saturation, or variable contributing area, the extent of which varies with the average level of subsurface soil water storage as represented by the store S_3 (Beven and Kirkby, 1979).

To summarize, TOPMODEL conceptualizes two pathways and flow contributions to stream runoff:

a) Q_b - a base flow component which is a delayed flow component supplied by the subsurface saturated zones, and

b) Q_{of} - a quick flow component derived from rainfall landing on saturated contributing areas and by excess infiltration; thus causing rapid movement to the stream via macropore flow, overland flow or old-water displacement. It is distinguised from the subsurface saturated zone discharge because of the much more rapid response. The saturated contributing area will both expand and shrink during the course of a storm event.

5.3 Digital Terrain Model and Topographic Index Distribution Theory

The topographic index, ln (a/tan β), is derived from the digital terrain model (DTM) of the catchment. Index values were calculated by running the GRIDATBG program supplied with the TOPMODEL package. The area, a, represents the area of the catchment which drains through a given grid square. These areas are accumulated down the catchment until they reach the outlet. The slope, tan β, is an average value of the outflow slopes. The grid must be sufficiently fine to resolve important characteristic slope formations. Grid squares with the same index value are assumed to behave in a hydrologically similar manner. A high index value usually indicates a wet part of the catchment; this can arise from either a large contributing area (valley bottoms, convergent hollows) or from very flat slopes (bogs or plateaus). Areas with low index values are usually drier resulting from either steep slopes or a small contributing drainage area. As a result of this assumption, the catchment's topography may be summarised by the distribution of the index values (Robson *et al.*, 1993).

Ln (a/tan β) maps can provide information which can be used to characterise catchment hydrological and hydrochemical behaviour (Robson *et al.*, 1993). The maps can be used to help identify source areas which are potentially important in the control of chemical characteristics of streams. The maps are also valuable in assessing the likely hydrological impacts of land-use changes. In addition, the maps can be used in combination with the soil data, if available. It has been shown that spatial variation in the transmissivity, T_o, can be taken into account in a combined topographic-soil index, ln ($a/T_o\tan\beta$) (Beven, 1986; Robson *et al.*, 1993).

5.4 TOPMODEL Parameters

A summary of TOPMODEL parameters is presented in Table 5.1. These parameters make up the basic structure on which can be built a series of variations to adapt TOPMODEL to specific modelling purposes (Durand *et al.*, 1992). A physical interpretation of the decay parameter, m, is that it controls the effective depth of the catchment soil profile. This it does interactively with the parameter T_o, which defines the transmissivity of the profile when saturated to the surface. A larger value of m effectively increases the active depth of the soil profile. A small value, especially if coupled with a relatively high T_o, generates a shallow effective soil, but with a pronounced transmissivity decay. Effectively an increase in m will reduce the proportion of rainfall that reaches the channel by a surface route (Beven and Kirkby, 1979). The T_o and K_o are the soil hydrodynamic properties at the surface, where T_o is the lateral transmissivity and K_o is the vertical conductivity. SRMax is the maximum storage capacity of the soil and is considered to be equivalent to the field capacity of the soil. This parameter is used to control the simulation of evaporation (Quinn and Beven, 1993).

In summary, the inputs of the model are the rainfall and potential evapotranspiration, and the distribution of the topographical index derived from the DTM. The outputs are the local soil moisture deficits below saturation, the discharge, separated into two components (surface runoff on the saturated area, and the subsurface flow/groundwater discharge).

Table 5.1

Summary of TOPMODEL Parameters

Parameter	Unit	Description
M	m	Exponential storage parameter
To	ln m2/h	Mean catchment value of ln To. Lateral transmissivity
TD	hr	Unsaturated time delay per unit storage deficit
CHV	m/hr	Main channel routing velocity
RV	m/hr	Internal subcatchment routing velocity
SR Max	m	Root zone available water capacity
SRo	m	Initial root zone deficit
Qo	m/time step	Initial stream discharge

There are three or four critical parameters that most directly control model response. These are the saturated zone parameter, m; the saturated transmissivity, T_o; and the root zone parameter, SRMax, and in large catchments a channel routing velocity, chv (Centre for Research on Environmental Systems and Statistic, 1995).

5.5 Previous Works on TOPMODEL

One attraction of TOPMODEL is the possibility of making predictions of the split between surface and subsurface runoff production. Robson *et al.*, 1992, has used this possibility to examine the mix of soil waters entering the stream channel and they showed that the model results compared well with a two soil component mixing interpretation of chemical signatures within the streamwater. The relationship between topographic characteristics of a catchment and its chemical characteristics has been explored by Wollock *et al.*, 1989. Within catchments in the North Eastern United States and Wales they showed that the mean ln (a/tan β) distribution is strongly related with catchment acidification. TOPMODEL predictions of areas susceptible to surface saturation have also been used in Wales to decide areas for liming (Waters *et al.*, 1991).

Durand *et al.*, 1992, used TOPMODEL to model the hydrology of sub-mediterranean montane catchments (Mont-Lozere, France). Good fits were obtained for the validation period, with R^2 of 0.93 for Les Cloutasses and 0.94 for the La Sapine catchments. Their results indicate that TOPMODEL tends to overestimate light showers and underestimate major peak flows which he attributed to insufficiently detailed topographical analysis.

They also pointed out that the model did not provide satisfactory response for a flood where Hortonian runoff is important.

5.6 Application of TOPMODEL to the Ythan catchment

5.6.1 Digital Terrain Analysis

A digital terrain model (DTM) for the Ythan catchment was created by digitising the Ordnance Survey Map (Ordnance Survey, 1986) Sheet No. 83/93 (scale 1:25,000, vertical scale 5 metres, grid reference: NJ 890 300, NJ 890 360, NJ 950 300, NJ 950 360). The DTM file created was named model4.dat which consisted of 99 x 99 cells, with grid size measuring 41 m. The file is then run on the GRIDATBG program, ditigal analysis program, which is part of the TOPMODEL suite of programs. The index distribution file, named dist4.dat, is then formatted for TOPMODEL. The index distribution is presented in Figure 5.2. The distribution is skewed towards low index values which indicates small percentage of areas likely to be represent saturated contributing area in this part of the catchment. But because only a small area is digitized it only represents a small percentage of the whole catchment area and therefore may not represent the mean index distribution. The area digitised for this purpose in shown in Figure 5.3. With the increasing availability of digitised topography maps, this problem can be rectified.

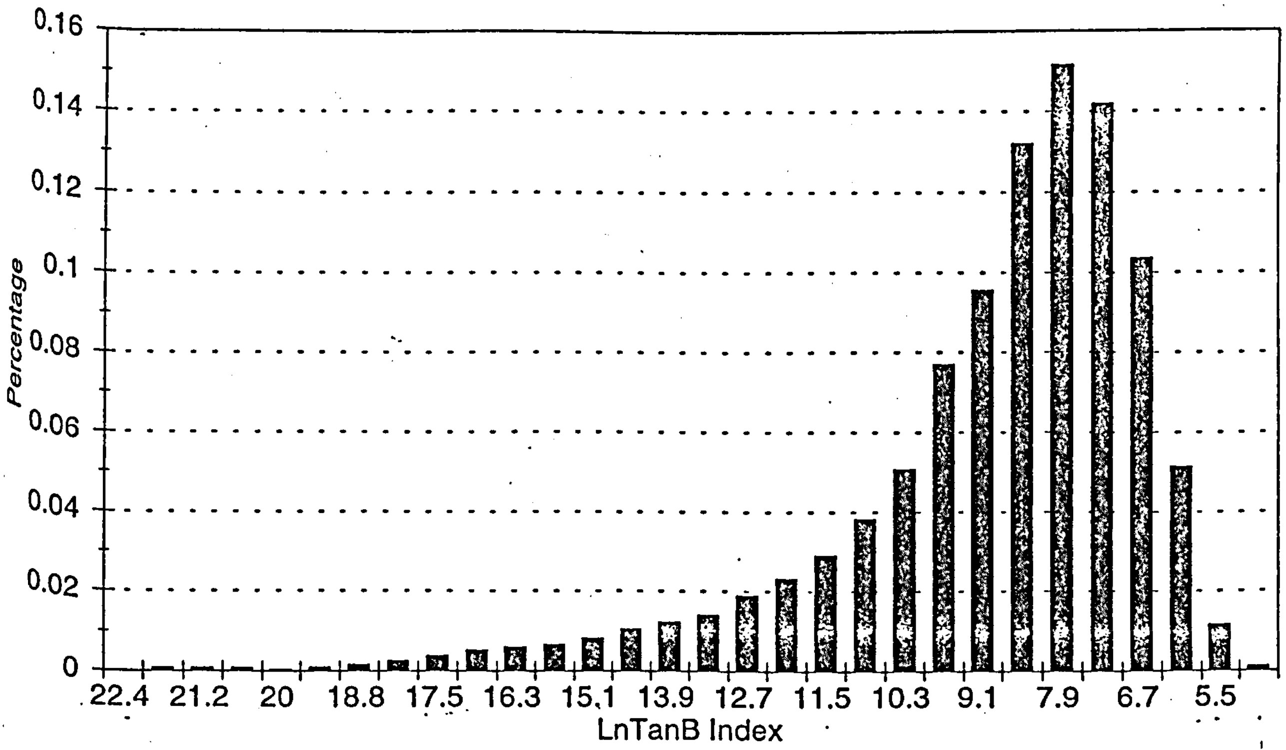
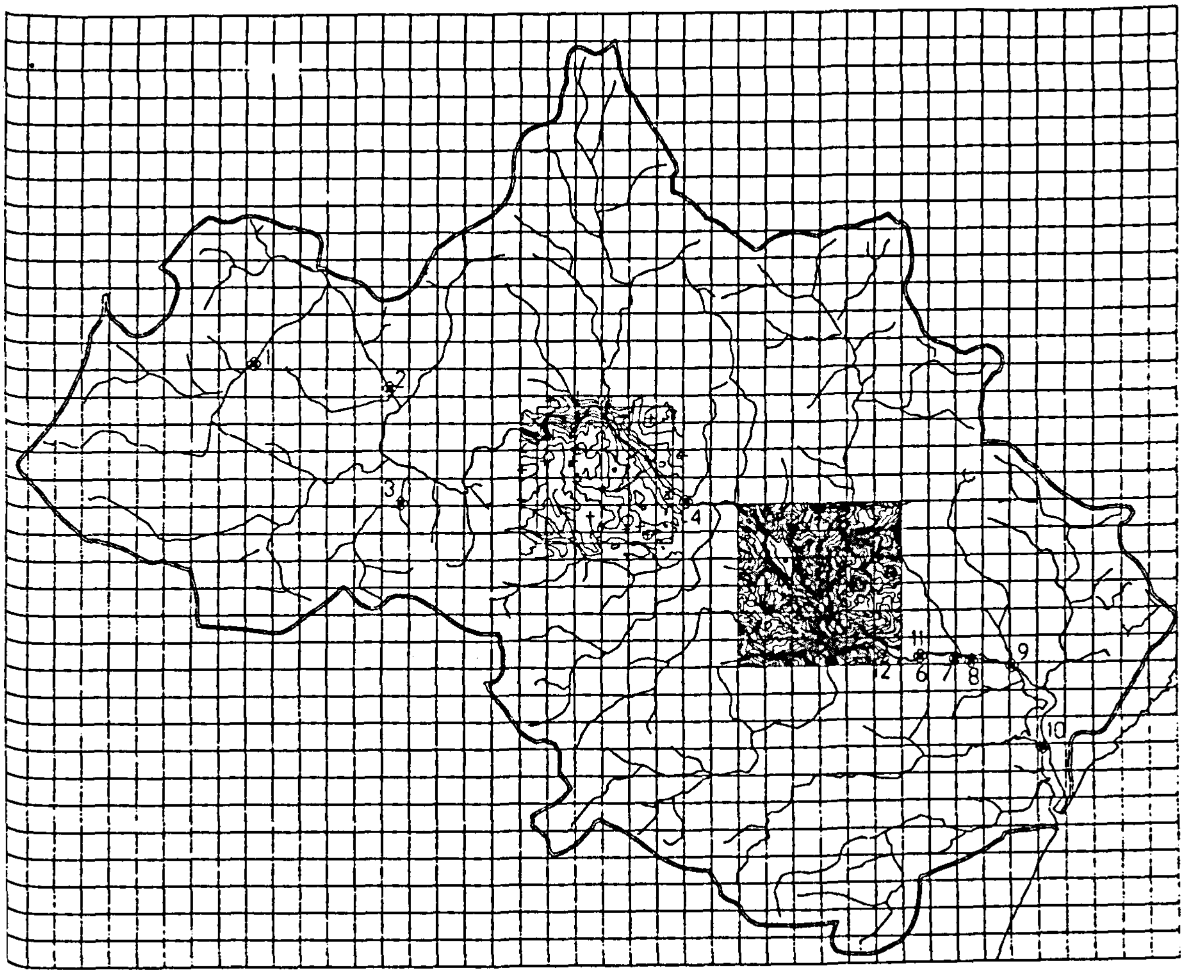


Figure 5.2

LnTanβ Index Distribution for a small area in the Ythan catchment.

Figure 5.3

The Ythan river and its tributaries.
(The area digitised for getting the topographic index of the catchment is shown in the second box to the right of the map)



5.6.2 Calibration and Verification of TOPMODEL to theYthan River Catchment.

TOPMODEL was calibrated for the Ythan Catchment using the daily rainfall and flow record for the water year October 1990 - September 1991. In each run the success of the model is evaluated in terms of its 'efficiency'. Efficiency is calculated as (Haan *et al.*, 1982)

$$E = 1 - \frac{\text{variance of the residual errors}}{\text{variance of the observed data}}$$

The optimised parameter values are shown in Table 5.2. An SRMAX of 15 mm was optimised for the Ythan catchment to ensure a correct water balance for the catchment. This value seems to be able to represent the water balance of the Ythan catchment as a higher SRMAX would mean higher losses of water to evapotranspiration. The recession decay value m of 0.038 represent the best value to simulate the recession of the hydrograph. A smaller value would produce a steeper recession which does not simulate the subsurface properties of the soil. The T_o value was optimised at 0.08 as higher value fails to represent the quick flow component that is shown by the spikes in the hydrograph.

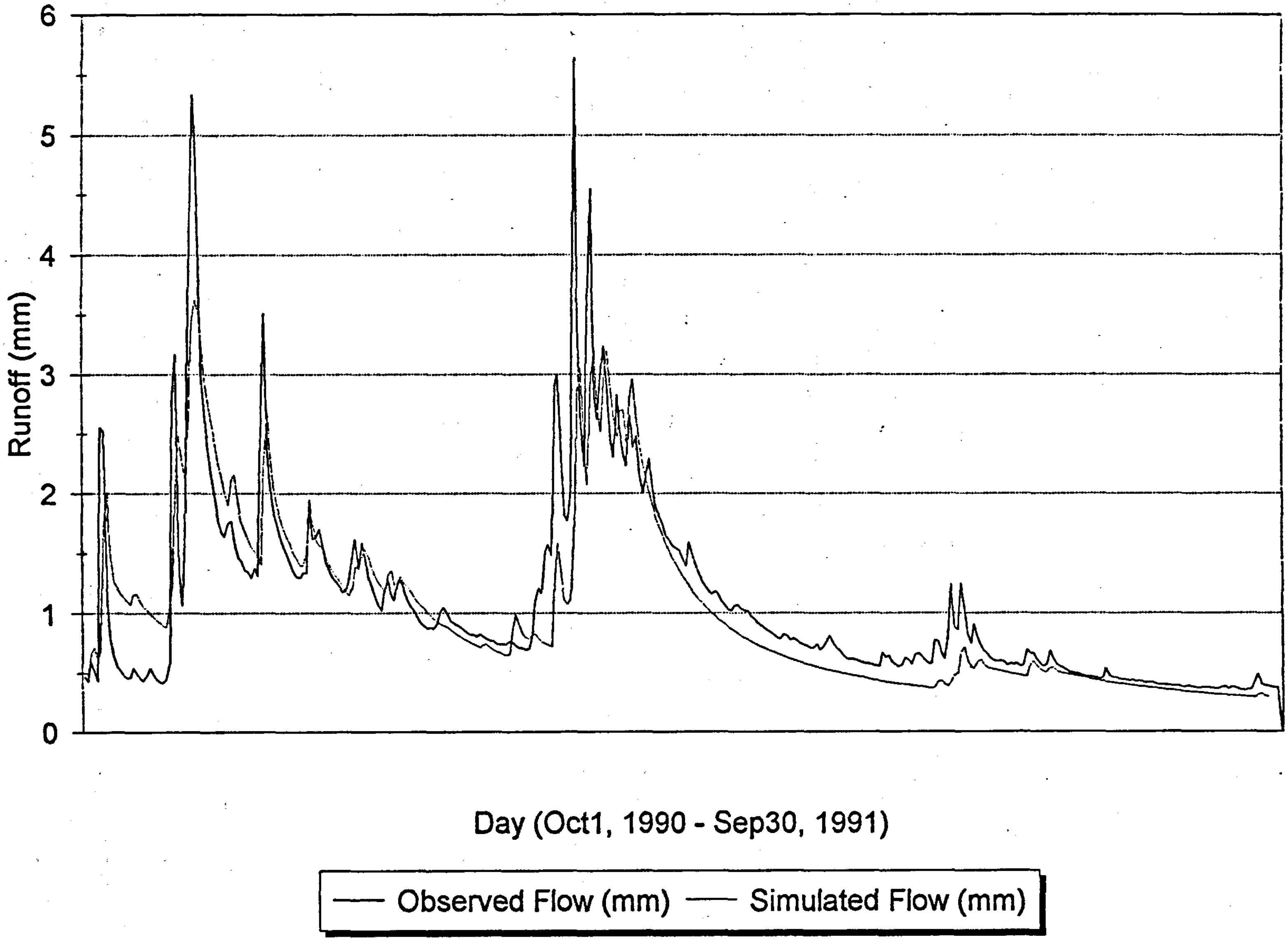
The full TOPMODEL calibration output is given in Appendix 3. The optimised parameter value produces an efficiency of 74 %. The simulated hydrograph represents the pattern of flow variation very well as depicted in the Figure 5.4.

Table 5.2

TOPMODEL parameter values optimised for the Ythan catchment

Model Parameter	Parameter Value
m	0.038 (m)
To	0.08 (m)
Td	0.04 (hr)
SrMax	0.015 (m)

Figure 5.4
TOPMODEL Calibration Run



The model is underpredicting saturation excess overland flow of the catchment as evident in the flat nature of the hydrograph as compared to the observed hydrograph. About 85 % of the runoff is contributed by the subsurface flow (Table 5.3). Figure 5.5 shows the hydrograph separation between surface and subsurface runoff for the catchment. The ratio of about 85 percent between surface and subsurface flow is a reasonable prediction for the Ythan catchment since most of the catchment comprises freely drained soil where subsurface stormflow will prevail (Anderson and Burt, 1990).

The parameter set is tested using the hydrological data set for 1993. The full result is presented in Appendix 4. The resulting modelling efficiency is reduced to 52 %. This drop in efficiency results from the inability of TOPMODEL to simulate peak flows effectively. Nevertheless, the predicted annual yield of 412 mm is not significantly different from the observed annual flow of 434 mm, representing an error of 5 % in annual yield (Table 5.3). The pattern of hydrograph produced is shown in Figure 5.6 which again shows the insufficient peak flow simulation as seen by the less spiky hydrographs compared to the observed one. The simulated hydrograph shows the dominance of subsurface flow on runoff production, where 83 % of the runoff is contributed by the subsurface drainage (Figure 5.7 and Table 5.3).

5.7 Model Evaluation

TOPMODEL provides a good total water yield simulation and the correct water balance (Table 5.3). On an annual basis TOPMODEL prediction of total runoff is within 95 %. However, on an event basis, TOPMODEL underpredicts peak flow as is evident in the lower peaks on the hydrograph (Figure 5.4). Thus, efficiency of modelling performance

Table 5.3

Summary of TOPMODEL results

	Calibration Period (1990/1991)	Verification Period (1993)
Precipitation (mm)	664.3	773.4
Observed Flow (mm)	396.3	434.0
Simulated Flow (mm)	373.3	411.9
Subsurface Flow (mm)	316.8 (85%)	341.0 (83 %)
Overland Flow (mm)	55.7 (15 %)	63.9 (17 %)
Modelling Efficiency	74 %	54 %

Figure 5.5
TOPMODEL Simulation: Split Hydrograph

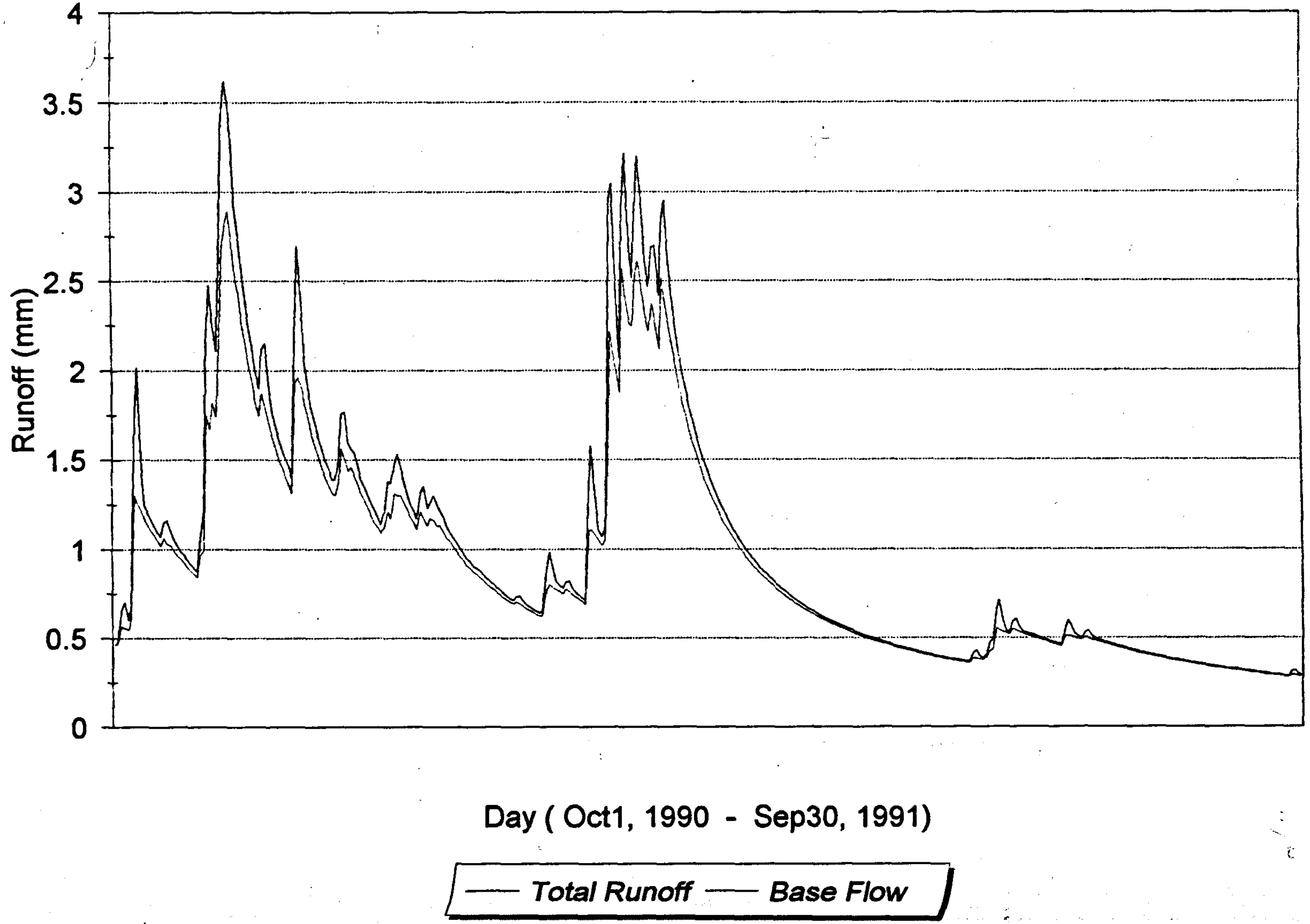


Figure 5.6
TOPMODEL Verification Run

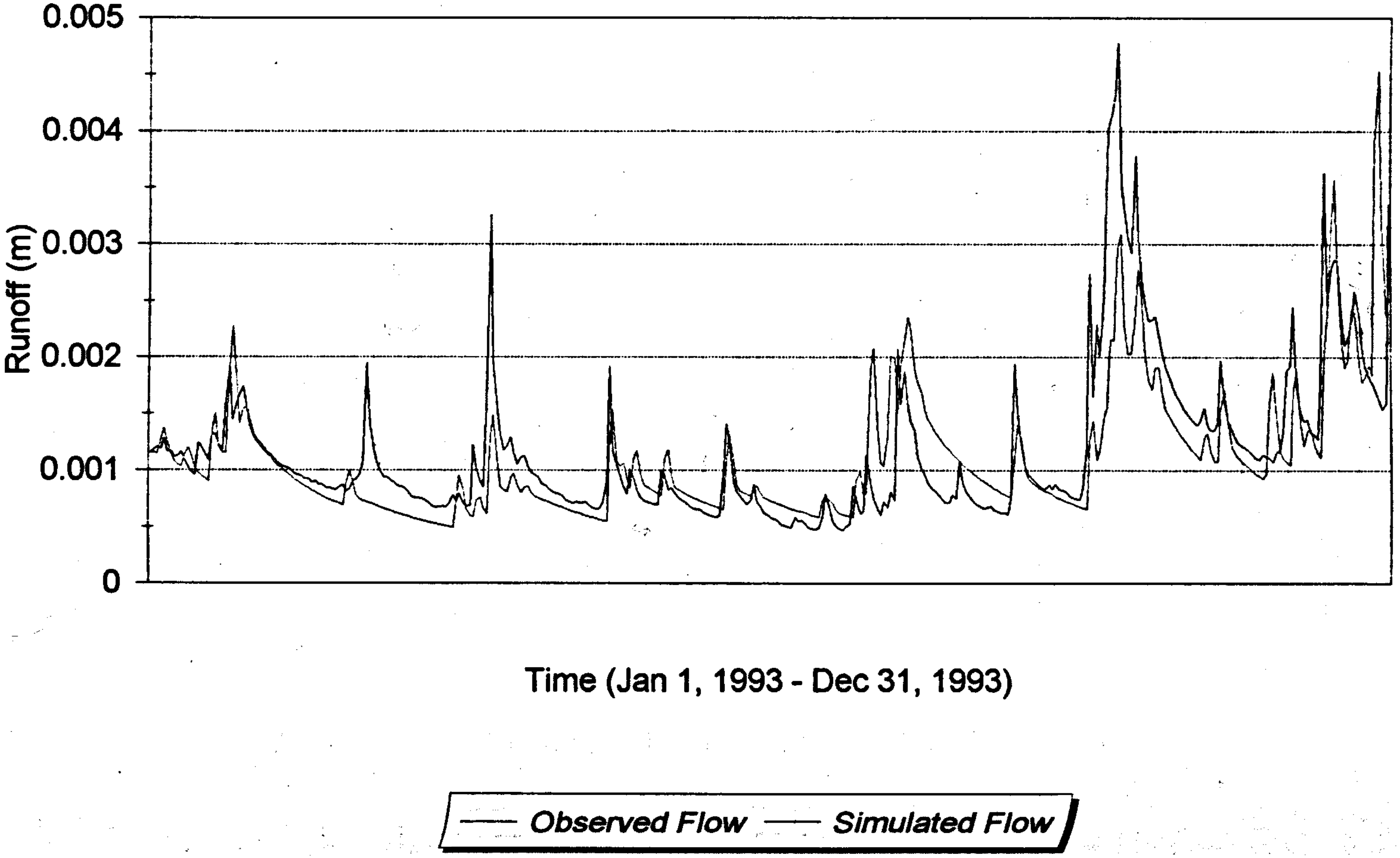
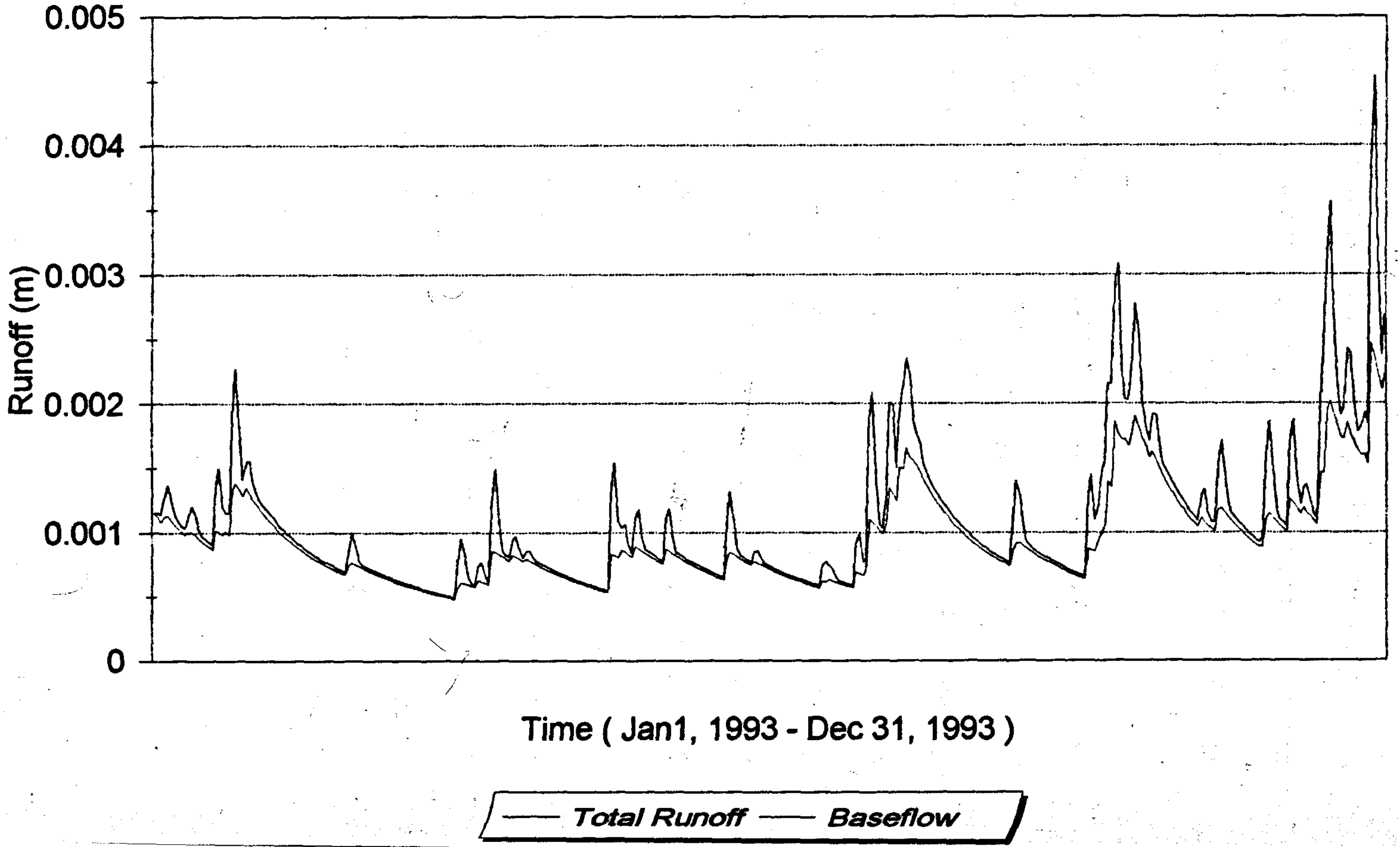


Figure 5.7
Verification Run: Split Hydrograph



is 74 % in the calibration period and 54 % in the verification period. This deficiency can be attributed to inaccuracy in assessing the mean ln (a/tan β) for the catchment. As shown in Figure 5.3 the area chosen to determine the topographic index of the catchment is not representative of the whole catchment. It can be said that the area selected was relativeley flat compared to the areas surrounding the catchment (Figure 1.3). This inaccurate representation of the topographic index results in lower peak flow simulation. It is believed that a more representative index value would produce better result. This can be achieved by digitizing the whole of the catchment or by sampling the catchments in various places. This work is not undertaken in this study due the extensive time requirement in digitizing and formatting the topographic data.

Despite displaying low modelling efficiency for monthly flow, TOPMODEL showed a good performance in simulating annual water yield which is an indication that the conceptual elements of the model has in essence captured the most important factors controlling catchment water balance using only three or four model parameters. Simplicity is the biggest advantage of TOPMODEL and in essence it successfully models runoff processes. The model can therefore be thought of as a conceptual toolkit for catchment hydrological analysis (Quinn and Beven, 1993).

This study has used a model that is essentially formulated for use in a small area and extends it to a catchment scale. Its subsurface processes are over simplified and cannot model the complexity of hillslope flow pathways present in a real catchment. At a catchment or basin scale other factors become important, one of which is the need for groundwater storage elements and instream flow routing.

TOPMODEL has the necessary structure which allows separation of runoff into surface and subsurface components. This is an advantage that can be used as a framework for nitrate transport study in a catchment. This feature is important in nitrate modelling because the subsurface route is the more dominant route for nitrate removal. The topographic index and the combined topographic-soil index, ln $(a/T_o\tan\beta)$, could be used to model areas susceptible to nitrate runoff since several studies have shown that topography has a significant impact on subsurface flow, which in turn is a major determinant of saturated areas and streamflow (Anderson and Burt, 1977, 1978a,b; Beven, 1978).

To extend TOPMODEL into a water quality model for simulating nitrate discharge, a nitrate submodel routine would have to be attached to TOPMODEL. Management parameters such as the timing and amount of fertiliser used as well as the planting and harvesting period should be incorporated into the model to adapt the model as a water resource management tool. This would allow the model to be used to study the effect of management changes on catchment response to nitrate.

This study has shown the versatility of TOPMODEL as a tool for understanding catchment response. With the advance of fast computers, the scope of TOPMODEL could be widened to allow larger areas to be simulated and if coupled with a GIS package it could be used as a spatial model to look at the effect of spatial patterns in controlling nitrate loadings.

Chapter 6

Simulating Catchment Hydrochemical Response of the Ythan River Using SWRRBWQ

6.1 Introduction

The model SWRRB (Simulator for Water Resources in Rural Basins) was developed for the United States Department of Agriculture for simulating hydrological and related processes in rural basins (Arnold *et al.*, 1990). The model has been used to predict the effect of management decisions on water quality and lately it has been upgraded to allow prediction of the effect of agricultural management on nutrient loadings to rivers. The version used in this thesis is called SWRRBWQ (Arnold *et al.*, 1992) which allows simulation of nutrient cycling and loadings to surface water.

SWRRBWQ uses a modified form of the CREAMS daily rainfall hydrology model to allow application to large and complex rural basins. Among the changes were (a) the model was expanded to allow simultaneous computations on several subbasins to predict the basin water yield; and (b) a return flow component was added. For predicting the effect of agricultural management, SWRRBWQ adapted the EPIC (Williams *et al.*, 1983) crop growth model to allow simulation of plant uptake and nutrient cycling.

The major components of SWRRBWQ are: hydrology, weather, sediment yield, and nutrient cycling. The major processes modelled include surface runoff, percolation, return flow, evapotranspiration, transmission losses, pond and reservoir storage, sedimentation, pesticide fate, nutrient cycling and crop growth (Arnold *et al.*, 1992).

In this chapter, the performance of SWRRBWQ in simulating catchment hydrochemical response of the Ythan catchment will be assessed. First a sensitivity analysis is performed on model parameters to determine the most sensitive parameters affecting catchment hydrological and nutrient simulations. The model is then calibrated for the Ythan catchment using the 1991 data and then tested and verified using 1990 and 1993 hydrological data. The calibrated model is then used to assess the effect of changes in agricultutal management practices on nitrate loadings.

6.2 SWRRBWQ Theory

The summary of physical theory of the processes simulated by SWRRBWQ is described below. The full theoretical background of the model can be found in Williams *et al.*, 1985 and Arnold *et al.*, 1992.

6.2.1 Hydrology

The hydrology model is based on the water balance equation

$$SW_t = SW + \sum(R_i - Q_i - ET_i - P_i - QR_i) \qquad \text{Eqn. 1}$$

where SW is the soil water content minus the 15-bar water content, t is time in days, and R, Q, ET, P, and QR are the daily amounts of precipitation, runoff, evapotranspiration, percolation, and return flow respectively; all units are in mm.

a) surface runoff

The model simulates surface runoff volumes and peak runoff rates, given daily rainfall amounts. Surface runoff volume is estimated by using a modification of the Soil Conservation Service (SCS) curve number equation (USDA, 1972);

$$Q = \frac{(R - 0.2\,s)^2}{R + 0.8\,s}, \quad R > 0.2\,s \qquad \text{Eqn.2}$$

$$Q = 0.0, \qquad R \leq 0.2\,s$$

where Q is the daily runoff, R is the daily rainfall, and s is a retention parameter which varies (a) among watersheds because soils, land use, management, and slope vary and (b) with time because of changes in soil water content. The parameter s is related to curve number (CN) by the SCS equation

$$s = 254\left(\frac{100}{CN} - 1\right) \qquad \text{Eqn.3}$$

(Arnold *et al.*, 1990).

b) Lateral flow

Lateral subsurface flow is estimated using the kinematic storage model which uses the mass continuity equation with the entire soil profile as the control volume. The mass continuity equation in finite difference form for the kinematic storage model is

$$\frac{S_2 - S_1}{t_2 - t_1} = iL - \frac{q_{lat1} + q_{lat2}}{2} \qquad \text{Eqn. 4}$$

where S is the drainable water stored in the saturated zone (water above field capacity), t is time in hours, q lat is the lateral flow in m^3h^{-1}, i is the rate of water input to the saturated zone in $m^2\ h^{-1}$, L is the hillslope length in m, and subscripts 1 and 2 refer to the beginning and end of time step, respectively. Lateral flow can be solved as

$$q_{lat} = 0.024 \frac{2SK_s \sin(\alpha)}{\Theta_d L} \qquad \text{Eqn.5}$$

where q_{lat} is in mmd^{-1}, S in mh^{-1}, α in mm^{-1}, Θ_d is the drainable porosity of the soil in mm^{-1}, and L is in m. Return flow is a function of soil water content and return flow travel time.

d) Percolation

The percolation component of SWRRBWQ uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded and if the layer below it is not saturated. The downward flow rate is governed by the saturated conductivity of the soil layer. Upward flow may occur when a lower layer exceeds field capacity and is regulated by the soil water to field capacity ratios of the two layers.

Lateral subsurface flow in the soil profile (0 to 2 m) is calculated simultaneously with percolation. A nonlinear function of lateral flow travel time is used to simulate the horizontal component of subsurface flow. The magnitudes of the vertical and horizontal components are determined by a simultaneous solution of the two governing equations.

e) Potential Evapotranspiration

The model offers two options for estimating potential evaporation - Hargreaves and Samani and the Priestley-Taylor method. The Priestley-Taylor method requires solar radiation and air temperature as input. The Hargreaves method requires air temperature only. Soil and plant evaporation is computed by an approach similar to that of Ritchie (1972). In this study the Hargreaves approach is adopted.

The Hargreaves and Samani (1985) method estimates potential evapotranspiration as a function of extraterrestrial radiation and air temperature. The Hargreave's method was modified for use in SWRRBWQ where the modified equation is

$$E_o = 0.0032 \left(\frac{RAMX}{HV}\right) (T + 17.8)(T_m - T_{mn})^{0.6} \qquad \text{Eqn.6}$$

where T_{mx} and T_{mn} are the daily maximum and daily minimum air temperatures in C.

6.2.2 SWRRBWQ - Nitrate Submodel

The nitrate yield and nitrate cycling component of SWRRBWQ were adopted from the EPIC model (Williams *et al.*, 1983). SWRRBWQ uses the EPIC concepts of phenological crop development based on daily accumulated heat units, harvest index for partioning grain yield, Monteith's approach for potential biomass, and water and temperature stress adjustments. In this study only the mineral nitrogen component is considered.

a) Nitrate concentration and loadings.

The total amount of water leaving the layer is the sum of runoff, lateral subsurface flow, and percolation.

$$QT = Q + Q_1 + QR_1 \qquad \text{Eqn.7}$$

where QT is the total water lost from the first layer in mm, Q is the runoff volume in mm, Q_1 is the percolation from the first layer in mm, and QR_1 is the lateral flow from the first layer in mm. The amount of NO_3-N lost with QT is

$$VNO_3 = (QT)(C_{NO3}) \qquad \text{Eqn.8}$$

where VNO_3 is the amount of NO_3-N lost from the first layer and C_{NO3} is the concentration of NO_3-N in the first layer. At the end of the day, the amount of NO_3-N left in the layer is

$$WNO3\text{-}N = WNO3_0 - (QT)(C_{NO3}) \qquad \text{Eqn.9}$$

where $WNO3_0$ AND WNO3 are the weights of NO_3-N contained in the layer at the beginning and ending of the day. The NO_3-N concentration can be estimated by dividing the NO_3-N by the water storage volume:

$$C'_{NO3} = C_{NO3} - C_{NO3}(-QT/PO_1-WP_1) \qquad \text{Eqn. 10}$$

where C'_{NO3} is the concentration of nitrate at the end of the day, PO is soil porosity, and WP is the wilting point water content for soil layer one in mm. Equation 10 is a finite difference approximation for the exponential equation

$$C'_{NO3} = C_{NO3} - \exp(-QT/PO1-WP1) \qquad \text{Eqn. 11}$$

VNO_3 can be computed for any QT value by integrating equation 11.

$$VNO_3 = WNO3(1-\exp(-QT/(PO1-WP1))) \qquad \text{Eqn. 12}$$

The average concentration of QT for the day is

$$C_{NO3} = VNO_3/QT \qquad \text{Eqn. 13}$$

Amounts of NO_3-N contained in runoff, lateral flow, and percolation are estimated as the products of the volume of water and the concentration from Eqn. 13. The amount of

NO_3-N in runoff is estimated for each subbasin by considering the top soil layer (10 mm thickness) only. Nitrate leaching and subsurface flow in lower layers are treated with the same approach used in the upper layer except surface runoff is not considered.

b) Soil Nitrate Budget

i) Crop uptake

Crop use of N is estimated using a supply and demand approach. The daily (day i) crop N demand can be computed using the equation

$$UNDi = (C_{NB})_i B_i - (C_{NB})_{i-1} B_{i-1} \qquad \text{Eqn.14}$$

where UND_i is the N demand of the crop in kgha^{-1}, C_{NB} is the optimal N concentration of the crop, and B is the accumulated nitrogen in kgha^{-1}. The optimal N uptake by crops is computed as a function of growth stage using the equation

$$C_{NB} = 4.0\,(bn) + 1.54\,(bn)\exp(-bnB_1) \qquad \text{Eqn. 15}$$

where bn is a crop parameter expressing N concentration and B_1 is the fraction of the growing season. The value of B_1 is estimated as a function of heat units

$$B_{1,i} = HUI/PHU \qquad \text{Eqn. 16}$$

where HUI is the daily heat units in C above the crop's base temperature and PHU is the potential heat unit.

ii) Fertiliser application

The date and rate of N application is input to the model. The entire amount of N added to the first layer is available for water transport, leaching and plant uptake.

6.3 Data Requirements

The weather variables necessary for driving SWRRBWQ are precipitation, air temperature, and solar radiation. If daily precipitation and temperature are available they can be input directly into the model, otherwise the model simulates daily rainfall and temperature. Solar radiation is always simulated. Measured daily precipitation and daily temperature are used as inputs in this study.

Measured daily precipitation and maximum and minimum temperatures were obtained from the meteorological office. The rainfall station selected was the Meiklemill Station at Ellon, and daily flow was provided by the Institute of Hydrology who monitored the river flow at Ellon gauging station. The weather and flow data were then formatted for SWRRBWQ.

The inorganic fertiliser inputs were obtained from the literature in which inorganic fertiliser use is calculated by combining the area for each crop with the appropriate fertiliser application rates and summing for the whole catchment area. The total area of each crop within the catchment was calculated by summing individual parish data. It was assumed that the distribution of crops within each parish was uniform (Wright *et al.*, 1991).

6.4 Sensitivity Analysis

A sensivity analysis of SWRRBWQ was carried out to identify those inputs which when modified, produce important changes in the water balance and nitrate output from the catchment. For sensitivity analysis SWRRBWQ parameters were classified into three groups; 1) general basin parameters 2) soil parameters and 3) crop parameters. The output considered were the correlation of coefficient (R^2), total water yield, water lost through surface flow, subsurface flow and percolation; and lost of nitrogen through plant uptake, deep percolation, surface flow and subsurface flow.

6.4.1 Sensitivity of general basin parameters

The results of the sensitivity analysis of SWRRBWQ catchment parameters are presented in Table 6.1 and the most sensitive parameters are discussed below.

a) SCS curve number.

This parameter affects the balance between surface flow and subsurface flow. Curve number affect the relative volume of water in surface flow versus subsurface flow component but do not alter the percolation component. Altering the curve number from

Table 6.1

Sensitivity analysis of SWRRBWQ general basin parameters

Parameter	Value	R2	Annual Yield	SQ	SSQ	Percolation
Basin Lag Time (15)	4	.835	288.32	1.36	286.96	2.58
	10	.907	270.91	1.36	279.05	2.58
	15	.923	270.91	1.36	269.55	2.58
	20	.921	262.56	1.36	261.20	2.58
	25	.909	254.33	1.36	252.33	2.58
Average Channel Slope (.002)	.002	.923	270.91	1.36	269.55	2.58
	.001	.923	270.91	1.36	269.55	2.58
	.01	.923	270.91	1.36	269.55	2.58
Channel n Value ●	.05					
	.07	.923	270.91	1.36	269.55	2.58
Overland Flow N Value (.6)	.15	.923	270.91	1.36	269.55	2.58
	.3	.923	270.91	1.36	269.55	2.58
	.6	.923	270.91	1.36	269.55	2.58
Average Slope Steepness (.002)	.002	.923	270.91	1.36	269.55	2.58
	.02	.923	270.91	1.36	269.55	2.58
SCS Curve Number (76)	65	.921	270.90	1.14	269.76	2.58
	70	.921	270.91	1.14	269.70	2.58
	76	.923	270.91	1.36	269.55	2.58
	86	.935	270.99	6.63	264.36	2.58
Return Flow Travel Time (.600)	.6	.923	270.91	1.36	269.55	2.58
	1.0	.938	268.90	2.28	266.622	2.86
	2	.916	264.52	4.09	199.22	3.26
	10	.851	229.46	30.25	167.87	6.08
	20	.777	221.16	53.28		9.08

Note: SQ refers to surface runoff

SSQ refers to subsurface runoff

The values in bracket refer to the bae value adopted

76 to 86 changes the surface flow volume from 1.36 to 6.63 mm and the NO_3 in surface flow from 0.02 to 0.08 kg ha^{-1}. This in turn results in higher nitrate lost through the surface route. The effect on the nutrient lost in subsurface flow, leaching and annual yield is minimal.

b) Return flow travel time (RFT)

Return flow travel time is the time required for the subsurface flow from the centroid to reach catchment outlet. This parameter is very sensitive and affects both the water balance components and the nutrient components. Increasing the return flow travel time reduces the annual yield. Higher RFT increases the volume of water attributed to surface flow and percolation while reducing water from subsurface flow. Higher RFT thus reduces nitrate output through the subsurface flow route but increases nutrient loss through leaching and surface flow. This parameter, however, does not affect nitrate uptake by crops.

c) Basin lag time

Basin lag time is defined as the number of days subsurface flow from a precipitation event takes to reach the catchment outlet. This parameter lags the subsurface flow output and is very sensitive in the simulation of annual water yield and R^2. An increase in basin lag time results in less annual yield as shown in Table 6.1. A lag time of 15 days results in best fit in terms of R^2. This parameter however does not change the surface flow and percolation output. The nitrate output is also unaffected.

6.4.2 Sensitivity of SWRRBWQ soil parameters

Sensitivity analysis results for soil parameters is shown in Table 6.2. The sensitivity of the most important parameters are discussed below.

a) Saturated conductivity

Saturated conductivity is an important property affecting the behaviour of soil water flow systems. Qualitatively, saturated conductivity is the ability of the soil to transmit water. This parameter is very sensitive to almost all output parameters especially percolation rate; since the model assumes the water that percolates is lost from the system, higher SC value tends to reduce annual yield. This parameter also is a sensitive parameter for nitrate leaching. Because of the high percolation rate, high nitrate is thus lost through leaching. Saturated conductivity value of 3.0 shows the highest R^2 for catchment water simulation. This parameter is therefore one of the most sensitive parameter affecting nutrient and water balance in catchment systems and therefore requires careful estimation.

b) Available water capacity (AWC)

Available water capacity is another sensitive parameter in catchment hydrological and nutrient simulation. Soil with less AWC tends to produce high annual water yield and high subsurface flow. Consequently, soils with lower AWC loses more nitrate through

Table 6.2

Sensitivity analysis of SWRRBWQ soil parameters

Parameter	Value	R^2	Annual yield (mm)	SQ (mm)	SSQ (mm)	Percolation (mm)	NO_3 (SQ) (kgha^{-1})	NO_3 (SSQ) (kgha^{-1})	NO_3 leached (kgha^{-1})	Plant uptake (kgha^{-1})
Available water capacity (.320 mmmm^{-1})	0.11 0.180 0.320	0.87 0.92 0.89	206.8 188.8 183.8	34.9 29.6 24.9	171.9 159.1 158.8	26.5 26.4 29.6	3.87 3.69 1.04	38.2 33.2 24.9	.92 .75 .7	78.77 99.11 99.87
Saturated conductivity (.29 mmhr^{-1})	1.0 3.0 6.0 30.0	0.89 0.92 0.92 0.96	202.6 270.9 195.0 225.6	29.5 29.6 29.9 23.7	173.1 159.1 165.1 201.8	17.2 26.4 31.4 43.2	3.79 3.69 3.7 4.2	44.3 33.2 34.0 58.4	.52 .75 .88 1.9	99.87 99.11 85.9 49.4
Initial NO_3 in soil layers (ppm)	1 5 10						3.66 3.69 3.71	24.76 55.46 93.9	.74 3.59 7.15	99.11 99.11 99.11

Note: SQ refers to surface flow

SSQ refers to subsurface flow

The values in bracket refer to the values adopted to run the sensitivity analysis the subsurface route. AWC is thus of the most important parameter in nitrate modelling because of the nature of its transport which is predominantly through subsurface route.

6.4.3 Sensitivity analysis of SWRRBWQ crop parameters

Biomass conversion factor, potential heat unit and maximum leaf area index are parameters most sensitive to nutrient output (Table 6.3). The biomass conversion factor effects all the nitrate output parameters where an increase in biomass conversion factor results in higher plant uptake and therefore less nutrient discharged through the leaching, subsurface and surface route. Potential heat unit also displays some effect although it is insignificant. The maximum leaf area index has a significant impact where a higher leaf area index results in higher plant uptake and less output to the surface and groundwater. Because the data for these parameters are not available the default value provided by SWRRBWQ are used. These values were then optimised to allow plant uptake level to give a reasonable estimate as compared to the value gathered from personal communication with the Macaulay Land Use Research Institute which estimated that about 120 kg ha^{-1} is the nitrate uptake for winter wheat (grain) and about 98 $kgha^{-1}$ for spring barley (grain). These parameters are important in nutrient loadings because an underestimate of plant uptake rate would mean a higher nitrate loss through leaching or through subsurface flow.

Table 6.3
Sensitivity Analysis of SWRRBWQ Crop Parameters

Crop Parameter	Parameter Value	Plant Uptake (kg ha^{-1})	Nitrate Leached (kg ha^{-1})	Nitrate in SSQ (kg ha^{-1})	Nitrate in SQ (kg ha^{-1})
Biomass Conversion Factor (50)	50 40 30	44.76 29.42 15.67	0.01 0.03 0.03	0.06 0.18 0.028	63.99 68.24 75.43
Potential Heat Unit 2000	3000	45.24	0.01	0.07	63.50
	2500	45.11	0.01	0.06	63.63
	2000				
	1500	44.10	0.01	0.06	64.65
	1000	42.57	0.02	0.06	66.17
Maximum Leaf Area Index 5	7	45.71	0.01	0.06	62.97
	6	45.37	0.01	0.06	63.34
	5				
	4	38.67	0.02	0.16	65.76
	3	27.67	0.03	0.27	68.34
Initial Residue Cover 500	500 1000 2000	44.76 44.76 44.76	0.01 0.01 0.01	0.06 0.06 0.06	63.99 63.99 63.99
Harvest Index					
Average C factor 0.030	0.05 0.1 0.2	44.76 44.76 44.76	0.01 0.01 0.01	0.06 0.06 0.06	63.99 63.99 63.99
Water stress yield factor 0.01	0.1 0.2	44.76 44.76	0.01 0.01	0.06 0.06	63.99 63.99

6.5 Calibration and testing of the SWRRBWQ model on the Ythan river

In fitting and testing the modelling results, some objective criterion is used to assess when the agreement between observed, Q_{obs}, and predicted flows, Q_{pred}, is acceptable. The most commonly used objective function used and also the one used in this model is the sums of squares of the residual

$$F = \sum [Q_{pred} - Q_{obs}]^2 \qquad \text{Eqn. 17}$$

When no further reduction in the value of F can be affected by modifying the parameter values then the optimum fit of the model-generated flow values on the observed data has abeen achieved (Anderson and Burt, 1985).

The choice of year to be used for calibration is critical because of the variability of rainfall and runoff characteristics from year to year. Calendar years 1990, 1991, and 1993 are selected for testing SWRRBWQ hydrology parameters because of the availability of complete sets of hydrological data (rainfall, runoff, temperature), fertiliser use and nutrient loadings data. The rainfall and runoff characteristics for the three years under study are shown in Table 6.4. The three years under study received relatively normal amount of rainfall (average annual rainfall for catchment is 780 mm), but year 1990 recorded below average runoff of 262 mm as compared to the average of 484 mm for the catchment. This could be the result of a very dry year in 1989 where the catchment recorded only 493 mm of rainfall and 170 mm of runoff. Therefore year 1991 is chosen instead for model calibration.

Table 6.4

Monthly Rainfall and Runoff Characteristics of the Ythan River in the Modelling Period

Month	J	F	M	A	M	J	J	A	S	O	N	D	Total
Rainfall (mm)													
1990	43	68	21	33	46	107	40	78	78	109	103	41	767
1991	21	82	78	42	36	108	42	23	32	92	19	28	703
1993	52	26	28	66	77	64	82	80	59	121	49	83	787
Runoff (mm)													
1990	14	21	21	15	13	13	10	10	9	26	67	43	262
1991	30	38	75	33	21	21	18	13	11	16	60	32	398
1993	39	27	27	33	25	22	18	30	26	78	41	68	434

Based on the sensitivity analysis results, and a few preliminary run, the parameters most sensitive to the catchment hydrological and nitrate response were selected and optimised for calibrating the model (Table 6.5). In selecting the range of parameter values to optimise, basic assumptions about the general characteristics of the catchment such as soil texture and geology of the catchment are taken into account. The parameter values were optimised manually until the best fit between simulated and observed hydrological response of the catchment was simulated. The basin lag time of 15 days and return flow travel time of 7 days were the optimised value that represent the best fit for the years under study. They are the composite value for the whole catchment for a rainfall event to reach the catchment outlet through the delayed subsurface route eventhough these parameters vary spatially and seasonally. Using Table 6.4 as a guide, these values are reasonable since the peak in monthly runoff tends to occur in the month after a wet month. Delayed subsurface stormflow has been said to dominate the runoff response both volumetrically and in terms of peak discharge in basins where deep permeable soils overlie impermeable bedrock (Anderson and Burt, 1990). Return flow travel time is less than the basin lag time because it is the number of days it takes for subsurface flow to travel from the centroid to reach catchment outlet.

The soil parameter values most sensitive to water balance and nutrient output are saturated conductivity (3.0) and AWC (0.18). These parameters reflect the ability of soils to conduct and store water (Black, 1965). The available water in the soil is the amount of water that can be used or removed from the soil in the support the life of higher plants. The available water content is estimated by the difference between the water content at field capacity and the water content at the permanent wilting point. Another important soil property which affects the behaviour of soil water flow system is

Table 6.5

Summary of Base Values Optimised to Calibrate the SWRRBWQ Model

Parameter	Value
Basin Lag Time	15 days
SCS Curve Number	76
Return Flow Travel Time	7 days
Available Water Capacity	.18
Saturated Conductivity	3.0

the conductivity of the soil to water (Black, 1965). Water moves through a soil in response to the various forces acting upon it. Among these are the pressure gradient, gravitational, adsorptive, and osmotic forces. One of the basic physical relationships used to describe the flow of water in soils is a flux equation, Darcy's law, relating the flux of water v to the driving force:

$$v = -(\kappa\rho/\eta)\nabla\Phi \qquad \text{Eqn.18}$$

where κ is the permeability of the soil, ρ is the fluid density, η is the fluid viscosity, and $\nabla\Phi$ is the driving force per unit mass of water (Black, 1965). Although SWRRBWQ has a built in automatic soil entry, this feature is not applicable in this study because the soil types prevalent in the Ythan catchment is not fully described in the Soils 5 database. As described in Chapter 2, most of the soil texture is loamy sand or loamy fine sand with moderate water holding capacity although some parts in the lower reaches of the catchment compose of clay soils. The optimised values for available water capacity and saturated conductivity are 0.18 and 3.0 respectively. Table 6.6 shows the water contents for several soils and Table 6.7 shows the range of hydraulic conductivity and permeability of different permeability classes which provide a guide for parameter estimation. Available water capacity is estimated based on texture while conductivity is derived from the permeability of soils.

For calibrating the nutrient submodel, the average nitrate fertiliser applied in 1991 estimated at 127 kg $ha^{-1}a^{-1}$ (MacDonald *et al.*, 1995) is used as input and applied twice a year on March 15 and April 15 with planting date, March 25, and harvested date, September 15. This value represents the aggregate value for fertiliser use for the whole

Table 6.6

Water contents of soils according to soil texture

Texture	Bulk density	Total porosity	Field capacity 1/3 bar	Wilting point 15 bar	Available water capacity (mm/mm)
Coarse sand	1.60	0.40	0.11	0.03	0.080
Sand	1.6	0.40	0.16	0.03	0.130
Fine sand	1.50	0.43	0.18	0.03	0.150
Very fine sand	1.50	0.40	0.27	0.03	0.250
L.coarse sand	1,60	0.40	0.16	0.05	0.110
Loamy sand	1.60	0.40	0.19	0.05	0.140
Loamy fine sand	1.60	0.40	0.22	0.05	0.180
Loamy very fine sand	1.60	0.40	0.37	0.05	0.320
Coarse sandy loam	1.6	0.40	0.19	0.08	0.110

(Source: Arnold and Williams, 1994)

Table 6.7

Permeability classes of saturated subsoils, and the corresponding ranges of hydraulic conductivity and permeability.

Class	Hydraulic conductivity		Permeability
	inches/hour	cm. /hour	cm.^{2}
Very slow	< 0.05	< 0.125	$< 3 \times 10^{-10}$
Slow	0.05- 0.2	0.125- 0.5	$3 \times 10^{-10} - 15 \times 10^{-10}$
Moderately slow	0.2 - 0.8	0.5 - 2.0	$15 \times 10^{-10} - 60 \times 10^{-10}$
Moderate	0.8 - 2.5	2.0 - 6.25	$60 \times 10^{-10} - 170 \times 10^{-10}$
Moderately rapid	2.5 - 5.0	6.25 -12.5	$170 \times 10^{-10} - 350 \times 10^{-10}$
Rapid	5.0 -10.0	12.5 -25.0	$350 \times 10^{-10} - 700 \times 10^{-10}$
Very rapid	> 10.0	> 25.0	$> 700 \times 10^{-10}$

(Source: Black, 1965)

catchment assuming 36 % of the catchment is used for spring crops, 22 % for winter crops, and 42 % for grass (Wright *et al.*, 1991). SWRRBWQ is not able to simulate a crop with a cycle extending to the following year as the case with winter crops. But this should not affect the result significantly since plant uptake is greatly reduced during winter period. As stated earlier the crop parameters were selected so as to optimise crop nitrate uptake.

SWRRBWQ is calibrated to the Ythan river for 1991 and tested and verified for 1990 and 1993. The full modelling result for the calibration run is given in Appendix 5. The modelling result for 1990 and 1993 are given in Appendix 6 and Appendix 7 respectively. The summary of hydrological simulation result for the three years under study is given in Table 6.8. The calibration run gives an R^2 of 0.92 and total water yield of 189 mm compared to the observed yield of 369.6 mm (see Figure 6.1a and 6.1b). The model is then verified using the 1990 data. For 1990, the simulation showed R^2 value of 0.87, with simulated water yield of 233 mm as compared to the observed yield of 269 mm which represents an error of 13 % (see Figure 6.2a and 6.2b). For 1993 verification period, the R^2 value is 0.74 with simulated total water yield of 238 mm compared to observed value of 434 mm, therefore underpredicting total yield by over 40 % (Figure 6.3a and 6.3b).

From the modelling results mentioned above, it is apparent that SWRRBWQ is capable of simulating the monthly flow pattern as is evident in the high correlation between the observed and simulated runoff. However, it was not able to simulate total runoff, which it consistently underpredicted throughout the three years under study. This discrepency seems to be a result of the structure of SWRRBWQ. SWRRBWQ simulates water yield

Table 6.8
Hydrological and Nutrient Modelling of Ythan River Using SWRRBWQ
1991

Month	Rainfall mm	SurQ mm	SSQ mm	Yield mm	Perc mm	ET mm	SW mm	SurQ NO3 kg/ha	Crop NO3 kg/ha	SSQ NO3 kg/ha	Per NO3 kg/ha
1	29.1	0.35	15.55	15.9	2.87	6.37	273.24	0.03	0	3.2	0.07
2	86.1	13.08	14.11	27.19	3.63	18.68	292	0.15	0	3.76	0.09
3	69.5	4.66	49.09	53.76	3.28	56.71	259.7	2.05	0	5.87	0.08
4	32.4	0.06	9.87	9.93	1.35	37.16	252.97	0	0	0.51	0.03
5	22.8	0	1.82	1.82	1.2	27.62	246.4	0	0.47	0.77	0.03
6	98.8	0.72	1.49	2.22	2.98	79.84	259.43	0.01	0.84	2.13	0.07
7	40.3	0.25	2.07	2.33	1.57	53.47	242.79	0	19.68	1.87	0.03
8	20.5	0	0.86	0.86	0.92	52.25	209.77	0	56.1	0.26	0.02
9	23.7	0	0.14	0.14	0.42	57.15	175.9	0	22.02	0	0.02
10	98.7	5.87	2.02	7.89	1.56	24.23	236.55	0.06	0	0.41	0.08
11	107.4	4.17	36.04	40.21	4.15	9.46	274.87	0.05	0	1.97	0.13
12	25.4	0.44	26.07	26.51	2.5	3.27	274.98	0.01	0	0.31	0.04
Annual	654.7	29.62	159.13	188.74	26.41	426.2	274.98	2.36	99.11	21.07	0.68

Figure 6.1a
Monthly Rainfall - 1991

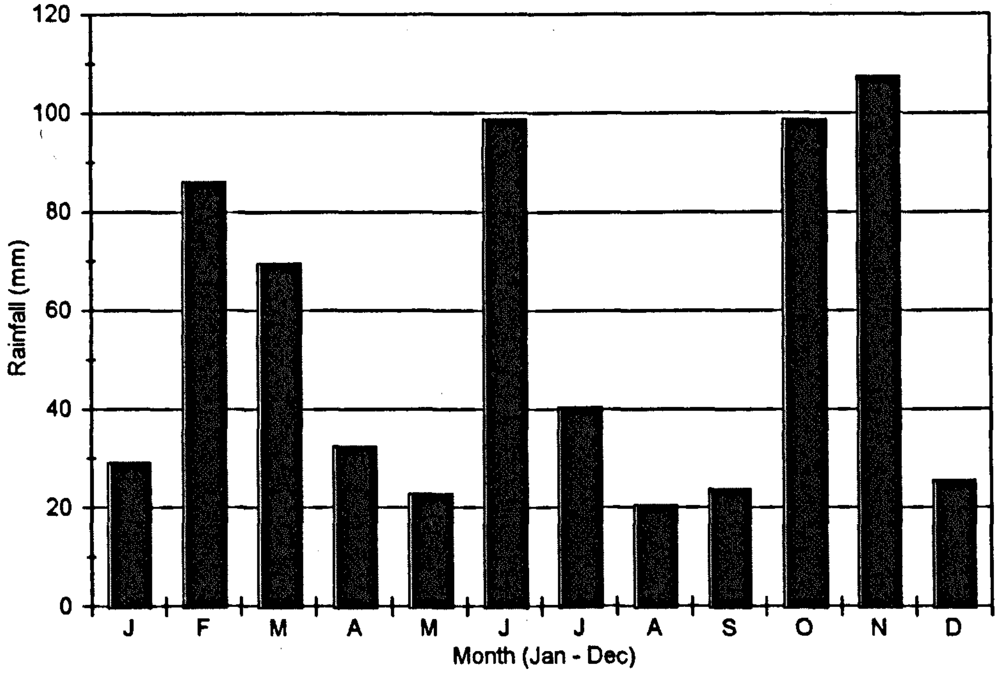


Figure 6.1b
SWRRBWQ Calibration Run (1991)

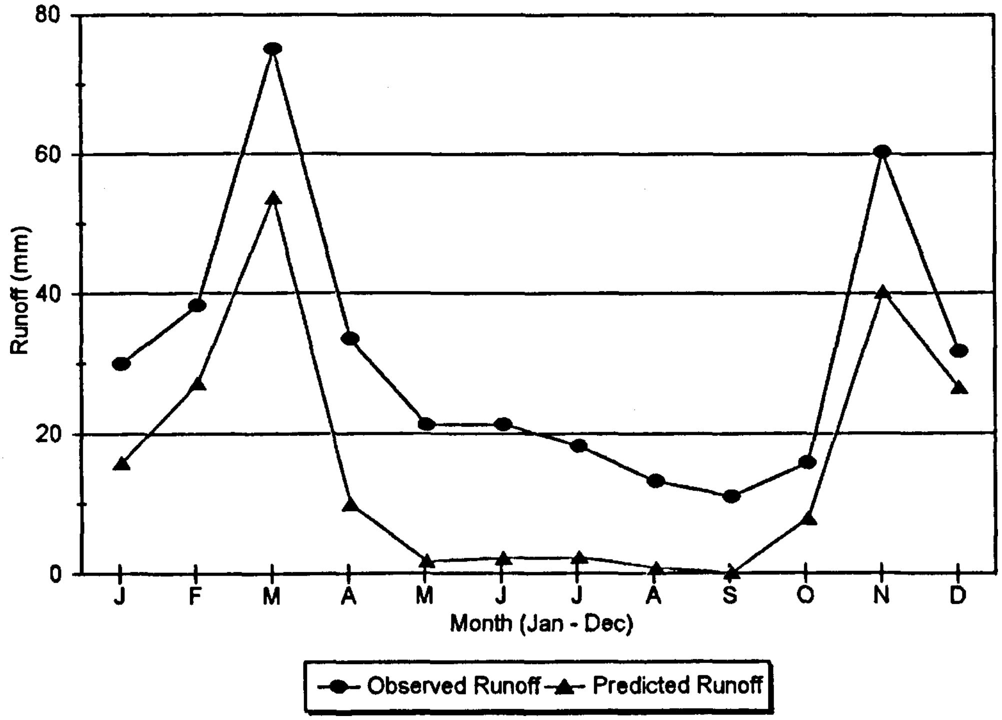


Figure 6.2a
Monthly Rainfall - 1990

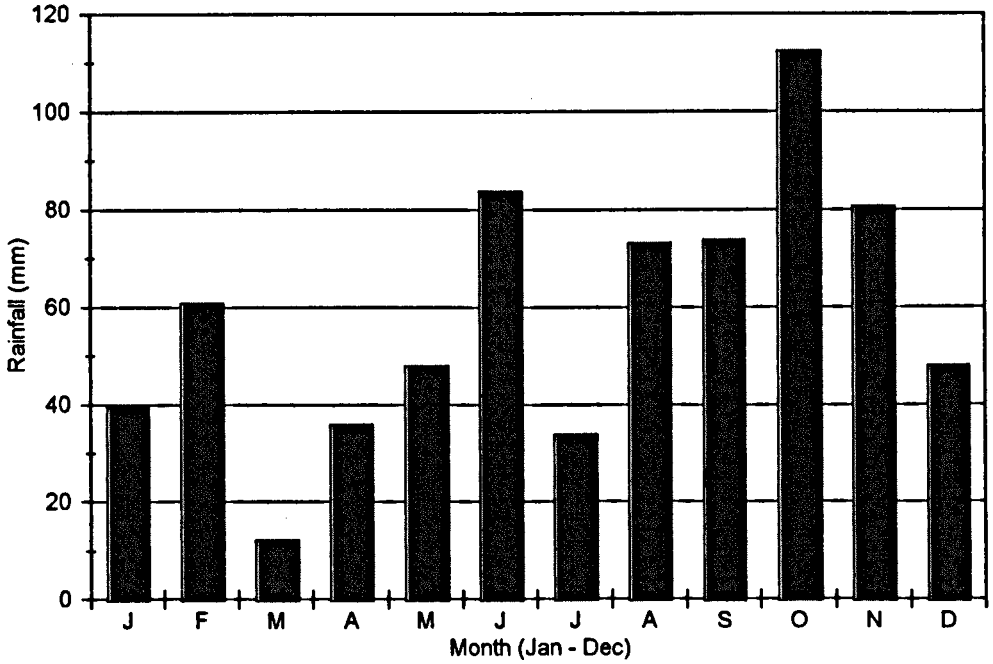
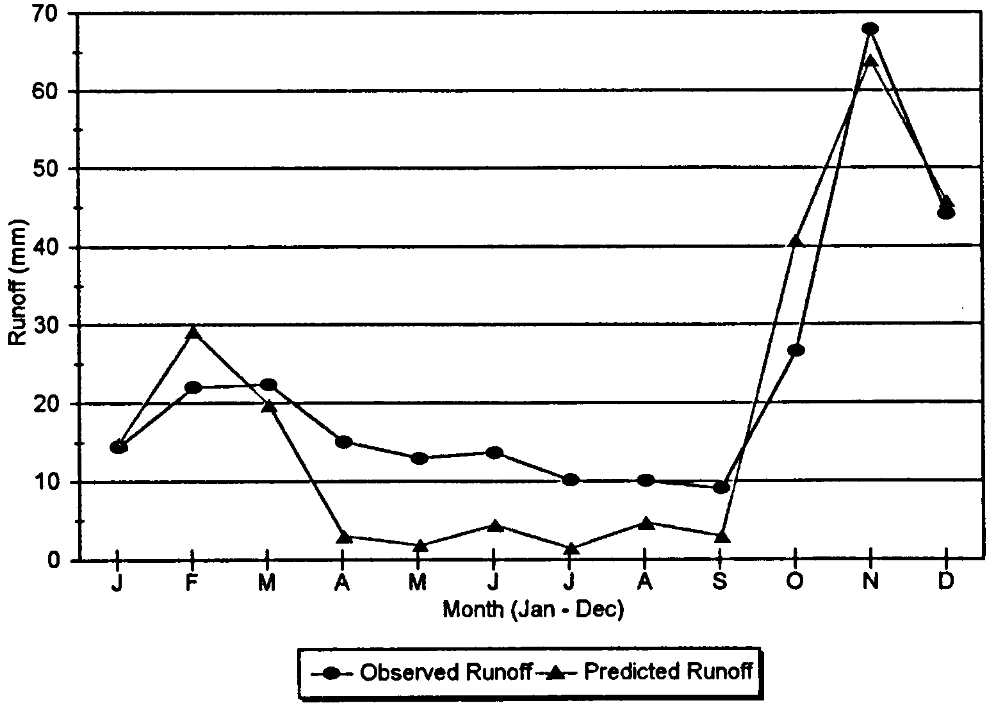


Figure 6.2b
SWRRBWQ Verification Run (1990)



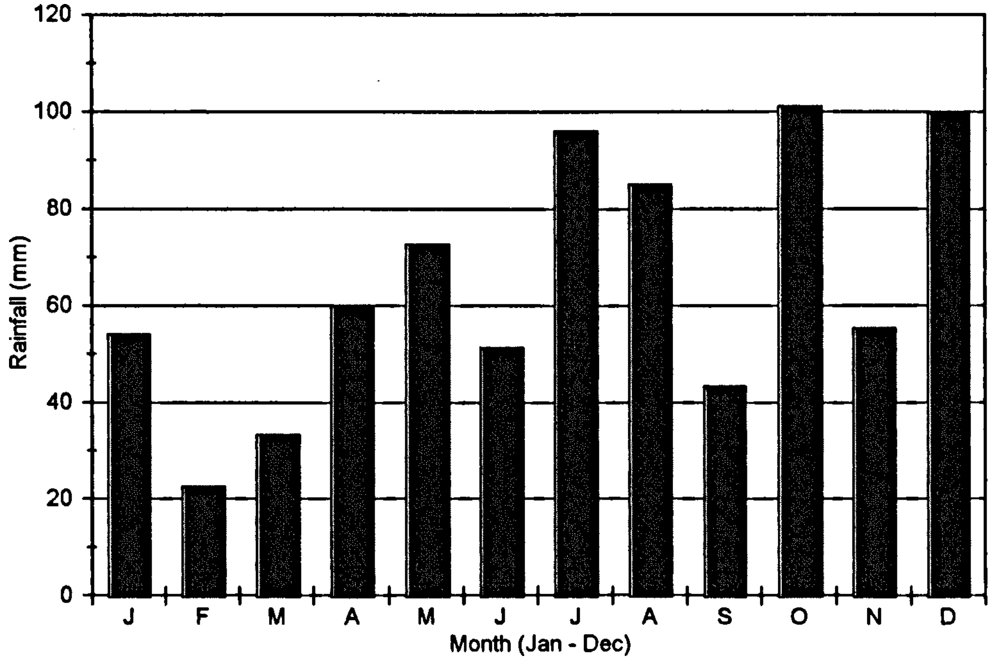


Figure 6.3a
Monthly Rainfall - 1993

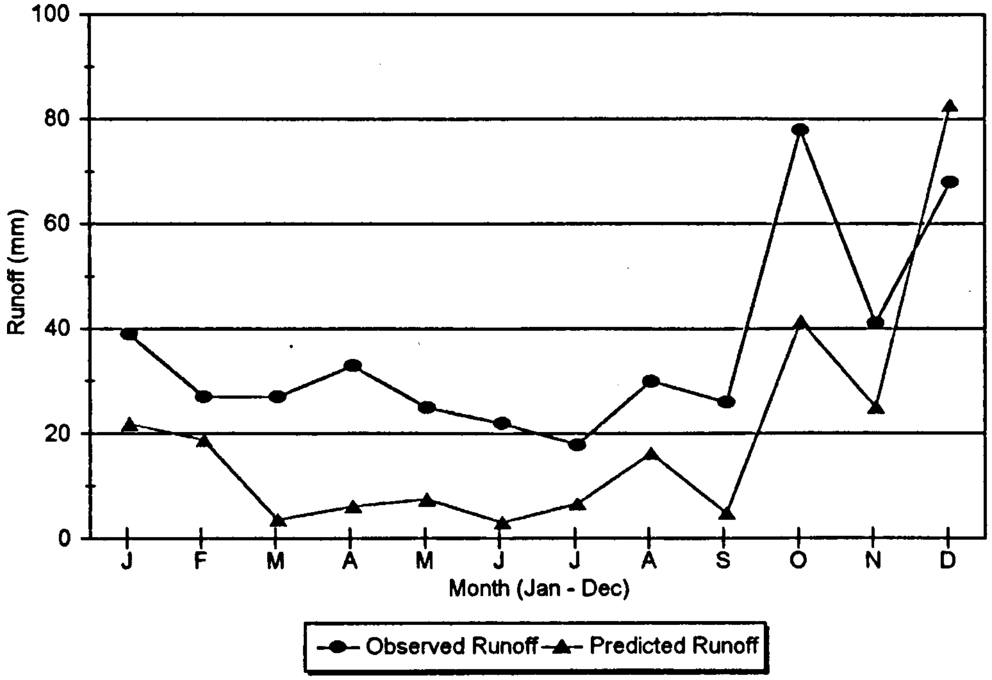


Figure 6.3b
SWRRBWQ Verification Run (1993)

as contribution from the surface and subsurface runoff, which therefore did not account for the contribution from groundwater recharge which contributes a high percentage to stream flow of the Ythan river (NERPB, 1994). The catchment has been reported to have a high baseflow index which adds significantly to total runoff of the river. This model therefore does not realistically model the groundwater recharge property of the Ythan catchment and therefore results in less total water yield. This problem also brings forth the problem of heterogeneity in the hydraulic properties of the catchment.

Although most of the areas in the catchment is underlain by impermeable clay, some areas are permeable to allow rapid movement of rainwater to the groundwater store. This somewhat limits the simulation capability of SWRRBWQ. Nevertheless, research has shown that the rate of movement of nitrate through groundwater to be slow. Nitrate that is leached from soil overlying permeable strata is going to remain in the groundwater for a number of years before being returned to the river through baseflow (Rodda, 1995). SWRRBWQ model has been continuously upgraded and recently allows the contribution from shallow aquifer to be simulated (Arnold *et al.*, 1993).

The two sources of water loss from the system are evapotranspiration and percolation. The model simulates 419.42 mm for the ET which is within acceptable range for the Ythan catchment. The potential evapotranspiration reported by the meteorological office is 510 mm for 30 year average of 1961 - 1990 (Table 2.4). For 1990, the calculated PE (Potential evapotranspiration) and AE (actual evapotranspiration) are 542mm and 493 mm respectively (Met. Office, 1994).

In terms of the ratio between surface and subsurface contribution to stream flow, the model predicts that 88 % of the water yield is derived from subsurface flow while 11 % is derived from surface runoff. This ratio is very similar to that of TOPMODEL prediction (Table 5.3). This prediction is realistic considering the soil drainage characteristics of the catchment since subsurface flow is found to be dominant in permeable soils (Anderson and Burt, 1990). Deep percolation is simulated at 21.3 mm which is a reasonable estimate considering the underlying geological characteristics which is mainly impermeable clay. The most sensitive parameter affecting simulated deep percolation is the saturated conductivity.

Simulation result for 1991 is used for assessing the performance of SWRRBWQ nutrient submodel because of the availability of fertiliser estimates. The simulated nitrate loadings (sum of nitrate in surface and subsurface flow) is 23.43 kg $ha^{-1}yr^{-1}$ for 1991 of which 2.36 kg $ha^{-1}yr^{-1}$ is transported through the surface runoff and 21.07 $kgha^{-1}yr^{-1}$ through the subsurface runoff (Table 6.9). The dominant subsurface route is in agreement with most of the research in nitrate pollution which reported the subsurface route as the dominant transport route in temperate climates with undulating topography. The simulated total annual loading is within close agreement to reported nitrate loadings to surface water of between 20 - 30 $kgha^{-1}$ for the Ythan catchment (Wright *et al.*, 1991). Simulated nitrate loading shows the typical pattern of high loadings in the winter months (Figure 6.4). The monthly simulated nitrate loadings is comparable to observed loadings as shown in Figures 6.5.

Crop nitrate uptake as simulated by SWRRBWQ for spring barley is 98 $kgha^{-1}$ which is a reasonable estimate. The observed nutrient uptake is about 120 kg ha^{-1} for winter

Table 6.9

Hydrological and Nitrate Modelling of the Ythan river using SWRRBWQ (1991)

Month	Rainfall mm	SurQ mm	SSQ mm	Yield mm	Perc mm	ET mm	SW mm	SurQ NO3 kg/ha	Crop NO3 kg/ha	SSQ NO3 kg/ha	Per NO3 kg/ha
1	29.1	0.35	15.55	15.9	2.87	6.37	273.24	0.03	0	3.2	0.07
2	86.1	13.08	14.11	27.19	3.63	18.68	292	0.15	0	3.76	0.09
3	69.5	4.66	49.09	53.76	3.28	56.71	259.7	2.05	0	5.87	0.08
4	32.4	0.06	9.87	9.93	1.35	37.16	252.97	0	0	0.51	0.03
5	22.8	0	1.82	1.82	1.2	27.62	246.4	0	0.47	0.77	0.03
6	98.8	0.72	1.49	2.22	2.98	79.84	259.43	0.01	0.84	2.13	0.07
7	40.3	0.25	2.07	2.33	1.57	53.47	242.79	0	19.68	1.87	0.03
8	20.5	0	0.86	0.86	0.92	52.25	209.77	0	56.1	0.26	0.02
9	23.7	0	0.14	0.14	0.42	57.15	175.9	0	22.02	0	0.02
10	98.7	5.87	2.02	7.89	1.56	24.23	236.55	0.06	0	0.41	0.08
11	107.4	4.17	36.04	40.21	4.15	9.46	274.87	0.05	0	1.97	0.13
12	25.4	0.44	26.07	26.51	2.5	3.27	274.98	0.01	0	0.31	0.04
Annual	654.7	29.62	159.13	188.74	26.41	426.2	274.98	2.36	99.11	21.07	0.58

Figure 6.4
Simulated vs Observed NO3 Loadings

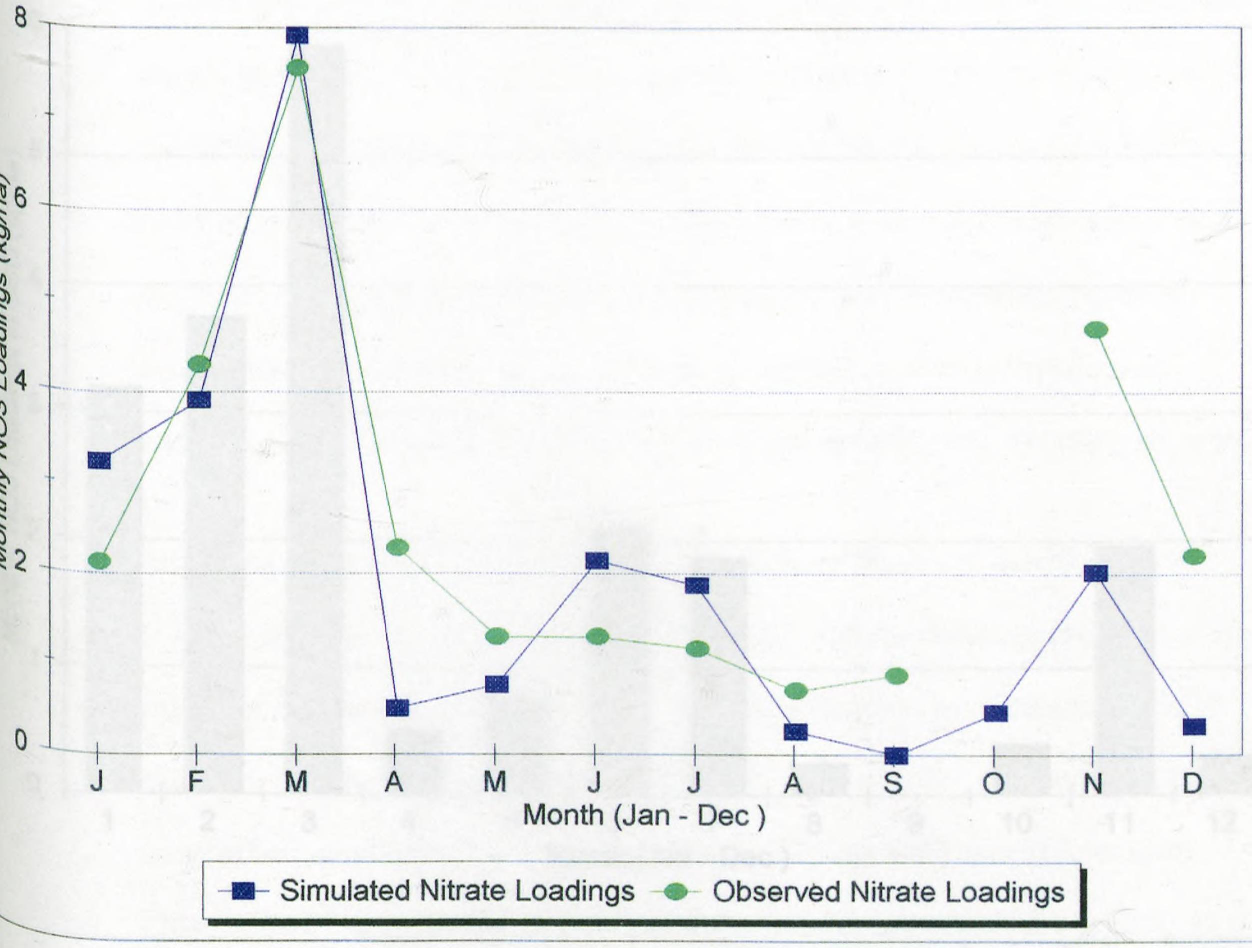
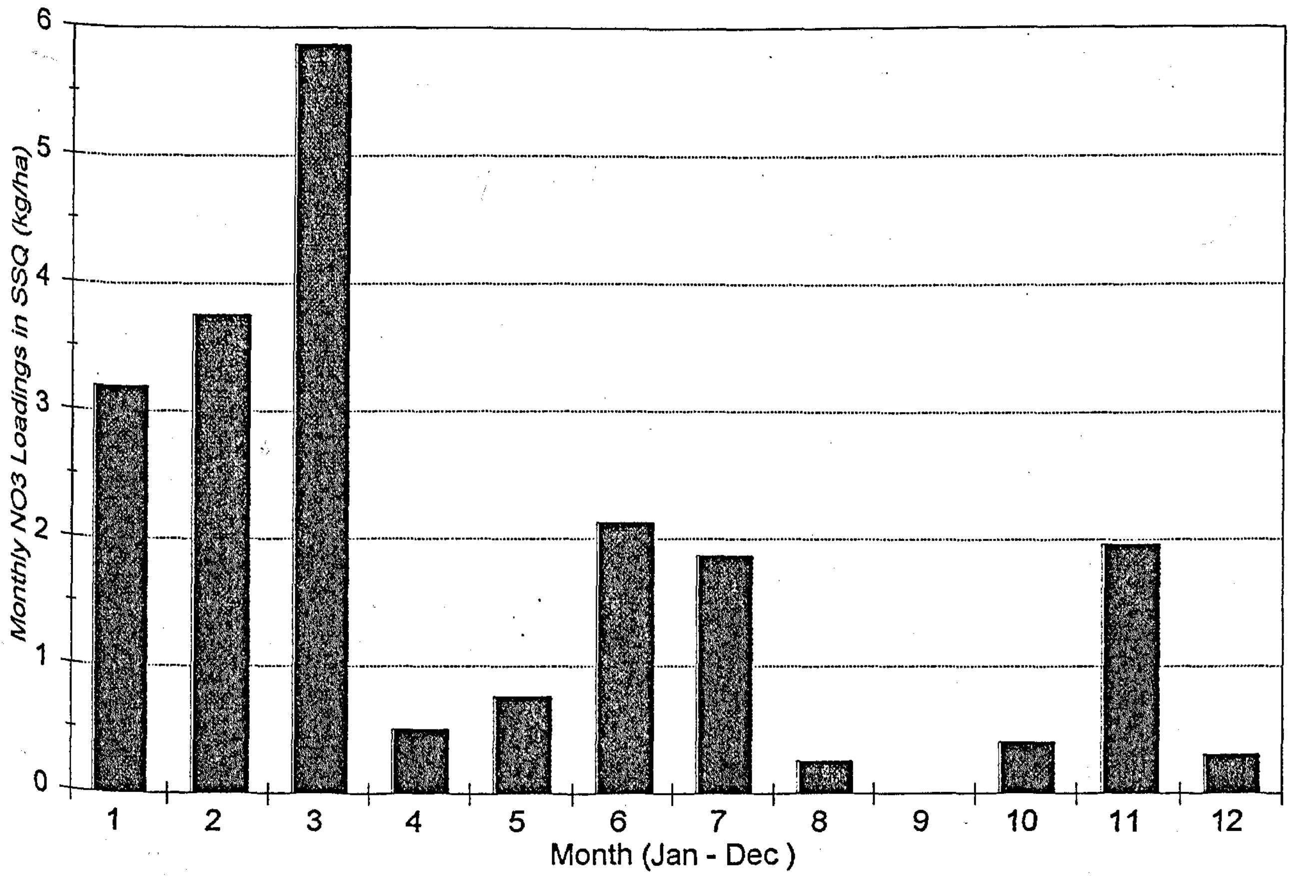


Figure 6.5
Predicted NO3 in Subsurface Flow



wheat and 98 kgha^{-1} for spring barley (personal communication with MacCaulay Land Use Institute).

6.6 Simulating Catchment Response to Different Management Practices

Despite the inability of the model to replicate fully all aspects of the hydrology of the Ythan catchment, given that the pattern of flow is successfully modelled and the nutrient submodel simulation of nitrate loadings are reasonable, the model prediction should be valid for testing the sensitivity of the catchment to different applications of nitrate fertiliser. Although the absolute value may not be accurate, the directions and the order of magnitude of change should be correct. Thus, a number of simulations were run under different management patterns. The agricultural management practices investigated were 1) different rates of fertiliser application with one application annually, 2) winter wheat, 3) winter barley, 4) spring barley and 5) temporary grass.

According to the model result, nitrate discharged to surface water is relatively low (12.99 kgha^{-1}) for fertiliser application of 78 kgha^{-1} and the discharge increases to 20 kgha^{-1} for application rate of 100 kgha^{-1}. Nitrate loading increases drastically to 78 kgha^{-1} for fertiliser application rate of 200 kgha^{-1} (Table 6.10). This finding confirms many other research findings (exp; Bergstrom and Brink, 1986; and Kolenbrander, 1981; Hansen and Djurhuus, 1996) which show that the rate of fertiliser application is the most significant factor affecting nitrate discharge and that nitrate application above the crop need, markedly increases nitrate loadings to surface water. A five year study (1987-1992), was conducted in a permanent field trial with continuous spring barley on a coarse sandy soil at Jyndevad, Denmark. The trial was fertilized with calcium

Table 6.10

The effect of different nitrate application rates on nitrate loadings

Fertiliser application rates kg ha^{-1}	Nitrate lost to surface water kg ha^{-1}	Nitrate leached kg ha^{-1}	Nitrate uptake kg ha^{-1}
78 - April 30	12.99	.47	94
100 - April 30	20.65	.47	95
200 - April 30	77.89	1.06	95

Note: Date of planting March 15

Date of harvest September 30

ammonium nitrate at 60 or 120 $kgha^{-1}y^{-1}$. The annual nitrate leaching from plots fertilized with 60 and 120 $kgNha^{-1}yr^{-1}$ were 38 and 52 kg N ha^{-1} yr^{-1}, respectively (Hansen and Djurhuus, 1996). In another experiment carried out at Lincolnshire, England on a shallow limestone soil, it was found that reducing N fertiliser applications reduce N losses in all husbandry systems. Greatest nitrate losses (58 $kgha^{-1}yr^{-1}$) were associated with wheat following peas (Johnson *et al.*, 1997). This is where a tradeoff has to be reached where the disadvantage to surface water may well outweigh the advantages in terms of crop productivity. The best way of avoiding excessive nitrate loadings to rivers is to apply the right amount of fertiliser so that crop need is met without creating excess nitrate in the soil.

The simulated nitrate loadings to the surface water was 22.3 $kgha^{-1}$ for spring barley, 72.25 $kgha^{-1}$ for winter wheat, 42.8 $kgha^{-1}$ for winter barley, and 73 $kgha^{-1}$ for temporary grass (Table 6.11). The simulated nutrient loadings indicate that winter wheat and grass resulted in the highest nitrate loadings compared to spring barley. This result confirms earlier works on nitrate leaching losses associated with crop types to increase in the sequence:

grass > winter cereals > spring cereals > root crops > irrigated vegetables

(Jones and Biagi, 1987) and modelling work with EPIC which showed winter wheat consistently yields the highest nitrate emission (Allanson *et al.*, 1993). Other more recent work which indicates a higher nitrate lost associated with wheat is Hansen and Djurhuus, 1996. This work thus further supports the hypothesis that the trend towards

Table 6.11

Effect of changing cropping pattern on nitrate loadings

Crop type	Amount of fertiliser applied (kgha$^{-1)}$	Nitrate lost to surface water (kgha$^{-1)}$	Nitrate uptake (kgha$^{-1)}$	Nitrate leached (kgha$^{-1)}$
Spring barley	March 15 78	22.3	85	.46
Winter wheat (205 kgha^{-1})	March 15; 40 April 1; 150 Sept. 15 15	72.25	95.21	1.07
Winter barley (140 kgha^{-1})	March 15; 40 April 1; 100	42.8	95.21	1.03
Temporary grass (190 kgha^{-1})	March 15; 40 April 1; 90 May 15; 30 June 15; 30	73.45	95.21	1.06

more land used for winter crops (mainly winter wheat) is one of the main reasons for the higher nitrate loadings to the Ythan river.

CHAPTER 7

Conclusion and Recommendations

Since their initial introduction in the mid 1950s and early 1960s, the use of computer models by individuals and organizations has increased continually. This research explores the use of process-based mathematical models specifically TOPMODEL and SWRRBWQ in simulating catchment scale hydrological and nitrate transport processes. TOPMODEL is a physically based model with a simple structure and takes advantage of the advances in computer technology in allowing the hydrological index to be derived from ordinary topographic data. SWRRBWQ is a fully distributed hydrological model and water quality model with built in nitrate submodel which allows simulation of nitrate loadings from different agricultural management practices.

The analysis of available data showed that the mean nitrate concentration in the Ythan river between 1983-1993 were 6.7 mgl^{-1} with seasonal averages of 7.2 mgl^{-1} for winter, 6.7 mgl^{-1} for spring, 5.41 mgl^{-1} for summer and 6.1 mgl^{-1} for autumn. It was also found that annual mean nitrate concentration had been increasing steadily in the study period especially after 1990. The seasonal nitrate concentrations in the Ythan catchment showed the typical nitrate pattern with high concentration in winter months and low concentration in the summer. This is a typical characteristics of the nitrate pattern in river water draining agricultural catchment which reflects the processes going on in the soil such as mineralization and the crop requirements for nitrate. The annual loadings, however, did not show the positive trends because of the high variation in annual flow. Since 1990, 1991, and 1992 experienced low annual runoff compared to year 1985 or 1986 for example, the increase in nitrate concentration was not evident in the loads. Even though there is no apparent trend in nitrate loadings, the fact that nitrate concentration has been on the increase is a factor which need to be taken seriously by the local authority. High nitrate concentrations have been said to be the cause of the eutrophication of the river estuary (Raffaelli, 1989).

Correlation analysis between nitrate and other variables were carried out. It was found that nitrate was most correlated to river flow with an R^2 value of 0.44 ($p > 0.01$) between nitrate concentration and flow and 0.56 ($p > 0.01$) with the logarithm of flow. This correlation shows the importance of flow as a determinant of nitrate concentrations in water, but flow variation alone could not account for differences in land use and fertilization rate that have occurred in the Ythan catchment.

TOPMODEL was applied to the Ythan catchment to evaluate its performance in simulating river flow. The most sensitive TOPMODEL parameters were M, T_o, and SRMAX. The parameter set optimized for the Ythan catchment for M, T_o, and SRMAX were 0.038m, 0.08 $m^2 h^{-1}$, and 0.015 m respectively. Using this parameter set TOPMODEL efficiency was 74 % for the calibration period and 54 % for the verification period. This low modelling efficiency can be attributed to inadequate representation of the saturated contributing area (which was derived from the catchment topographic index) which in turn affects model prediction of catchment response to quick flow. This deficiency needs to be addressed in future work through more extensive topographic analysis. Nevertheless, TOPMODEL adequately simulates total water yield (prediction of 412 mm versus 434 observed). This indicates that TOPMODEL, with its minimal model parameters, is capable of capturing the most important elements affecting catchment water balance.

Even though TOPMODEL is a physically based model, its catchment representation is conceptual in nature, and is most useful as a tool to understand certain catchment response at a small scale. The model is a simplified physical representation of the flow processes with the aim of minimizing the number of parameters to be calibrated. More research needs to be done to apply TOPMODEL as a catchment scale model and to subsequently extend it to understand catchment response to changing agricultural management practices. A nitrate submodel which fits the TOPMODEL hydrological structure could be constructed and tested. This could be in the form of subroutines for daily mass balance model of nitrate in soil . In addition, the topographic index and the combined topographic and soil index, which are indices of hydrological similarity at a point within the catchment, should be explored further since similarity implied by this index could be used in terms of leaching allowing areas susceptible to nitrate leaching to be mapped.

As a conclusion it can be summarized that the main advantages of TOPMODEL are:

1) its simplicity and therefore require small number of parameters to be calibrated
2) its model structure which allows runoff to be separated into surface and baseflow

components which is useful in nitrate modelling, and

3) the ln (a/tanβ) and ln ($a/T_o\tan\beta$) index are potentially useful in mapping areas susceptible to nitrate leaching

SWRRBWQ is another process-based model which was calibrated and tested to the Ythan river using available hydrological and climate data. The research indicates the ability of the model to simulate the pattern of flow in the Ythan catchment but the total annual yield simulated was disappointing. The model underpredicted total runoff in all the three years under study. Nevertheless, the model showed a good performance in simulating the monthly variation in runoff. The underestimateion of the annual flow must relate to a value of some model attribute such as hydraulic property being inadequately quantified or not represented by the model.

The capability of SWRRBWQ to assess catchment nitrate loadings under different fertilization rates was also demonstrated. Application rates of 78, 100, and 200 kg ha^{-1} resulted in simulated nitrate loadings of 13, 20, and 78 $kgha^{-1}$ respectively. Changing agricultural management practices were simulated by changing the rate and timing of fertilizer application. Simulated nitrate loadings for grass, winter wheat, winter barley, and spring barley were 72.3, 73, 43, and 23 $kgha^{-1}$ respectively. This result is in agreement with other studies (such as; Jones and Biagi, 1987, Hansen and Djurhuus, 1996; Johnson *et al.*, 1997) which show winter crops and grass tends to lose more nitrates compared to spring crops mainly as a result of more fertilizer being applied. The simulated loading also showed the seasonal characteristics of nitrate loadings with peaks during late autumn and winter.

From the sensitivity analysis of SWRRBWQ parameters, it was determined that basin lag time, return flow travel time, and SCS curve number were the most sensitive basin parameters, while AWC, SC, and the initial nitrate contents of soil were the most sensitive soil parameters for calibrating the hydrological and nitrate submodel. SC is a very sensitive parameter that controls leaching of nitrate from soils. Soils with higher saturated conductivity tend to lose more nitrate through leaching. Since saturated conductivity is closely related to permeability of soils, less permeable soil such as clay tends to lose less nitrate through leaching compared to loamy soils. This leaching rates confirm the work of Webster *et al.*, 1986 and Kolenbrander (1981) who showed leaching rate of 74 $kgha^{-1}$ for sandy loam and 41 kg ha^{-1} for clay loams. AWC, which is closely associated to soil texture, is another sensitive model parameter in controlling nitrate loadings. Lateral transport of nitrate is sensitive to this parameter where soils with lower AWC is shown to lose more nitrate through subsurface route. Soils with high AWC such as clay and peat soils tend to lose less nitrate through subsurface flow compared to sandy or sandy loam soil. Initial nitrate concentration in the soil also controls nitrate lost through leaching and subsurface runoff. Obviously when there is more nitrate in the soil either through fertilization or the mineralization of organic nitrogen in soil, more nitrate is available for transport. A knowledge of soil nitrate concentration at the beginning of the modelling period would greatly enhance the accuracy of model simulations.

This study has shown the application of SWRRBWQ in simulating the relative amount of nitrate loadings as affected by different agricultural management practices. Nevertheless, the nutrient submodel contains a number of weaknesses. As discussed in Chapter 3, nitrate cycling in agricultural lands is complex. Nitrate transported into the water course may come from sources such as mineralisation of soil organic matter in addition to direct contribution from fertiliser application. One of the inadequacy of SWRRBWQ nutrient submodel is that it does not account for nitrate contribution from the mineralisation of soil organic matter. Mineralisation of soil organic matter is known to contribute significantly to soil nitrate budget in agricultural systems (Burt *et al.*, 1993). The other elements of nitrate cycling that were not accounted for were nitrate contribution from the rainfall and denitrification processes. These processes might change the nitrate budget of the system under study and therefore needs to be addressed in future work.

One important aspect of modelling that is not examined in this study is the spatial component which is becoming very popular with the advance of fast computers. TOPMODEL and SWRRBWQ are both physically distributed models that can be used for this purpose in combination with a geographic information systems package. It would be very interesting to apply these two models as spatially distributed parameter models for assessing the importance of spatial variability in the control of catchment response to land use changes.

This study is a first effort at applying process-based hydrological models to the Ythan catchment. There was very little process-based hydrological modelling of this catchment prior to this. As a good hydrological model is a prerequisite for good nutrient modelling, further work needs to be done to verify the hydrological parameter values selected for the catchment. Thus the model results should be regarded as a pioneering work rather than a definitive model for the Ythan catchment.

This study has shown the advantage of using process-based model in water resource management in an agricultural watershed. Even-though more effort is required to build and run these models, they are more useful than statistical models especially in a changing environmental system.

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Appendix 1

	C1	C2	C3	C4	C6	C7
	Date	Nitrate	Flow	Load	Temp	Log Flow
1	830818	5.56	1.914	0.9190	17.0	0.28194
2	830906	5.61	1.380	0.6690	11.5	0.13988
3	831110	5.22	2.018	0.9100	8.5	0.30492
4	840111	7.66	13.360	8.8420	5.0	1.12581
5	840209	7.81	22.070	14.8920	3.0	1.34380
6	840315	6.24	10.910	5.8820	5.0	1.03782
7	840426	6.55	6.032	3.4140	10.5	0.78046
8	840524	5.68	3.728	1.9300	13.5	0.57148
9	840614	5.76	2.996	1.4910	13.0	0.47654
10	840718	4.34	1.781	0.6680	17.5	0.25066
11	840726	4.81	1.409	0.5860	15.5	0.14891
12	840726	4.90	1.409	0.5960	15.5	0.14891
13	840726	4.94	1.409	0.6010	15.5	0.14891
14	840816	4.69	1.239	0.5020	16.0	0.09307
15	840822	4.61	1.104	0.4400	18.0	0.04297
16	840925	4.11	3.195	1.1350	10.5	0.50447
17	841016	4.90	2.566	1.0860	10.0	0.40926
18	841113	7.92	17.950	12.2830	8.5	1.25406
19	841204	7.22	14.320	8.9330	7.5	1.15594
20	850109	6.86	22.170	13.1402	5.0	1.34577
21	850206	6.82	12.730	7.5011	5.5	1.10483
22	850305	6.40	7.103	3.9277	6.0	0.85144
23	850326	6.81	8.913	5.2443	6.0	0.95002
24	850507	6.61	6.131	3.5014	10.0	0.78753
25	850604	6.06	5.297	2.7734	14.0	0.72403
26	850703	5.67	5.602	2.7443	13.5	0.74834
27	850731	5.84	10.480	5.2879	13.0	1.02036
28	850829	5.45	9.531	4.4879	11.0	0.97914
29	851003	6.10	9.135	4.8145	12.0	0.96071
30	851126	5.10	14.880	6.5567	5.0	1.17260
31	860121	7.03	16.030	9.7365	3.0	1.20493
32	860220	6.31	8.019	4.3718	2.0	0.90412
33	860320	6.38	8.363	4.6100	6.0	0.92236
34	860416	7.19	11.690	7.2620	5.0	1.06781
35	860605	5.57	3.778	1.8182	11.0	0.57726
36	860723	4.55	2.613	1.0272	14.0	0.41714
37	860909	4.12	2.168	0.7717	11.0	0.33606
38	861113	4.74	2.895	1.1856	8.0	0.46165
39	870226	7.55	9.358	6.1044	4.0	0.97118
40	870324	6.71	11.110	6.4409	5.5	1.04571
41	870415	7.44	16.400	10.5421	9.5	1.21484
42	870609	5.49	5.240	2.4855	11.0	0.71933
43	870915	5.37	3.316	1.5385	11.5	0.52061
44	871021	5.79	33.330	16.6735	10.0	1.52284
45	871119	6.73	7.254	4.2180	6.0	0.86058
46	871126	7.59	12.280	8.0529	3.0	1.08920
47	880106	7.31	12.040	7.6043	3.0	1.08063
48	880211	6.49	24.730	13.8670	4.0	1.39322
49	880303	6.68	16.960	9.7885	4.0	1.22943
50	880406	7.64	9.341	6.1660	9.5	0.97039
51	880526	7.28	5.163	3.2475	13.0	0.71290
52	880607	6.47	4.181	2.3372	17.0	0.62128
53	880811	5.24	3.423	1.5497	15.0	0.53441
54	881005	5.81	4.005	2.0104	12.0	0.60260
55	881020	5.89	37.350	19.0073	10.0	1.57229
56	881108	7.34	8.757	5.5535	7.5	0.94236
57	881129	6.88	10.080	5.9919	6.0	1.00346
58	890111	7.41	5.274	3.3765	4.0	0.72214
59	890209	7.42	3.617	2.3188	7.0	0.55835
60	890314	6.17	5.083	2.7097	6.0	0.70612

Appendix 1

C1 Date	C2 Nitrate	C3 Flow	C4 Load	C6 Temp	C7 Log Flow
890426	6.22	3.601	1.9354	7.0	0.55642
890523	5.59	2.876	1.3890	15.0	0.45879
890705	5.27	1.879	0.8556	21.0	0.27393
890815	4.60	1.348	0.5357	18.0	0.12969
890913	5.34	1.471	0.6787	13.9	0.16761
891018	5.20	1.897	0.8523	10.8	0.27807
891114	5.52	1.783	0.8504	8.0	0.25115
891213	5.91	1.692	0.8640	2.0	0.22840
901118	6.11	2.078	1.0970	3.5	0.31765
900221	8.93	3.999	3.0854	6.0	0.60195
900327	6.72	3.283	1.9061	6.5	0.51627
900426	5.86	2.498	1.2647	9.5	0.39759
900523	5.25	2.323	1.0537	14.5	0.36605
900719	4.21	1.593	0.5794	19.5	0.20222
900808	4.53	1.523	0.5961	15.5	0.18270
901004	5.95	3.072	1.5792	10.5	0.48742
901025	6.70	2.436	1.4102	10.0	0.38668
901121	8.13	7.748	5.4424	5.0	0.88919
901211	8.72	9.804	7.3864	4.5	0.99140
910116	7.99	5.195	3.5863	2.5	0.71559
910220	8.89	9.437	7.2485	4.5	0.97483
910314	9.70	15.220	12.7556	7.0	1.18241
910423	7.65	5.834	3.8560	8.5	0.76597
910530	6.74	3.353	1.9526	12.5	0.52543
910619	5.52	4.586	2.1872	12.5	0.66143
910718	5.77	3.946	1.9672	13.5	0.59616
910828	5.91	2.326	1.1877	14.0	0.36661
910924	5.97	2.897	1.4943	11.5	0.46195
911113	8.28	11.090	7.9337	5.0	1.04493
911120	9.71	14.120	11.8489	5.5	1.14983
911117	8.09	5.370	3.7535	5.0	0.72997
920107	7.92	6.209	4.2487	6.0	0.79302
920212	7.98	4.826	3.3274	3.0	0.68359
920305	8.05	4.699	3.2682	7.0	0.67201
920402	10.40	11.120	9.9920	5.5	1.04610
920507	8.99	8.435	6.5518	12.0	0.92609
920618	7.39	3.430	2.1900	14.5	0.53529
920716	6.69	2.365	1.3670	15.5	0.37383
920806	6.05	1.645	0.8598	15.5	0.21617
920826	5.25	2.298	1.0424	14.0	0.36135
920922	5.69	7.184	3.5318	10.5	0.85637
921103	8.14	20.860	14.6708	6.5	1.31931
921118	9.01	11.650	9.0691	5.0	1.06633
930113	8.59	5.909	4.3855	2.5	0.77151
930224	8.15	4.926	3.4687	6.0	0.69249
930324	8.18	4.080	2.8835	5.5	0.61066
930406	7.07	6.140	3.7506	6.5	0.78817
930505	7.93	4.306	2.9503	10.0	0.63407
930630	6.74	3.561	2.0737	14.0	0.55157
930802	6.04	3.575	1.8656	14.5	0.55328
930817	6.75	5.030	2.9334	12.5	0.70157
930915	6.64	5.549	3.1834	10.5	0.74421
931014	8.04	17.580	12.2120	7.5	1.24502
931020	8.89	14.040	10.7841	8.5	1.14737
931123	8.10	6.605	4.6224	2.5	0.81987
940112	8.95	25.550	19.7573	*	1.40739
940202	8.62	11.720	8.7287	*	1.06893
940302	6.60	41.960	23.9273	*	1.62284
940406	9.07	6.562	5.1423	*	0.81704
940504	8.21	5.120	3.6318	*	0.70927

Appendix 1

C1	C2	C3	C4	C6	C7
Date	Nitrate	Flow	Load	Temp	Log Flow
940531	7.63	3.524	2.3231	*	0.54704
940615	7.39	2.988	1.9078	*	0.47538
940720	6.68	1.947	1.1237	*	0.28937
940809	6.76	1.539	0.8989	*	0.18724
941005	5.67	2.958	1.4491	*	0.47100
941019	6.71	1.559	0.9038	*	0.19285
941115	7.72	6.174	4.1181	*	0.79057

APPENDIX 2

```
C  TOPMODEL DEMONSTRATION PROGRAM VERSION 95.01
C
C
C  Compiled using Lahey Fortran77 and Grafmatic Graphics
C
C  This version by Keith Beven 1985
C  Revised for distribution 1993,1995
C
C*************************************************************
************
C  This program is distributed freely with only two
conditions.
C
C  1. In any use for commercial or paid consultancy purposes a

C     suitable royalty agreement must be negotiated with
Lancaster
C     University (Contact Keith Beven)
C
C  2. In any publication arising from use for research
purposes the
C     source of the program should be properly acknowledged
and a
C     pre-print of the publication sent to Keith Beven at the
address
C     below.
C
C  All rights retained 1993, 1995
C  Keith Beven
C  Centre for Research on Environmental Systems and Statistics
C  Institute of Environmental and Biological Sciences
C  Lancaster University, Lancaster LA1 4YQ, UK
C
C  Tel: (+44) 1524 593892  Fax: (+44) 1524 593985
C  Email:  K.Beven@UK.AC.LANCASTER
C
C*************************************************************
************
C
C  SIMPLE SUBCATCHMENT VERSION OF TOPMODEL
C
C  This program allows single or multiple subcatchment
calculations
C  but with single average rainfall and potential
evapotranspiration
C  inputs to the whole catchment.  Subcatchment discharges are
routed
C  to the catchment outlet using a linear routing algorithm
with
C  constant main channel velocity and internal subcatchment
C  routing velocity.  The program requires ln(a/tanB)
distributions
C  for each subcatchment.  These may be calculated using the
C  GRIDATB program which requires raster elevation data as
input.
C  It is recommended that those data should be 50 m resolution
or
```

```
C  better.
C
C  NOTE that TOPMODEL is not intended to be a traditional
model
C  package but is more a collection of concepts that can be
used
C  **** where appropriate ****. It is up to the user to verify
that
C  the assumptions are appropriate (see discussion in
C  Beven et al.(1994).   This version of the model  will be
C  best suited to catchments with shallow soils and moderate
C  topography which do not suffer from excessively long dry
C  periods.  Ideally predicted contributing areas should be
C  checked against what actually happens in the catchment.
C
C  It includes infiltration excess calculations and parameters
C  based on the exponential conductivity Green-Ampt model of
C  Beven (HSJ, 1984) but if infiltration excess does occur it
C  does so over whole area of a subcatchment.  Spatial
variability
C  in conductivities can however be handled by specifying
C  Ko parameter values for different subcatchments, even if
they
C  have the same ln(a/tanB) and routing parameters, ie. to
C  represent different parts of the area.
C
C  Note that time step calculations are explicit ie. SBAR
C  at start of time step is used to determine contributing
area.
C  Thus with long (daily) time steps contributing area depends
on
C  initial value together with any volume filling effect of
daily
C  inputs.  Also baseflow at start of time step is used to
update
C  SBAR at end of time step
C
C*****************************************************************
************001
C  Current program limits are:
C          Number of time steps = 2500
C          Number of subcatchments = 10
C          Number of ln(a/tanB) increments = 30
C          Number of subcatchment routing ordinates = 10
C          Number of time delay histogram ordinates = 20
C          Size of subcatchment pixel maps = 100 x 100
C
C  Limits are mostly set in Common blocks in file TMCOMMON.FOR
C-----------------------------------------------------------------
------------002
C
C  This version uses five files as follows:
C       Channel 4 "TOPMOD.DAT" contains run and file
information
C       Channel 7 <INPUTS$> contains rainfall, pe and qobs
data
C       Channel 8 <SUBCAT$> contains subcatchment data
```

```
C        Channel 9 <PARAMS$> contains parameter data
C        Channel 10 <OUTPUT$> is output file

C   In addition
C        Channel 12 <MAPFILE$> is used to read subcatchment
ln(a/tanB)
C                    maps if IMAP = 1
C
C
C*****************************************************************
************003
*
*  Declarations
      INCLUDE TMCOMMON.FOR
      CHARACTER*15 INPUTS$,SUBCAT$,PARAMS$,OUTPUT$
*-----------------------------------------------------------------
------------004
      OPEN(4,FILE="TOPMOD.RUN",STATUS="OLD")
      READ(4,"(A)")TITLE
      READ(4,"(A)")INPUTS$
      READ(4,"(A)")SUBCAT$
      READ(4,"(A)")PARAMS$
      READ(4,"(A)")OUTPUT$
      OPEN(7,FILE=INPUTS$,STATUS="OLD")
      OPEN(8,FILE=SUBCAT$,STATUS="OLD")
      OPEN(9,FILE=PARAMS$,STATUS="OLD")
      OPEN(10,FILE=OUTPUT$)
*-----------------------------------------------------------------
------------005
      WRITE(10,1001)TITLE
 1001 FORMAT(1x,A)
      Write(6,1002)title
 1002 Format(///1x,'TOPMODEL Version: TMOD95.01'////
     11x,'This run :'/1x,A//////////
     11x,'Centre for Research on Environmental Systems and
Statistics'/
     21x,'Lancaster University, Lancaster LA1 4YQ, UK')
      Write(6,602)
  602 format(/1x,'                            Press return to
continue'/)
      Read(5,*)
*-----------------------------------------------------------------
------------006
C
C  READ IN DT and RAINFALL, PE, QOBS INPUTS
      CALL INPUTS
C
C  READ IN SUBCATCHMENT TOPOGRAPHIC DATA
      READ(8,*)NSC,IMAP,IOUT
C
C  OPEN PARAMETER FILE AND READ CHV

C  START LOOP ON SUBCATCHMENTS
      DO 10 ISC=1,NSC
      If(iout.ge.2)Write(10,600)ISC
  600 Format(1x,'Starting Subcatchment',I6)
C
```

```
C  INITIALISATION FOR THIS SUBCATCHMENT
      CALL TREAD
      CALL INIT
C
C  RUN MODEL FOR THIS SUBCATCHMENT INCLUDING LINEAR ROUTING
CALCULATIONS
      CALL TOPMOD

C
C  END LOOP ON SUBCATCHMENTS
C
   10 CONTINUE
C  CALL RESULTS ROUTINE:  if IRUN = 0 on return stop
      CALL RESULTS
c  IRUN Disabled at present
      CLOSE(5)
      CLOSE(7)
      CLOSE(8)
      CLOSE(9)
      CLOSE(10)
      STOP
      END
C*************************************************************
************007
C
      SUBROUTINE TOPMOD
C
      INCLUDE TMCOMMON.FOR
      DIMENSION EX(30)
C
C*************************************************************
****
C
C  THIS ROUTINE RUNS TOPMODEL FOR ONE SUBCATCHMENT, INCLUDING
THE
C  LINEAR CHANNEL ROUTING CALCULATIONS.
C
C  The calculations are made for areal subdivisions based on
the
C  NAC ln(a/tanB) subdivisions.  The saturation deficit for
each
C  subdivision is calculated from SBAR at the start of each
time
C  step.
C
C  Each increment also has a root zone storage (SRZ) deficit
which
C  is 0 at 'field capcacity' and becomes more positive as the
soil
C  dries out; and an unsaturated zone storage (SUZ) which is
zero at
C  field capacity and becomes more positive as storage
increases.
C  SUZ has an upper limit of the local saturation deficit SD.
C  The local contributing area is where SD - SUZ is less than
or
C  equal to zero.
```

```
C
C  REMEMBER SBAR,SD AND SRZ VALUES ARE DEFICITS; SUZ IS A
STORAGE.
C
***************************************************************
****
      IROF=0
      REX=0.
      CUMF=0.
      ACMAX=0.
      SUMP=0.
      SUMAE = 0.
      SUMQ=0.
C
C  Initialise contributing area counts
      IHROF = 0
      do 5 ia = 1, nac
    5 ihour(ia)=0
*------------------------------------------------------------
------------008
C
C  START LOOP ON TIME STEPS
      If(IOUT.ge.2)Write(10,101)
  101 format(1x,'  it        p        ep        q(it)
quz',
     1'       q        sbar       qof')
C
      DO 10 IT=1,NSTEP
      QOF=0.
      QUZ=0.
C
      EP=PE(IT)
      P=R(IT)
      SUMP = SUMP + P
*------------------------------------------------------------
------------009
C
C  SKIP INFILTRATION EXCESS CALCULATIONS IF INFEX = 0
      IF(INFEX.EQ.1) THEN
C
C  INFILTRATION EXCESS CALCULATIONS USING EXPINF ROUTINE BASED
ON
C  GREEN-AMPT INFILTRATION IN A SOIL WITH CONDUCTIVITY
DECLINING
C  EXPONENTIALLY WITH DEPTH (REF. BEVEN, HSJ, 1984)
C
C  NOTE THAT IF INFILTRATION EXCESS DOES OCCUR IT WILL DO SO
OVER
C  THE WHOLE SUBCATCHMENT BECAUSE OF HOMOGENEOUS SOIL
ASSUMPTION
C  BUT AREAS OF DIFFERENT SOIL CHARACTERISTCS  CAN BE HANDLED
AS
C  DIFFERENT SUBCATCHMENT CONTRIBUTIONS TO THE WHOLE
C
C  ALL PARAMETERS AND VARIABLES ON INPUT MUST BE IN M/H
C
C  THIS SECTION CAN BE OMITTED WITHOUT PROBLEM
```

```
*-------------------------------------------------------------
------------010
C
      IF(P.GT.0.)THEN
C
C  Adjust Rainfall rate from m/time step to m/h
            RINT = P/DT
            CALL EXPINF(IROF,IT,RINT,DF,CUMF)
C  DF is volumetric increment of infiltration and is returned
in m/DT
            REX = P - DF
            P= P - REX
     If(IROF.EQ.1)IHROF = IHROF + 1
        ELSE
            REX=0.
     IROF=0
            CUMF=0.
        ENDIF
       ENDIF
C
C P IS RAINFALL AVAILABLE FOR INFILTRATION AFTER SURFACE
CONTROL
C   CALCULATION
*-------------------------------------------------------------
------------011
C
      ACM=0.
C  START LOOP ON A/TANB INCREMENTS
      DO 30 IA=1,NAC
      ACF=0.5*(AC(IA)+AC(IA+1))
      UZ=0.
      EX(IA)=0.
C
C  CALCULATE LOCAL STORAGE DEFICIT
      SD(IA)=SBAR+SZM*(TL-ST(IA))
      IF(SD(IA).LT.0.)SD(IA)=0.
C
C  ROOT ZONE CALCULATIONS
      SRZ(IA) = SRZ(IA) - P
      IF(SRZ(IA).LT.0.)THEN
       SUZ(IA) = SUZ(IA) - SRZ(IA)
       SRZ(IA) = 0.
      ENDIF
C
C  UZ CALCULATIONS
      IF(SUZ(IA).GT.SD(IA))THEN
       EX(IA) = SUZ(IA) - SD(IA)
       SUZ(IA)=SD(IA)
      ENDIF
C
C  CALCULATE DRAINAGE FROM SUZ
      IF(SD(IA).GT.0.)THEN
       UZ=SUZ(IA)/(SD(IA)*TD)
       IF(UZ.GT.SUZ(IA))UZ=SUZ(IA)
       SUZ(IA)=SUZ(IA)-UZ
       IF(SUZ(IA).LT.0.0000001)SUZ(IA)=0.
       QUZ=QUZ+UZ*ACF
```

```
      ENDIF
*-----------------------------------------------------------------
------------012
C
C  CALCULATE EVAPOTRANSPIRATION FROM ROOT ZONE DEFICIT
C
      EA=0.
      IF(EP.GT.0.)THEN
       EA=EP*(1 - SRZ(IA)/SRMAX)
       IF(EA.GT.SRMAX-SRZ(IA))EA=SRMAX-SRZ(IA)
       SRZ(IA)=SRZ(IA)+EA
      ENDIF
      SUMAE = SUMAE + EA * ACF
      SAE = SAE + EA *ACF
*-----------------------------------------------------------------
------------013
C
C
C  CALCULATION OF FLOW FROM FULLY SATURATED AREA
C  This section assumes that a/tanB values are ordered from
high to low
C
      OF=0.
      IF(IA.GT.1)THEN
       IB=IA-1
       IF(EX(IA).GT.0.)THEN
c  Both limits are saturated
            OF=AC(IA)*(EX(IB)+EX(IA))/2
            ACM=ACM+ACF
            ihour(ib) = ihour(ib) + 1
        ELSE
c  Check if lower limit saturated (higher a/tanB value)
            IF(EX(IB).GT.0.)THEN
             ACF=ACF*EX(IB)/(EX(IB)-EX(IA))
             OF=ACF*EX(IB)/2
             ACM=ACM+ACF
             ihour(ib) = ihour(ib) + 1
            ENDIF
        ENDIF
      ENDIF
      QOF=QOF+OF
C
C  Set contributing area plotting array
      CA(IT) = ACM
      IF(ACM.GT.ACMAX)ACMAX=ACM
C
C  END OF A/TANB LOOP
   30 CONTINUE

*-----------------------------------------------------------------
------------014
C
C  ADD INFILTRATION EXCESS
      QOF=QOF+REX

      IF(IROF.EQ.1)ACMAX=1.
C
```

```
C  CALCULATE SATURATED ZONE DRAINAGE
      QB=SZQ*EXP(-SBAR/SZM)
      SBAR=SBAR-QUZ+QB
      QOUT=QB+QOF
      SUMQ=SUMQ+QOUT
*-----------------------------------------------------------------
------------015
C
C  CHANNEL ROUTING CALCULATIONS
C  allow for time delay to catchment outlet ND as well as
C  internal routing array
      DO 40 IR=1,NR
      IN=IT+ND+IR-1
      IF(IN.GT.NSTEP)GO TO 10
      Q(IN)=Q(IN)+QOUT*AR(IR)
   40 CONTINUE
C
      If(IOUT.ge.2) write(10,100)it, p, ep, q(it), quz, qb,
sbar, qof
  100 format(1x,i4,7e10.3)

C  END OF TIME STEP LOOP
   10 CONTINUE
*-----------------------------------------------------------------
------------016
C
C  CALCULATE BALANCE TERMS
      SUMRZ = 0.
      SUMUZ = 0.
      DO 50 IA =1,NAC
      ACF=0.5*(AC(IA)+AC(IA+1))
      SUMRZ = SUMRZ + SRZ(IA)*ACF
      SUMUZ = SUMUZ + SUZ(IA)*ACF
   50 CONTINUE
      BAL = BAL + SBAR +SUMP - SUMAE - SUMQ + SUMRZ - SUMUZ
      Write(10,650)SUBCAT,SUMP,SUMAE,SUMQ,SUMRZ,SUMUZ,SBAR,BAL
      WRITE(6,650)SUBCAT,SUMP,SUMAE,SUMQ,SUMRZ,SUMUZ,SBAR,BAL
  650 FORMAT(1X,'Water Balance for Subcatchment : ',A/
     11x,'   SUMP       SUMAE       SUMQ       SUMRZ    ',
     2   '  SUMUZ       SBAR        BAL'/7e11.4)
      If(IOUT.ge.1)WRITE(10,651)ACMAX
  651 FORMAT(1X,'Maximum contributing area ', e12.5)
      RETURN
      END
*
C****************************************************************
************017
*
      SUBROUTINE INPUTS

*
      INCLUDE TMCOMMON.FOR
*
*  This subroutine must read in rainfall, pe and observed
*  discharges for T = 1,NSTEP with time step DT hours
*
      READ(7,*)NSTEP,DT
```

```
      READ(7,*)(R(I),PE(I),QOBS(I),I=1,NSTEP)
      CLOSE(7)
      DO 10 IT = 1,NSTEP
   10 Q(IT)=0.
      RETURN
      END
C
C*****************************************************************
************018
C
      SUBROUTINE TREAD
C
      INCLUDE TMCOMMON.FOR
C
      READ(8,"(A)")subcat
      Write(10,1010)subcat
 1010 Format(1x,'Subcatchment : ',A)
      READ(8,*)NAC,AREA
*  NAC IS NUMBER OF A/TANB ORDINATES
*  AREA IS SUBCATCHMENT AREA AS PROPORTION OF TOTAL CATCHMENT
      READ(8,*)(AC(J),ST(J),J=1,NAC)
*  AC IS DISTRIBUTION OF AREA WITH LN(A/TANB)
*  ST IS LN(A/TANB) VALUE
       tarea = ac(1)
       do 10 j=2,nac
       tarea = tarea + ac(j)
   10  continue

*-----------------------------------------------------------------
------------019
*
*  CALCULATE AREAL INTEGRAL OF LN(A/TANB)
*  NB.  a/tanB values should be ordered from high to low with
ST(1)
*  as an upper limit such that AC(1) should be zero, with
AC(2) representing
*  the area between ST(1) and ST(2)
      TL=0.
      AC(1)=AC(1)/tarea
      SUMAC=AC(1)
      DO 11 J=2,NAC
      AC(J)=AC(J)/tarea
      SUMAC=SUMAC+AC(J)
      TL=TL+AC(J)*(ST(J)+ST(J-1))/2
   11 CONTINUE
      AC(NAC+1)=0.
*
*  READ CHANNEL NETWORK DATA
      READ(8,*)NCH
      READ(8,*)(ACH(J),D(J),J=1,NCH)
*  ACH IS CUMULATIVE DISTRIBUTION OF AREA WITH DISTANCE D
*  FROM OUTLET.  D(1) is distance from subcatchment outlet
*  ACH(1) = 0.
*
      If(IOUT.ge.1)Write(10,600)TL, SUMAC
  600 Format(1x,'TL = ',f8.2,/'SUMAC = ', f8.2)
      RETURN
```

```
      END
*
C*************************************************************
************020
*
*
      SUBROUTINE INIT
      DIMENSION TCH(10)
      INCLUDE TMCOMMON.FOR
*
*  READ PARAMETER DATA
      READ(9,"(A)")SUBCAT
      READ(9,*)SZM,T0,TD,CHV,RV,SRMAX,Q0,SR0,INFEX,XK0,HF,DTH
*
*  Convert parameters to m/time step DT
*  with exception of XK0 which must stay in m/h
*                    Q0 is already in m/time step
*                    T0 is input as Ln(To)
      RV = RV * DT
      CHV = CHV * DT
      TD = TD * DT
      T0 = T0 + ALOG(DT)

*  Calculate SZQ parameter
      SZQ = EXP(T0-TL)
*-------------------------------------------------------------
------------021
*
*
*  CONVERT DISTANCE/AREA FORM TO TIME DELAY HISTOGRAM
ORDINATES
*
      TCH(1) = D(1)/CHV
      DO 15 J = 2,NCH
      TCH(J) = TCH(1) + (D(J) - D(1))/RV
   15 CONTINUE
      NR = INT(TCH(NCH))
      IF(FLOAT(NR).LT.TCH(NCH))NR=NR+1
      ND = INT(TCH(1))
      NR = NR - ND
      DO 20 IR=1,NR
      TIME = ND+IR
      IF(TIME.GT.TCH(NCH))THEN
      AR(IR)=1.0
      ELSE
      DO 21 J=2,NCH
      IF(TIME.LE.TCH(J))THEN
         AR(IR)=ACH(J-1)+(ACH(J)-ACH(J-1))*(TIME-TCH(J-1))/
     1        (TCH(J)-TCH(J-1))
         GOTO 20
      ENDIF
   21    CONTINUE
      ENDIF
   20 CONTINUE
      A1= AR(1)
      SUMAR=AR(1)
      AR(1)=AR(1)*AREA
```

```
      IF(NR.GT.1)THEN
      DO 22 IR=2,NR
      A2=AR(IR)
      AR(IR)=A2-A1
      A1=A2
      SUMAR=SUMAR+AR(IR)
      AR(IR)=AR(IR)*AREA
   22    CONTINUE
      ENDIF
      If(IOUT.ge.1)write(10,603)szq
  603 format(1x,'SZQ  ',e12.5)

If(IOUT.ge.1)WRITE(10,604)TCH(NCH),SUMAR,(AR(IR),IR=1,NR)
  604 FORMAT(1X,'SUBCATCHMENT ROUTING DATA'/
     1  1X,'Maximum Routing Delay  ',E12.5/
     2  1X,'Sum of histogram ordinates  ',f10.4/(1X,5E12.5))
*-------------------------------------------------------------
------------022
*
*  INITIALISE SRZ AND Q0 VALUES HERE
*  SR0 IS INITIAL ROOT ZONE STORAGE DEFICIT BELOW FIELD
CAPACITY
*  Q0 IS THE INITIAL DISCHARGE FOR THIS SUBCATCHMENT
*
*  INITIALISE STORES
      DO 25 IA=1,NAC
      SUZ(IA)=0.
   25 SRZ(IA)=SR0
      SBAR=-SZM*ALOG(Q0/SZQ)
c
c  Reinitialise discharge array
      do 28 I=1,NSTEP
   28 Q(I)=0.
      SUM=0.
      DO 29 I=1,ND
   29 Q(I) = Q(I) + Q0*AREA
      DO 30 I=1,NR
      SUM=SUM+AR(I)
      IN = ND + I
   30 Q(IN)=Q(IN)+Q0*(AREA-SUM)
*
*  Initialise water balance.  BAL is positive for storage
      BAL = - SBAR - SR0
      If(IOUT.ge.1)Write(10,605)BAL,SBAR,SR0
  605 Format(1x,'Initial Balance BAL ',e12.5/
     1       1x,'Initial SBAR        ',e12.5/
     2       1x,'Initial SR0         ',e12.5)
*
      RETURN
      END
C
C*************************************************************
************023
C
      SUBROUTINE EXPINF(IROF,IT,RINT,DF,CUMF)
C
      INCLUDE TMCOMMON.FOR
```

```
      DOUBLE PRECISION CONST,SUM,FC,FUNC,CD,SZF,XKF
      DATA E/0.00001/
*-------------------------------------------------------------
------------
C
C  SUBROUTINE TO CALCULATE INFILTRATION EXCESS RUNOFF USING
THE
C  EXPONENTIAL GREEN-AMPT MODEL.
C
*-------------------------------------------------------------
------------
C
C
C  Note that HF and DTH only appear in product CD
      CD=HF*DTH
      SZF = 1./SZM
      XKF = XK0
      IF(IROF.EQ.1)GO TO 10
C  PONDING HAS ALREADY OCCURRED - GO TO EXCESS CALCULATION
C
      IF(CUMF.EQ.0.)GOTO 7
*-------------------------------------------------------------
------------
C  FIRST TIME STEP, OVERFLOW IF CUMF=0, GO DIRECT TO F2
CALCULATION
C  INITIAL ESTIMATE OF TIME TO PONDING
      F1=CUMF
      R2=-XKF*SZF*(CD+F1)/(1-EXP(SZF*F1))
      IF(R2.LT.RINT)THEN
C  PONDING STARTS AT BEGINNING OF TIME STEP
      TP=(IT-1.)*DT
      IROF=1
      F=CUMF
      GO TO 8
      ENDIF
*-------------------------------------------------------------
------------
    7 F2=CUMF+DT*RINT
      IF(F2.EQ.0.)GO TO 20
      R2=-XKF*SZF*(CD+F2)/(1-EXP(SZF*F2))
      IF(R2.GT.RINT)GO TO 20
      F=CUMF+R2*DT
      DO 9 I=1,20
      R2=-XKF*SZF*(CD+F)/(1-EXP(SZF*F))
      IF(R2.GT.RINT)THEN
       F1=F
       F=(F2+F)*0.5
      IF(ABS(F-F1).LT.E)GO TO 11
      ELSE
       F2=F
       F=(F1+F)*0.5
      IF(ABS(F-F2).LT.E)GO TO 11
      ENDIF
    9 CONTINUE
      WRITE(6,600)
  600 FORMAT(1X,'MAXIMUM NO OF ITERATIONS EXCEEDED')
   11 CONTINUE
```

```
      TP=(IT-1)*DT+(F-CUMF)/RINT
      IF(TP.GT.IT*DT)GO TO 20
*-------------------------------------------------------------
------------
C
C   SET UP DEFINITE INTEGRAL CONSTANT USING FP
C
    8 CONST =0
      FAC=1
      FC=(F+CD)
      DO 12 J=1,10
      FAC=FAC*J
      ADD=(FC*SZF)**J/(J*FAC)
      CONST=CONST+ADD
   12 CONTINUE
      CONST=DLOG(FC)-(DLOG(FC)+CONST)/DEXP(SZF*CD)
C
      IROF=1
      F=F+0.5*RINT*(IT*DT-TP)
   10 CONTINUE
C
C   NEWTON-RAPHSON SOLUTION FOR F(T)
      DO 14 I=1,20
C
C   CALCULATE SUM OF SERIES TERMS
      FC=(F+CD)
      SUM=0.
      FAC=1.
      DO 13 J=1,10
      FAC=FAC*J
      ADD=(FC*SZF)**J/(J*FAC)
      SUM=SUM+ADD
   13 CONTINUE

FUNC=-(DLOG(FC)-(DLOG(FC)+SUM)/DEXP(SZF*CD)-CONST)/(XKF*SZF)
     1     -(IT*DT-TP)
      DFUNC=(EXP(SZF*F)-1)/(XKF*SZF*FC)
      DF=-FUNC/DFUNC
      F=F+DF
      IF(ABS(DF).LE.E)GO TO 15
   14 CONTINUE
      WRITE(6,600)
   15 CONTINUE
*
*-------------------------------------------------------------
------------
      IF(F.LT.CUMF+RINT)THEN
     DF=F-CUMF
     CUMF=F
C   SET UP INITIAL ESTIMATE FOR NEXT TIME STEP
     F=F+DF
     RETURN
      ENDIF
   20 CONTINUE
C   THERE IS NO PONDING IN THIS TIME STEP
      IROF=0
      DF = RINT*DT
```

```
      CUMF=CUMF+DF
      RETURN
      END
C
C
C**************************************************************
************024
C
      SUBROUTINE RESULTS
      INCLUDE TMCOMMON.FOR
C
C  OBJECTIVE FUNCTION CALCULATIONS
      F1=0.
      F2=0.
      SUMQ=0.
      SSQ=0.
      DO 60 IT=1,NSTEP
      SUMQ=SUMQ+QOBS(IT)
      SSQ = SSQ + QOBS(IT)*QOBS(IT)
      F1=F1 + (Q(IT)-QOBS(IT))**2
      F2=F2 + ABS(Q(IT)-QOBS(IT))
   60 CONTINUE
      QBAR = SUMQ / NSTEP
      VARQ = (SSQ/NSTEP - QBAR*QBAR)
      VARE = F1/NSTEP
      E=1-VARE/VARQ
c
c  add objective function values to output file
      write(6,621)f1,e,f2,qbar,varq,vare
      write(10,621)f1,e,f2,qbar,varq,vare
  621 format(//1x,'Objective function values'/
     1 1x,'F1 ',e12.5,'   E ',f12.5,'   F2 'e12.5//
     2 1x,'Mean Obs Q ',e12.5,'    Variance Obs Q ',e12.5/
     3 '     Error Variance',e12.5)
c
c
c
      RETURN
      END
C
C**************************************************************
************
C
```

APPENDIX 3
TOPMODEL Calibration Run
(Oct 90 - Oct 91)

```
n Catchment:  Calibration Data
   8.50  SUMAC=    1.00
.0380    0.0800    0.0400   19.0000   19.0000    0.0150    0.0005    0.0
  0.52973E-02
ATCHMENT ROUTING DATA
mum Routing Delay   0.32895E+01
of histogram ordinates      1.0000
1200E+00 0.45600E+00 0.13200E+00
     p         ep        q(it)       quz          qb        sbar       qof
0.130E-02 0.600E-03 0.453E-03 0.742E-03 0.453E-03 0.932E-01 0.748E-04
0.830E-02 0.150E-02 0.484E-03 0.714E-02 0.456E-03 0.865E-01 0.720E-03
0.900E-03 0.190E-02 0.785E-03 0.000E+00 0.544E-03 0.870E-01 0.000E+00
0.300E-03 0.900E-03 0.830E-03 0.000E+00 0.537E-03 0.876E-01 0.000E+00
0.820E-02 0.700E-03 0.625E-03 0.492E-02 0.529E-03 0.832E-01 0.496E-03
0.319E-01 0.190E-02 0.739E-03 0.281E-01 0.594E-03 0.556E-01 0.395E-02
0.700E-03 0.130E-02 0.241E-02 0.000E+00 0.123E-02 0.568E-01 0.000E+00
0.500E-03 0.190E-02 0.271E-02 0.000E+00 0.119E-02 0.580E-01 0.000E+00
0.000E+00 0.150E-02 0.165E-02 0.000E+00 0.115E-02 0.592E-01 0.000E+00
0.000E+00 0.100E-02 0.118E-02 0.000E+00 0.112E-02 0.603E-01 0.000E+00
0.110E-02 0.100E-02 0.114E-02 0.000E+00 0.108E-02 0.614E-01 0.000E+00
0.000E+00 0.600E-03 0.111E-02 0.000E+00 0.105E-02 0.624E-01 0.000E+00
0.000E+00 0.141E-02 0.108E-02 0.000E+00 0.102E-02 0.635E-01 0.000E+00
0.000E+00 0.120E-02 0.105E-02 0.000E+00 0.997E-03 0.645E-01 0.000E+00
0.970E-02 0.200E-03 0.102E-02 0.239E-02 0.972E-03 0.630E-01 0.399E-03
0.000E+00 0.500E-03 0.115E-02 0.000E+00 0.101E-02 0.640E-01 0.000E+00
0.120E-02 0.600E-03 0.117E-02 0.449E-03 0.982E-03 0.646E-01 0.749E-04
0.000E+00 0.600E-03 0.108E-02 0.000E+00 0.968E-03 0.655E-01 0.000E+00
0.600E-03 0.800E-03 0.101E-02 0.000E+00 0.944E-03 0.665E-01 0.000E+00
0.150E-02 0.150E-02 0.970E-03 0.137E-03 0.921E-03 0.673E-01 0.229E-04
0.000E+00 0.130E-02 0.947E-03 0.000E+00 0.902E-03 0.682E-01 0.000E+00
0.000E+00 0.300E-03 0.927E-03 0.000E+00 0.881E-03 0.691E-01 0.000E+00
0.000E+00 0.500E-03 0.899E-03 0.000E+00 0.861E-03 0.699E-01 0.000E+00
0.130E-02 0.800E-03 0.875E-03 0.000E+00 0.841E-03 0.708E-01 0.000E+00
0.240E-02 0.600E-03 0.855E-03 0.000E+00 0.823E-03 0.716E-01 0.000E+00
0.720E-02 0.800E-03 0.836E-03 0.561E-02 0.805E-03 0.668E-01 0.896E-03
0.300E-02 0.100E-02 0.119E-02 0.195E-02 0.914E-03 0.657E-01 0.325E-03
0.257E-01 0.200E-03 0.139E-02 0.215E-01 0.939E-03 0.452E-01 0.416E-02
0.000E+00 0.400E-03 0.289E-02 0.000E+00 0.161E-02 0.468E-01 0.000E+00
0.620E-02 0.100E-02 0.315E-02 0.459E-02 0.154E-02 0.438E-01 0.128E-02
0.400E-03 0.100E-02 0.257E-02 0.000E+00 0.167E-02 0.455E-01 0.000E+00
0.142E-01 0.700E-03 0.219E-02 0.104E-01 0.160E-02 0.367E-01 0.289E-02
0.111E-01 0.800E-03 0.299E-02 0.852E-02 0.202E-02 0.302E-01 0.238E-02
0.610E-02 0.600E-03 0.408E-02 0.434E-02 0.239E-02 0.283E-01 0.121E-02
0.490E-02 0.500E-03 0.408E-02 0.352E-02 0.252E-02 0.273E-01 0.984E-03
0.800E-03 0.200E-03 0.367E-02 0.246E-03 0.259E-02 0.296E-01 0.686E-04
0.600E-03 0.300E-03 0.317E-02 0.328E-03 0.243E-02 0.317E-01 0.915E-04
0.130E-02 0.800E-03 0.271E-02 0.819E-03 0.230E-02 0.332E-01 0.229E-03
0.000E+00 0.500E-03 0.254E-02 0.000E+00 0.221E-02 0.354E-01 0.000E+00
0.000E+00 0.100E-03 0.240E-02 0.000E+00 0.209E-02 0.375E-01 0.000E+00
0.300E-03 0.300E-03 0.220E-02 0.000E+00 0.198E-02 0.395E-01 0.000E+00
0.000E+00 0.500E-03 0.206E-02 0.000E+00 0.188E-02 0.413E-01 0.000E+00
0.110E-02 0.700E-03 0.195E-02 0.000E+00 0.179E-02 0.431E-01 0.000E+00
0.120E-02 0.110E-02 0.185E-02 0.000E+00 0.170E-02 0.448E-01 0.000E+00
0.630E-02 0.140E-02 0.176E-02 0.413E-02 0.163E-02 0.423E-01 0.115E-02
0.100E-03 0.110E-02 0.216E-02 0.000E+00 0.174E-02 0.441E-01 0.000E+00
0.100E-02 0.110E-02 0.221E-02 0.000E+00 0.166E-02 0.457E-01 0.000E+00
0.210E-02 0.100E-02 0.185E-02 0.000E+00 0.159E-02 0.473E-01 0.000E+00
0.000E+00 0.600E-03 0.164E-02 0.000E+00 0.153E-02 0.488E-01 0.000E+00
0.000E+00 0.200E-03 0.157E-02 0.000E+00 0.147E-02 0.503E-01 0.000E+00
0.100E-02 0.100E-03 0.151E-02 0.000E+00 0.141E-02 0.517E-01 0.000E+00
```

```
0.150E-02 0.140E-02 0.145E-02 0.427E-03 0.136E-02 0.526E-01 0.713E-04
0.500E-03 0.110E-02 0.143E-02 0.000E+00 0.133E-02 0.540E-01 0.000E+00
0.120E-02 0.800E-03 0.138E-02 0.000E+00 0.128E-02 0.552E-01 0.000E+00
0.193E-01 0.300E-03 0.132E-02 0.151E-01 0.124E-02 0.414E-01 0.343E-02
0.310E-02 0.500E-03 0.268E-02 0.229E-02 0.178E-02 0.409E-01 0.641E-03
0.140E-02 0.400E-03 0.330E-02 0.737E-03 0.181E-02 0.419E-01 0.206E-03
0.000E+00 0.800E-03 0.255E-02 0.000E+00 0.176E-02 0.437E-01 0.000E+00
0.000E+00 0.600E-03 0.196E-02 0.000E+00 0.168E-02 0.454E-01 0.000E+00
0.160E-02 0.500E-03 0.176E-02 0.000E+00 0.161E-02 0.470E-01 0.000E+00
0.000E+00 0.800E-03 0.166E-02 0.000E+00 0.154E-02 0.485E-01 0.000E+00
0.000E+00 0.150E-02 0.159E-02 0.000E+00 0.148E-02 0.500E-01 0.000E+00
0.000E+00 0.800E-03 0.152E-02 0.000E+00 0.142E-02 0.514E-01 0.000E+00
0.400E-03 0.200E-03 0.146E-02 0.000E+00 0.137E-02 0.528E-01 0.000E+00
0.200E-02 0.900E-03 0.141E-02 0.000E+00 0.132E-02 0.541E-01 0.000E+00
0.000E+00 0.400E-03 0.136E-02 0.000E+00 0.128E-02 0.554E-01 0.000E+00
0.360E-02 0.100E-02 0.131E-02 0.111E-02 0.123E-02 0.555E-01 0.186E-03
0.450E-02 0.300E-03 0.134E-02 0.310E-02 0.123E-02 0.536E-01 0.517E-03
0.710E-02 0.500E-03 0.154E-02 0.599E-02 0.129E-02 0.489E-01 0.104E-02
0.200E-03 0.150E-02 0.195E-02 0.000E+00 0.146E-02 0.504E-01 0.000E+00
0.000E+00 0.170E-02 0.190E-02 0.000E+00 0.141E-02 0.518E-01 0.000E+00
0.530E-02 0.500E-03 0.155E-02 0.180E-02 0.136E-02 0.514E-01 0.300E-03
0.100E-03 0.100E-03 0.152E-02 0.000E+00 0.137E-02 0.527E-01 0.000E+00
0.000E+00 0.000E+00 0.151E-02 0.000E+00 0.132E-02 0.541E-01 0.000E+00
0.000E+00 0.100E-03 0.139E-02 0.000E+00 0.128E-02 0.553E-01 0.000E+00
0.700E-03 0.400E-03 0.131E-02 0.938E-04 0.124E-02 0.565E-01 0.157E-04
0.000E+00 0.600E-03 0.127E-02 0.000E+00 0.120E-02 0.577E-01 0.000E+00
0.000E+00 0.900E-03 0.123E-02 0.000E+00 0.116E-02 0.588E-01 0.000E+00
0.000E+00 0.300E-03 0.119E-02 0.000E+00 0.113E-02 0.600E-01 0.000E+00
0.900E-03 0.800E-03 0.115E-02 0.000E+00 0.109E-02 0.610E-01 0.000E+00
0.200E-03 0.700E-03 0.112E-02 0.000E+00 0.106E-02 0.621E-01 0.000E+00
0.490E-02 0.150E-02 0.109E-02 0.226E-02 0.103E-02 0.609E-01 0.378E-03
0.580E-02 0.160E-02 0.121E-02 0.381E-02 0.107E-02 0.581E-01 0.635E-03
0.000E+00 0.200E-03 0.149E-02 0.000E+00 0.115E-02 0.593E-01 0.000E+00
0.770E-02 0.130E-02 0.144E-02 0.524E-02 0.111E-02 0.552E-01 0.875E-03
0.230E-02 0.900E-03 0.157E-02 0.885E-03 0.124E-02 0.555E-01 0.148E-03
0.230E-02 0.140E-02 0.163E-02 0.124E-02 0.123E-02 0.555E-01 0.207E-03
0.000E+00 0.800E-03 0.149E-02 0.000E+00 0.123E-02 0.567E-01 0.000E+00
0.000E+00 0.100E-02 0.134E-02 0.000E+00 0.119E-02 0.579E-01 0.000E+00
0.000E+00 0.700E-03 0.124E-02 0.000E+00 0.115E-02 0.591E-01 0.000E+00
0.000E+00 0.150E-02 0.118E-02 0.000E+00 0.112E-02 0.602E-01 0.000E+00
0.000E+00 0.400E-03 0.114E-02 0.000E+00 0.109E-02 0.613E-01 0.000E+00
0.950E-02 0.100E-02 0.111E-02 0.402E-02 0.106E-02 0.583E-01 0.670E-03
0.700E-03 0.130E-02 0.135E-02 0.000E+00 0.114E-02 0.595E-01 0.000E+00
0.000E+00 0.120E-02 0.140E-02 0.000E+00 0.111E-02 0.606E-01 0.000E+00
0.520E-02 0.100E-02 0.120E-02 0.226E-02 0.108E-02 0.594E-01 0.377E-03
0.200E-02 0.400E-03 0.125E-02 0.885E-03 0.111E-02 0.596E-01 0.148E-03
0.000E+00 0.200E-03 0.133E-02 0.000E+00 0.110E-02 0.607E-01 0.000E+00
0.170E-02 0.400E-03 0.122E-02 0.979E-03 0.107E-02 0.608E-01 0.163E-03
0.000E+00 0.800E-03 0.118E-02 0.000E+00 0.107E-02 0.619E-01 0.000E+00
0.300E-03 0.300E-03 0.115E-02 0.000E+00 0.104E-02 0.629E-01 0.000E+00
0.000E+00 0.700E-03 0.108E-02 0.000E+00 0.101E-02 0.639E-01 0.000E+00
0.100E-02 0.100E-03 0.103E-02 0.000E+00 0.985E-03 0.649E-01 0.000E+00
0.500E-03 0.200E-03 0.100E-02 0.000E+00 0.960E-03 0.659E-01 0.000E+00
0.000E+00 0.500E-03 0.978E-03 0.000E+00 0.936E-03 0.668E-01 0.000E+00
0.000E+00 0.500E-03 0.953E-03 0.000E+00 0.913E-03 0.677E-01 0.000E+00
0.000E+00 0.200E-03 0.930E-03 0.000E+00 0.891E-03 0.686E-01 0.000E+00
0.300E-03 0.120E-02 0.907E-03 0.000E+00 0.871E-03 0.695E-01 0.000E+00
0.200E-03 0.120E-02 0.886E-03 0.000E+00 0.851E-03 0.703E-01 0.000E+00
0.370E-02 0.400E-03 0.865E-03 0.335E-03 0.832E-03 0.708E-01 0.559E-04
0.200E-03 0.100E-03 0.869E-03 0.000E+00 0.821E-03 0.717E-01 0.000E+00
0.000E+00 0.100E-03 0.856E-03 0.000E+00 0.804E-03 0.725E-01 0.000E+00
0.000E+00 0.100E-03 0.823E-03 0.000E+00 0.787E-03 0.732E-01 0.000E+00
0.100E-03 0.100E-03 0.799E-03 0.000E+00 0.771E-03 0.740E-01 0.000E+00
0.400E-03 0.000E+00 0.783E-03 0.000E+00 0.755E-03 0.748E-01 0.000E+00
```

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0.000E+00 0.100E-03 0.767E-03 0.000E+00 0.740E-03 0.755E-01 0.000E+00
0.000E+00 0.200E-03 0.751E-03 0.000E+00 0.726E-03 0.762E-01 0.000E+00
0.000E+00 0.400E-03 0.737E-03 0.000E+00 0.712E-03 0.770E-01 0.000E+00
0.300E-03 0.500E-03 0.722E-03 0.000E+00 0.699E-03 0.777E-01 0.000E+00
0.000E+00 0.300E-03 0.709E-03 0.000E+00 0.686E-03 0.783E-01 0.000E+00
0.300E-03 0.200E-03 0.696E-03 0.000E+00 0.674E-03 0.790E-01 0.000E+00
0.250E-02 0.100E-03 0.683E-03 0.127E-02 0.662E-03 0.784E-01 0.128E-03
0.200E-03 0.200E-03 0.724E-03 0.928E-04 0.673E-03 0.790E-01 0.935E-05
0.100E-03 0.100E-02 0.731E-03 0.000E+00 0.663E-03 0.796E-01 0.000E+00
0.000E+00 0.110E-02 0.689E-03 0.000E+00 0.651E-03 0.803E-01 0.000E+00
0.000E+00 0.900E-03 0.661E-03 0.000E+00 0.640E-03 0.809E-01 0.000E+00
0.000E+00 0.700E-03 0.648E-03 0.000E+00 0.630E-03 0.816E-01 0.000E+00
0.200E-03 0.700E-03 0.637E-03 0.000E+00 0.619E-03 0.822E-01 0.000E+00
0.500E-03 0.300E-03 0.627E-03 0.000E+00 0.609E-03 0.828E-01 0.000E+00
0.460E-02 0.200E-03 0.616E-03 0.989E-03 0.600E-03 0.824E-01 0.997E-04
0.840E-02 0.100E-03 0.648E-03 0.761E-02 0.606E-03 0.754E-01 0.767E-03
0.300E-02 0.000E+00 0.965E-03 0.269E-02 0.728E-03 0.734E-01 0.271E-03
0.100E-03 0.100E-03 0.113E-02 0.928E-04 0.767E-03 0.741E-01 0.935E-05
0.300E-03 0.300E-03 0.957E-03 0.186E-03 0.753E-03 0.747E-01 0.187E-04
0.600E-03 0.200E-03 0.804E-03 0.278E-03 0.742E-03 0.751E-01 0.280E-04
0.000E+00 0.200E-03 0.772E-03 0.000E+00 0.733E-03 0.759E-01 0.000E+00
0.250E-02 0.600E-03 0.755E-03 0.195E-02 0.719E-03 0.747E-01 0.197E-03
0.400E-03 0.600E-03 0.813E-03 0.000E+00 0.743E-03 0.754E-01 0.000E+00
0.300E-03 0.600E-03 0.820E-03 0.000E+00 0.728E-03 0.761E-01 0.000E+00
0.100E-03 0.800E-03 0.760E-03 0.000E+00 0.715E-03 0.768E-01 0.000E+00
0.000E+00 0.800E-03 0.725E-03 0.000E+00 0.701E-03 0.775E-01 0.000E+00
0.800E-03 0.500E-03 0.711E-03 0.000E+00 0.688E-03 0.782E-01 0.000E+00
0.000E+00 0.900E-03 0.698E-03 0.000E+00 0.676E-03 0.789E-01 0.000E+00
0.223E-01 0.700E-03 0.685E-03 0.176E-01 0.664E-03 0.620E-01 0.244E-02
0.230E-02 0.130E-02 0.168E-02 0.142E-02 0.104E-02 0.616E-01 0.236E-03
0.000E+00 0.900E-03 0.203E-02 0.000E+00 0.105E-02 0.627E-01 0.000E+00
0.000E+00 0.100E-03 0.142E-02 0.000E+00 0.102E-02 0.637E-01 0.000E+00
0.000E+00 0.100E-03 0.106E-02 0.000E+00 0.991E-03 0.647E-01 0.000E+00
0.450E-02 0.300E-03 0.101E-02 0.195E-02 0.966E-03 0.637E-01 0.326E-03
0.167E-01 0.400E-03 0.112E-02 0.145E-01 0.991E-03 0.502E-01 0.242E-02
0.184E-01 0.100E-02 0.213E-02 0.149E-01 0.141E-02 0.366E-01 0.389E-02
0.100E-03 0.900E-03 0.391E-02 0.000E+00 0.202E-02 0.387E-01 0.000E+00
0.200E-03 0.900E-03 0.370E-02 0.000E+00 0.191E-02 0.406E-01 0.000E+00
0.000E+00 0.700E-03 0.241E-02 0.000E+00 0.182E-02 0.424E-01 0.000E+00
0.184E-01 0.200E-03 0.189E-02 0.127E-01 0.174E-02 0.315E-01 0.354E-02
0.000E+00 0.100E-03 0.325E-02 0.000E+00 0.231E-02 0.338E-01 0.000E+00
0.400E-03 0.100E-03 0.360E-02 0.830E-04 0.218E-02 0.359E-01 0.232E-04
0.250E-02 0.200E-03 0.266E-02 0.197E-02 0.206E-02 0.360E-01 0.549E-03
0.810E-02 0.800E-03 0.238E-02 0.647E-02 0.206E-02 0.316E-01 0.181E-02
0.480E-02 0.110E-02 0.307E-02 0.328E-02 0.231E-02 0.306E-01 0.915E-03
0.000E+00 0.700E-03 0.343E-02 0.000E+00 0.237E-02 0.330E-01 0.000E+00
0.000E+00 0.400E-03 0.296E-02 0.000E+00 0.222E-02 0.352E-01 0.000E+00
0.320E-02 0.100E-02 0.242E-02 0.899E-03 0.210E-02 0.364E-01 0.251E-03
0.650E-02 0.900E-03 0.230E-02 0.450E-02 0.203E-02 0.339E-01 0.126E-02
0.110E-02 0.130E-02 0.272E-02 0.164E-03 0.217E-02 0.359E-01 0.458E-04
0.120E-02 0.180E-02 0.272E-02 0.000E+00 0.206E-02 0.380E-01 0.000E+00
0.117E-01 0.180E-02 0.229E-02 0.804E-02 0.195E-02 0.319E-01 0.224E-02
0.800E-03 0.170E-02 0.296E-02 0.000E+00 0.229E-02 0.342E-01 0.000E+00
0.350E-02 0.150E-02 0.313E-02 0.748E-03 0.215E-02 0.356E-01 0.209E-03
0.200E-03 0.210E-02 0.257E-02 0.000E+00 0.208E-02 0.377E-01 0.000E+00
0.120E-02 0.130E-02 0.224E-02 0.000E+00 0.197E-02 0.396E-01 0.000E+00
0.170E-02 0.110E-02 0.207E-02 0.000E+00 0.187E-02 0.415E-01 0.000E+00
0.140E-02 0.130E-02 0.194E-02 0.000E+00 0.178E-02 0.433E-01 0.000E+00
0.120E-02 0.140E-02 0.184E-02 0.000E+00 0.170E-02 0.450E-01 0.000E+00
0.000E+00 0.400E-03 0.176E-02 0.000E+00 0.162E-02 0.466E-01 0.000E+00
0.000E+00 0.700E-03 0.168E-02 0.000E+00 0.155E-02 0.482E-01 0.000E+00
0.000E+00 0.130E-02 0.160E-02 0.000E+00 0.149E-02 0.496E-01 0.000E+00
0.000E+00 0.200E-02 0.154E-02 0.000E+00 0.143E-02 0.511E-01 0.000E+00
0.000E+00 0.800E-03 0.148E-02 0.000E+00 0.138E-02 0.525E-01 0.000E+00
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0.000E+00 0.900E-03 0.142E-02 0.000E+00 0.133E-02 0.538E-01 0.000E+00
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0.300E-03 0.290E-02 0.132E-02 0.000E+00 0.124E-02 0.563E-01 0.000E+00
0.000E+00 0.190E-02 0.127E-02 0.000E+00 0.120E-02 0.575E-01 0.000E+00
0.000E+00 0.140E-02 0.123E-02 0.000E+00 0.117E-02 0.587E-01 0.000E+00
0.180E-02 0.180E-02 0.119E-02 0.000E+00 0.113E-02 0.598E-01 0.000E+00
0.900E-02 0.260E-02 0.116E-02 0.000E+00 0.110E-02 0.609E-01 0.000E+00
0.110E-02 0.280E-02 0.112E-02 0.000E+00 0.107E-02 0.620E-01 0.000E+00
0.100E-02 0.180E-02 0.109E-02 0.000E+00 0.104E-02 0.630E-01 0.000E+00
0.250E-02 0.160E-02 0.106E-02 0.000E+00 0.101E-02 0.640E-01 0.000E+00
0.000E+00 0.130E-02 0.103E-02 0.000E+00 0.982E-03 0.650E-01 0.000E+00
0.000E+00 0.190E-02 0.100E-02 0.000E+00 0.957E-03 0.660E-01 0.000E+00
0.000E+00 0.160E-02 0.976E-03 0.000E+00 0.934E-03 0.669E-01 0.000E+00
0.000E+00 0.200E-02 0.951E-03 0.000E+00 0.911E-03 0.678E-01 0.000E+00
0.720E-02 0.200E-02 0.927E-03 0.000E+00 0.889E-03 0.687E-01 0.000E+00
0.000E+00 0.230E-02 0.905E-03 0.000E+00 0.869E-03 0.696E-01 0.000E+00
0.000E+00 0.160E-02 0.884E-03 0.000E+00 0.849E-03 0.704E-01 0.000E+00
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0.000E+00 0.240E-02 0.844E-03 0.000E+00 0.812E-03 0.721E-01 0.000E+00
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0.000E+00 0.280E-02 0.390E-03 0.000E+00 0.383E-03 0.100E+00 0.000E+00
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0.000E+00 0.390E-02 0.609E-03 0.000E+00 0.528E-03 0.882E-01 0.000E+00
0.000E+00 0.380E-02 0.627E-03 0.000E+00 0.520E-03 0.887E-01 0.000E+00
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0.500E-03 0.150E-02 0.491E-03 0.000E+00 0.481E-03 0.917E-01 0.000E+00
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0.000E+00 0.330E-02 0.400E-03 0.000E+00 0.393E-03 0.992E-01 0.000E+00
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0.000E+00 0.260E-02 0.384E-03 0.000E+00 0.378E-03 0.101E+00 0.000E+00
0.000E+00 0.280E-02 0.380E-03 0.000E+00 0.374E-03 0.101E+00 0.000E+00
0.420E-02 0.170E-02 0.377E-03 0.000E+00 0.370E-03 0.101E+00 0.000E+00
0.120E-02 0.350E-02 0.373E-03 0.000E+00 0.367E-03 0.102E+00 0.000E+00
0.140E-02 0.360E-02 0.369E-03 0.000E+00 0.363E-03 0.102E+00 0.000E+00
0.900E-03 0.160E-02 0.366E-03 0.000E+00 0.360E-03 0.103E+00 0.000E+00
0.000E+00 0.250E-02 0.362E-03 0.000E+00 0.356E-03 0.103E+00 0.000E+00
0.500E-03 0.210E-02 0.359E-03 0.000E+00 0.353E-03 0.103E+00 0.000E+00
0.000E+00 0.220E-02 0.355E-03 0.000E+00 0.350E-03 0.104E+00 0.000E+00
0.000E+00 0.200E-02 0.352E-03 0.000E+00 0.346E-03 0.104E+00 0.000E+00
0.000E+00 0.160E-02 0.349E-03 0.000E+00 0.343E-03 0.104E+00 0.000E+00
0.000E+00 0.220E-02 0.346E-03 0.000E+00 0.340E-03 0.105E+00 0.000E+00
0.000E+00 0.340E-02 0.342E-03 0.000E+00 0.337E-03 0.105E+00 0.000E+00
0.000E+00 0.240E-02 0.339E-03 0.000E+00 0.334E-03 0.105E+00 0.000E+00
0.000E+00 0.160E-02 0.336E-03 0.000E+00 0.331E-03 0.106E+00 0.000E+00
0.000E+00 0.240E-02 0.333E-03 0.000E+00 0.328E-03 0.106E+00 0.000E+00
0.000E+00 0.900E-03 0.330E-03 0.000E+00 0.326E-03 0.106E+00 0.000E+00
0.000E+00 0.220E-02 0.328E-03 0.000E+00 0.323E-03 0.107E+00 0.000E+00
0.000E+00 0.260E-02 0.325E-03 0.000E+00 0.320E-03 0.107E+00 0.000E+00
0.000E+00 0.100E-02 0.322E-03 0.000E+00 0.317E-03 0.107E+00 0.000E+00
0.000E+00 0.230E-02 0.319E-03 0.000E+00 0.315E-03 0.108E+00 0.000E+00
0.000E+00 0.160E-02 0.317E-03 0.000E+00 0.312E-03 0.108E+00 0.000E+00
0.000E+00 0.180E-02 0.314E-03 0.000E+00 0.310E-03 0.108E+00 0.000E+00
0.000E+00 0.120E-02 0.311E-03 0.000E+00 0.307E-03 0.109E+00 0.000E+00
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0.000E+00 0.200E-02 0.306E-03 0.000E+00 0.302E-03 0.109E+00 0.000E+00
0.000E+00 0.170E-02 0.304E-03 0.000E+00 0.300E-03 0.109E+00 0.000E+00
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0.000E+00 0.210E-02 0.299E-03 0.000E+00 0.295E-03 0.110E+00 0.000E+00
0.000E+00 0.270E-02 0.297E-03 0.000E+00 0.293E-03 0.110E+00 0.000E+00
0.350E-02 0.260E-02 0.294E-03 0.000E+00 0.291E-03 0.111E+00 0.000E+00
0.000E+00 0.310E-02 0.292E-03 0.000E+00 0.288E-03 0.111E+00 0.000E+00
0.900E-03 0.250E-02 0.290E-03 0.000E+00 0.286E-03 0.111E+00 0.000E+00
0.100E-02 0.200E-02 0.288E-03 0.000E+00 0.284E-03 0.111E+00 0.000E+00
0.300E-03 0.230E-02 0.286E-03 0.000E+00 0.282E-03 0.112E+00 0.000E+00
0.000E+00 0.270E-02 0.283E-03 0.000E+00 0.280E-03 0.112E+00 0.000E+00
0.000E+00 0.250E-02 0.281E-03 0.000E+00 0.278E-03 0.112E+00 0.000E+00
0.000E+00 0.290E-02 0.279E-03 0.000E+00 0.276E-03 0.113E+00 0.000E+00
0.180E-02 0.360E-02 0.277E-03 0.000E+00 0.274E-03 0.113E+00 0.000E+00
0.000E+00 0.140E-02 0.275E-03 0.000E+00 0.272E-03 0.113E+00 0.000E+00
0.143E-01 0.120E-02 0.273E-03 0.161E-02 0.270E-03 0.112E+00 0.101E-03
0.000E+00 0.700E-03 0.313E-03 0.000E+00 0.280E-03 0.112E+00 0.000E+00
0.100E-03 0.130E-02 0.320E-03 0.000E+00 0.278E-03 0.112E+00 0.000E+00
0.170E-02 0.110E-02 0.291E-03 0.000E+00 0.276E-03 0.113E+00 0.000E+00
0.000E+00 0.150E-02 0.277E-03 0.000E+00 0.274E-03 0.113E+00 0.000E+00
r Balance for Subcatchment : SUBCATCHMENT 1
UMP        SUMAE        SUMQ        SUMRZ       SUMUZ        SBAR          BAL
43E+00 0.3310E+00 0.3733E+00 0.8196E-02 0.0000E+00 0.1137E+00-0.1205E-01

s return to continue.....
mum contributing area  0.27648E+00
ctive function values
0.63786E-04   E      0.74120   F2  0.90065E-01
```

```
 Obs Q  0.10887E-02    Variance Obs Q  0.67527E-06
Error Variance 0.17476E-06

 return to continue.....
```

APPENDIX 4
Ythan Catchment
TOPMODEL Verification Run (Jan 93 Dec 93)

```
n Catchment:  Calibration Data
   8.50  SUMAC=     1.00
.0380     0.0800     0.0400     19.0000     19.0000     0.0150     0.0011     0.0
  0.52973E-02
ATCHMENT ROUTING DATA
mum Routing Delay    0.32895E+01
of histogram ordinates        1.0000
1200E+00 0.45600E+00 0.13200E+00
   p          ep        q(it)       quz         qb         sbar        qof
0.000E+00 0.271E-03 0.114E-02 0.000E+00 0.114E-02 0.595E-01 0.000E+00
0.000E+00 0.271E-03 0.114E-02 0.000E+00 0.111E-02 0.606E-01 0.000E+00
0.380E-02 0.229E-03 0.113E-02 0.246E-02 0.107E-02 0.592E-01 0.411E-03
0.150E-02 0.229E-03 0.127E-02 0.113E-02 0.111E-02 0.592E-01 0.188E-03
0.000E+00 0.229E-03 0.136E-02 0.000E+00 0.111E-02 0.603E-01 0.000E+00
0.100E-03 0.229E-03 0.125E-02 0.000E+00 0.108E-02 0.614E-01 0.000E+00
0.000E+00 0.229E-03 0.113E-02 0.000E+00 0.105E-02 0.625E-01 0.000E+00
0.100E-03 0.229E-03 0.107E-02 0.000E+00 0.102E-02 0.635E-01 0.000E+00
0.100E-02 0.229E-03 0.104E-02 0.756E-04 0.996E-03 0.644E-01 0.126E-04
0.210E-02 0.786E-03 0.102E-02 0.166E-02 0.972E-03 0.637E-01 0.277E-03
0.210E-02 0.786E-03 0.111E-02 0.116E-02 0.990E-03 0.636E-01 0.194E-03
0.000E+00 0.786E-03 0.119E-02 0.000E+00 0.995E-03 0.646E-01 0.000E+00
0.000E+00 0.786E-03 0.111E-02 0.000E+00 0.969E-03 0.655E-01 0.000E+00
0.110E-02 0.786E-03 0.101E-02 0.000E+00 0.945E-03 0.665E-01 0.000E+00
0.120E-02 0.786E-03 0.962E-03 0.000E+00 0.921E-03 0.674E-01 0.000E+00
0.700E-03 0.786E-03 0.938E-03 0.000E+00 0.899E-03 0.683E-01 0.000E+00
0.000E+00 0.771E-03 0.915E-03 0.000E+00 0.878E-03 0.692E-01 0.000E+00
0.960E-02 0.771E-03 0.894E-03 0.659E-02 0.858E-03 0.634E-01 0.110E-02
0.170E-02 0.771E-03 0.133E-02 0.822E-03 0.998E-03 0.636E-01 0.137E-03
0.500E-03 0.771E-03 0.148E-02 0.000E+00 0.993E-03 0.646E-01 0.000E+00
0.330E-02 0.771E-03 0.119E-02 0.201E-02 0.968E-03 0.636E-01 0.336E-03
0.000E+00 0.771E-03 0.114E-02 0.000E+00 0.995E-03 0.646E-01 0.000E+00
0.156E-01 0.771E-03 0.114E-02 0.125E-01 0.969E-03 0.530E-01 0.208E-02
0.390E-02 0.586E-03 0.188E-02 0.277E-02 0.131E-02 0.516E-01 0.462E-03
0.000E+00 0.586E-03 0.225E-02 0.000E+00 0.136E-02 0.529E-01 0.000E+00
0.400E-03 0.586E-03 0.177E-02 0.000E+00 0.132E-02 0.543E-01 0.000E+00
0.490E-02 0.586E-03 0.140E-02 0.318E-02 0.127E-02 0.523E-01 0.531E-03
0.500E-03 0.586E-03 0.152E-02 0.000E+00 0.134E-02 0.537E-01 0.000E+00
0.000E+00 0.586E-03 0.155E-02 0.000E+00 0.129E-02 0.550E-01 0.000E+00
0.000E+00 0.586E-03 0.138E-02 0.000E+00 0.125E-02 0.562E-01 0.000E+00
0.000E+00 0.857E-03 0.128E-02 0.000E+00 0.121E-02 0.574E-01 0.000E+00
0.000E+00 0.857E-03 0.124E-02 0.000E+00 0.117E-02 0.586E-01 0.000E+00
0.000E+00 0.857E-03 0.120E-02 0.000E+00 0.113E-02 0.597E-01 0.000E+00
0.000E+00 0.857E-03 0.116E-02 0.000E+00 0.110E-02 0.608E-01 0.000E+00
0.000E+00 0.857E-03 0.112E-02 0.000E+00 0.107E-02 0.619E-01 0.000E+00
0.000E+00 0.857E-03 0.109E-02 0.000E+00 0.104E-02 0.629E-01 0.000E+00
0.000E+00 0.857E-03 0.106E-02 0.000E+00 0.101E-02 0.639E-01 0.000E+00
0.000E+00 0.614E-03 0.103E-02 0.000E+00 0.985E-03 0.649E-01 0.000E+00
0.000E+00 0.614E-03 0.100E-02 0.000E+00 0.959E-03 0.659E-01 0.000E+00
0.000E+00 0.614E-03 0.978E-03 0.000E+00 0.935E-03 0.668E-01 0.000E+00
0.200E-03 0.614E-03 0.953E-03 0.000E+00 0.913E-03 0.677E-01 0.000E+00
0.000E+00 0.614E-03 0.929E-03 0.000E+00 0.891E-03 0.686E-01 0.000E+00
0.000E+00 0.614E-03 0.907E-03 0.000E+00 0.870E-03 0.695E-01 0.000E+00
0.000E+00 0.614E-03 0.885E-03 0.000E+00 0.851E-03 0.704E-01 0.000E+00
0.120E-02 0.657E-03 0.865E-03 0.000E+00 0.832E-03 0.712E-01 0.000E+00
0.100E-03 0.657E-03 0.845E-03 0.000E+00 0.814E-03 0.720E-01 0.000E+00
0.110E-02 0.657E-03 0.827E-03 0.000E+00 0.797E-03 0.728E-01 0.000E+00
0.000E+00 0.657E-03 0.809E-03 0.000E+00 0.780E-03 0.736E-01 0.000E+00
0.800E-03 0.657E-03 0.792E-03 0.000E+00 0.764E-03 0.743E-01 0.000E+00
0.000E+00 0.657E-03 0.776E-03 0.000E+00 0.749E-03 0.751E-01 0.000E+00
0.340E-02 0.657E-03 0.760E-03 0.000E+00 0.734E-03 0.758E-01 0.000E+00
```

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0.180E-02 0.914E-03 0.745E-03 0.000E+00 0.720E-03 0.765E-01 0.000E+00
0.150E-02 0.914E-03 0.731E-03 0.000E+00 0.707E-03 0.772E-01 0.000E+00
0.000E+00 0.914E-03 0.717E-03 0.000E+00 0.694E-03 0.779E-01 0.000E+00
0.000E+00 0.914E-03 0.703E-03 0.000E+00 0.681E-03 0.786E-01 0.000E+00
0.200E-02 0.914E-03 0.690E-03 0.000E+00 0.669E-03 0.793E-01 0.000E+00
0.680E-02 0.914E-03 0.678E-03 0.368E-02 0.657E-03 0.763E-01 0.370E-03
0.270E-02 0.914E-03 0.819E-03 0.166E-02 0.712E-03 0.753E-01 0.167E-03
0.200E-03 0.117E-02 0.919E-03 0.000E+00 0.730E-03 0.761E-01 0.000E+00
0.400E-03 0.117E-02 0.837E-03 0.000E+00 0.716E-03 0.768E-01 0.000E+00
0.110E-02 0.117E-02 0.744E-03 0.000E+00 0.702E-03 0.775E-01 0.000E+00
0.000E+00 0.117E-02 0.712E-03 0.000E+00 0.690E-03 0.782E-01 0.000E+00
0.180E-02 0.117E-02 0.699E-03 0.000E+00 0.677E-03 0.788E-01 0.000E+00
0.000E+00 0.117E-02 0.686E-03 0.000E+00 0.665E-03 0.795E-01 0.000E+00
0.000E+00 0.117E-02 0.674E-03 0.000E+00 0.654E-03 0.802E-01 0.000E+00
0.000E+00 0.121E-02 0.662E-03 0.000E+00 0.643E-03 0.808E-01 0.000E+00
0.000E+00 0.121E-02 0.651E-03 0.000E+00 0.632E-03 0.814E-01 0.000E+00
0.000E+00 0.121E-02 0.640E-03 0.000E+00 0.621E-03 0.821E-01 0.000E+00
0.120E-02 0.121E-02 0.629E-03 0.000E+00 0.611E-03 0.827E-01 0.000E+00
0.800E-03 0.121E-02 0.619E-03 0.000E+00 0.602E-03 0.833E-01 0.000E+00
0.100E-03 0.121E-02 0.609E-03 0.000E+00 0.592E-03 0.839E-01 0.000E+00
0.400E-03 0.121E-02 0.599E-03 0.000E+00 0.583E-03 0.844E-01 0.000E+00
0.000E+00 0.123E-02 0.590E-03 0.000E+00 0.574E-03 0.850E-01 0.000E+00
0.300E-02 0.123E-02 0.580E-03 0.000E+00 0.565E-03 0.856E-01 0.000E+00
0.000E+00 0.123E-02 0.572E-03 0.000E+00 0.557E-03 0.861E-01 0.000E+00
0.000E+00 0.123E-02 0.563E-03 0.000E+00 0.549E-03 0.867E-01 0.000E+00
0.000E+00 0.123E-02 0.555E-03 0.000E+00 0.541E-03 0.872E-01 0.000E+00
0.000E+00 0.123E-02 0.547E-03 0.000E+00 0.533E-03 0.878E-01 0.000E+00
0.100E-02 0.123E-02 0.539E-03 0.000E+00 0.526E-03 0.883E-01 0.000E+00
0.000E+00 0.196E-02 0.531E-03 0.000E+00 0.519E-03 0.888E-01 0.000E+00
0.000E+00 0.196E-02 0.524E-03 0.000E+00 0.512E-03 0.893E-01 0.000E+00
0.000E+00 0.196E-02 0.517E-03 0.000E+00 0.505E-03 0.898E-01 0.000E+00
0.000E+00 0.196E-02 0.510E-03 0.000E+00 0.498E-03 0.903E-01 0.000E+00
0.000E+00 0.196E-02 0.503E-03 0.000E+00 0.492E-03 0.908E-01 0.000E+00
0.000E+00 0.196E-02 0.496E-03 0.000E+00 0.485E-03 0.913E-01 0.000E+00
0.000E+00 0.196E-02 0.490E-03 0.000E+00 0.479E-03 0.918E-01 0.000E+00
0.000E+00 0.171E-02 0.484E-03 0.000E+00 0.473E-03 0.923E-01 0.000E+00
0.920E-02 0.171E-02 0.478E-03 0.000E+00 0.467E-03 0.927E-01 0.000E+00
0.820E-02 0.171E-02 0.472E-03 0.316E-02 0.462E-03 0.900E-01 0.318E-03
0.610E-02 0.171E-02 0.597E-03 0.407E-02 0.496E-03 0.865E-01 0.410E-03
0.100E-03 0.171E-02 0.790E-03 0.000E+00 0.544E-03 0.870E-01 0.000E+00
0.000E+00 0.171E-02 0.740E-03 0.000E+00 0.537E-03 0.875E-01 0.000E+00
0.100E-02 0.171E-02 0.589E-03 0.000E+00 0.529E-03 0.881E-01 0.000E+00
0.000E+00 0.163E-02 0.535E-03 0.000E+00 0.522E-03 0.886E-01 0.000E+00
0.930E-02 0.163E-02 0.527E-03 0.314E-02 0.515E-03 0.860E-01 0.316E-03
0.800E-03 0.163E-02 0.650E-03 0.000E+00 0.552E-03 0.865E-01 0.000E+00
0.000E+00 0.163E-02 0.675E-03 0.000E+00 0.544E-03 0.871E-01 0.000E+00
0.300E-02 0.163E-02 0.585E-03 0.000E+00 0.536E-03 0.876E-01 0.000E+00
0.180E-01 0.163E-02 0.541E-03 0.146E-01 0.528E-03 0.736E-01 0.147E-02
0.230E-02 0.163E-02 0.114E-02 0.623E-03 0.765E-03 0.737E-01 0.628E-04
0.160E-02 0.210E-02 0.132E-02 0.000E+00 0.762E-03 0.745E-01 0.000E+00
0.100E-02 0.210E-02 0.955E-03 0.000E+00 0.747E-03 0.752E-01 0.000E+00
0.000E+00 0.210E-02 0.764E-03 0.000E+00 0.732E-03 0.759E-01 0.000E+00
0.000E+00 0.210E-02 0.743E-03 0.000E+00 0.718E-03 0.767E-01 0.000E+00
0.900E-02 0.210E-02 0.728E-03 0.262E-02 0.705E-03 0.747E-01 0.264E-03
0.000E+00 0.210E-02 0.823E-03 0.000E+00 0.741E-03 0.755E-01 0.000E+00
0.700E-03 0.210E-02 0.842E-03 0.000E+00 0.727E-03 0.762E-01 0.000E+00
0.000E+00 0.190E-02 0.765E-03 0.000E+00 0.713E-03 0.769E-01 0.000E+00
0.720E-02 0.190E-02 0.723E-03 0.981E-03 0.700E-03 0.766E-01 0.989E-04
0.200E-03 0.190E-02 0.750E-03 0.000E+00 0.705E-03 0.773E-01 0.000E+00
0.500E-03 0.190E-02 0.749E-03 0.000E+00 0.692E-03 0.780E-01 0.000E+00
0.600E-03 0.190E-02 0.712E-03 0.000E+00 0.680E-03 0.787E-01 0.000E+00
0.450E-02 0.190E-02 0.689E-03 0.000E+00 0.668E-03 0.794E-01 0.000E+00
0.000E+00 0.190E-02 0.676E-03 0.000E+00 0.656E-03 0.800E-01 0.000E+00
0.100E-03 0.257E-02 0.664E-03 0.000E+00 0.645E-03 0.807E-01 0.000E+00
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0.000E+00 0.257E-02 0.653E-03 0.000E+00 0.634E-03 0.813E-01 0.000E+00
0.000E+00 0.257E-02 0.642E-03 0.000E+00 0.623E-03 0.819E-01 0.000E+00
0.000E+00 0.257E-02 0.631E-03 0.000E+00 0.613E-03 0.826E-01 0.000E+00
0.000E+00 0.257E-02 0.621E-03 0.000E+00 0.603E-03 0.832E-01 0.000E+00
0.100E-03 0.257E-02 0.610E-03 0.000E+00 0.594E-03 0.837E-01 0.000E+00
0.000E+00 0.257E-02 0.601E-03 0.000E+00 0.585E-03 0.843E-01 0.000E+00
0.000E+00 0.264E-02 0.591E-03 0.000E+00 0.576E-03 0.849E-01 0.000E+00
0.000E+00 0.264E-02 0.582E-03 0.000E+00 0.567E-03 0.855E-01 0.000E+00
0.900E-03 0.264E-02 0.573E-03 0.000E+00 0.559E-03 0.860E-01 0.000E+00
0.270E-02 0.264E-02 0.565E-03 0.000E+00 0.551E-03 0.866E-01 0.000E+00
0.200E-03 0.264E-02 0.556E-03 0.000E+00 0.543E-03 0.871E-01 0.000E+00
0.190E-02 0.264E-02 0.548E-03 0.000E+00 0.535E-03 0.877E-01 0.000E+00
0.000E+00 0.264E-02 0.540E-03 0.000E+00 0.527E-03 0.882E-01 0.000E+00
0.000E+00 0.140E-02 0.533E-03 0.000E+00 0.520E-03 0.887E-01 0.000E+00
0.000E+00 0.140E-02 0.525E-03 0.000E+00 0.513E-03 0.892E-01 0.000E+00
0.000E+00 0.140E-02 0.518E-03 0.000E+00 0.506E-03 0.897E-01 0.000E+00
0.330E-02 0.140E-02 0.511E-03 0.000E+00 0.500E-03 0.902E-01 0.000E+00
0.220E-02 0.140E-02 0.504E-03 0.000E+00 0.493E-03 0.907E-01 0.000E+00
0.235E-01 0.140E-02 0.498E-03 0.144E-01 0.487E-03 0.768E-01 0.145E-02
0.220E-02 0.140E-02 0.109E-02 0.742E-03 0.702E-03 0.768E-01 0.748E-04
0.110E-02 0.166E-02 0.127E-02 0.000E+00 0.702E-03 0.775E-01 0.000E+00
0.570E-02 0.166E-02 0.899E-03 0.350E-02 0.689E-03 0.747E-01 0.353E-03
0.000E+00 0.166E-02 0.852E-03 0.000E+00 0.742E-03 0.754E-01 0.000E+00
0.000E+00 0.166E-02 0.874E-03 0.000E+00 0.728E-03 0.761E-01 0.000E+00
0.180E-02 0.166E-02 0.776E-03 0.000E+00 0.714E-03 0.769E-01 0.000E+00
0.880E-02 0.166E-02 0.724E-03 0.445E-02 0.701E-03 0.731E-01 0.448E-03
0.000E+00 0.166E-02 0.895E-03 0.000E+00 0.774E-03 0.739E-01 0.000E+00
0.000E+00 0.294E-02 0.937E-03 0.000E+00 0.758E-03 0.746E-01 0.000E+00
0.000E+00 0.294E-02 0.817E-03 0.000E+00 0.743E-03 0.754E-01 0.000E+00
0.000E+00 0.294E-02 0.754E-03 0.000E+00 0.729E-03 0.761E-01 0.000E+00
0.000E+00 0.294E-02 0.739E-03 0.000E+00 0.715E-03 0.768E-01 0.000E+00
0.000E+00 0.294E-02 0.725E-03 0.000E+00 0.701E-03 0.775E-01 0.000E+00
0.900E-03 0.294E-02 0.711E-03 0.000E+00 0.689E-03 0.782E-01 0.000E+00
0.400E-02 0.294E-02 0.698E-03 0.000E+00 0.676E-03 0.789E-01 0.000E+00
0.131E-01 0.190E-02 0.685E-03 0.415E-02 0.664E-03 0.754E-01 0.418E-03
0.300E-03 0.190E-02 0.845E-03 0.000E+00 0.728E-03 0.761E-01 0.000E+00
0.230E-02 0.190E-02 0.883E-03 0.000E+00 0.714E-03 0.769E-01 0.000E+00
0.100E-02 0.190E-02 0.769E-03 0.000E+00 0.701E-03 0.776E-01 0.000E+00
0.000E+00 0.190E-02 0.711E-03 0.000E+00 0.688E-03 0.782E-01 0.000E+00
0.000E+00 0.190E-02 0.697E-03 0.000E+00 0.676E-03 0.789E-01 0.000E+00
0.450E-02 0.190E-02 0.685E-03 0.000E+00 0.664E-03 0.796E-01 0.000E+00
0.000E+00 0.201E-02 0.673E-03 0.000E+00 0.652E-03 0.802E-01 0.000E+00
0.000E+00 0.201E-02 0.661E-03 0.000E+00 0.641E-03 0.809E-01 0.000E+00
0.000E+00 0.201E-02 0.649E-03 0.000E+00 0.631E-03 0.815E-01 0.000E+00
0.400E-03 0.201E-02 0.638E-03 0.000E+00 0.620E-03 0.821E-01 0.000E+00
0.400E-03 0.201E-02 0.628E-03 0.000E+00 0.610E-03 0.827E-01 0.000E+00
0.000E+00 0.201E-02 0.617E-03 0.000E+00 0.600E-03 0.833E-01 0.000E+00
0.000E+00 0.201E-02 0.607E-03 0.000E+00 0.591E-03 0.839E-01 0.000E+00
0.000E+00 0.220E-02 0.598E-03 0.000E+00 0.582E-03 0.845E-01 0.000E+00
0.000E+00 0.220E-02 0.588E-03 0.000E+00 0.573E-03 0.851E-01 0.000E+00
0.000E+00 0.220E-02 0.579E-03 0.000E+00 0.564E-03 0.856E-01 0.000E+00
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0.500E-02 0.220E-02 0.865E-03 0.260E-02 0.658E-03 0.773E-01 0.262E-03
0.800E-03 0.220E-02 0.105E-02 0.000E+00 0.693E-03 0.780E-01 0.000E+00
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0.000E+00 0.251E-02 0.638E-03 0.000E+00 0.609E-03 0.828E-01 0.000E+00
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0.430E-02 0.429E-03 0.309E-02 0.317E-02 0.190E-02 0.378E-01 0.886E-03
0.800E-03 0.257E-03 0.348E-02 0.304E-03 0.196E-02 0.394E-01 0.850E-04
0.200E-03 0.257E-03 0.272E-02 0.000E+00 0.188E-02 0.413E-01 0.000E+00
0.000E+00 0.257E-03 0.207E-02 0.000E+00 0.179E-02 0.431E-01 0.000E+00
0.220E-02 0.257E-03 0.186E-02 0.134E-02 0.170E-02 0.435E-01 0.374E-03
0.560E-02 0.257E-03 0.192E-02 0.438E-02 0.169E-02 0.408E-01 0.122E-02
0.100E-03 0.257E-03 0.238E-02 0.000E+00 0.181E-02 0.426E-01 0.000E+00
0.200E-03 0.257E-03 0.235E-02 0.000E+00 0.173E-02 0.443E-01 0.000E+00
0.900E-03 0.543E-03 0.192E-02 0.356E-03 0.165E-02 0.456E-01 0.995E-04
0.160E-02 0.543E-03 0.175E-02 0.866E-03 0.160E-02 0.463E-01 0.242E-03
0.250E-02 0.543E-03 0.178E-02 0.160E-02 0.156E-02 0.463E-01 0.448E-03
0.500E-03 0.543E-03 0.190E-02 0.000E+00 0.157E-02 0.479E-01 0.000E+00
0.245E-01 0.543E-03 0.181E-02 0.196E-01 0.150E-02 0.297E-01 0.542E-02
0.170E-02 0.543E-03 0.383E-02 0.948E-03 0.242E-02 0.312E-01 0.265E-03
0.700E-03 0.543E-03 0.447E-02 0.129E-03 0.233E-02 0.334E-01 0.359E-04
0.000E+00 0.543E-03 0.311E-02 0.000E+00 0.220E-02 0.356E-01 0.000E+00
0.630E-02 0.543E-03 0.234E-02 0.429E-02 0.207E-02 0.334E-01 0.120E-02
0.670E-02 0.543E-03 0.266E-02 0.504E-02 0.220E-02 0.306E-01 0.141E-02
er Balance for Subcatchment : SUBCATCHMENT 1
SUMP        SUMAE       SUMQ        SUMRZ       SUMUZ       SBAR         BAL
734E+00 0.3852E+00 0.3803E+00 0.1477E-02 0.0000E+00 0.3693E-01-0.1254E-0

ss return to continue.....
imum contributing area  0.27648E+00
ective function values
 0.94390E-04   E      0.51065   F2  0.10728E+00
```

```
n Obs Q  0.11938E-02    Variance Obs Q  0.52846E-06
 Error Variance 0.25860E-06

e return to continue.....
```

```
SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                    13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
    NO YRS =    1
    BASIN AREA =   523.000 KM**2
    AVE A RAINFALL/AVE A FOR GAGE
      SUBBASIN
         1    1.00
    BASEFLOW FACTOR =    1.000
    BASIN LAG TIME =   15.00 D
    GENERATOR CYCLES =     0
    WATER STATS =  1
    SEDIMENT STATS =  0


    GENERATOR SEEDS
            9  98 915  92
          135  28 203  85
           43  54 619  33
          645   9 948  65
          885  41 696  62
           51  78 648   0
          227  57 929  37
           20  90 215  31
          320  73 631  49

    TP-40 RAINFALL AMOUNTS (10 YR FREQ) FOR DUR
         0.5 H =  46.74 MM
         6H= 66.29 MM

    NO YRS RECORD MAX.5H RAIN= 11.0

    LATITUDE= 57.75 DEG

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                    13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
CLIMATE DATA

    RAINFALL DATA USED IN THIS RUN ARE:
     **MEASURED SINGLE RAINGAGE**

    TEMPERATURE DATA USED IN THIS RUN ARE;
     **MEASURED FOR ENTIRE BASIN**

                  -MO RAIN PROB--     -MO STATS FOR DAILY RAIN-
                   W/D       W/W      MEAN      ST DV     SKW CF
                   .350      .800    11.430    12.700      .310
                   .310      .800     9.140    12.190     1.910
                   .450      .660     6.600     6.860     -.300
                   .320      .690     6.350     6.600      .170
                   .440      .810     9.400    12.450     2.130
                   .250      .700     7.370     9.400     1.100
                   .330      .660     5.840     8.890     1.940
                   .270      .660     8.380    12.450     2.320
                   .390      .680    11.430    12.950      .210
                   .360      .710    12.450    14.480     1.020
                   .440      .700    10.920    12.700      .650
                   .350      .710     9.650    11.430     1.180
```

```
        R5MX       TMX       TMN        RA       CVT      RAIN      DAYP     ALI
 JAN     8.89      2.20     -2.80     26.00      .30    225.48     19.73
 FEB     8.64      2.10     -3.70     84.00      .29    161.11     17.63
 MAR     7.11      4.10     -1.90    232.00      .21    116.54     17.66
 APR     7.37      6.80       .60    363.00      .15     96.76     15.24
 MAY     8.64      9.40      3.60    445.00      .11    203.52     21.65
 JUN    12.95     13.40      6.60    477.00      .11    100.50     13.64
 JUL    12.70     15.70      9.30    418.00      .09     89.17     15.27
 AUG    22.10     16.40      9.30    315.00      .09    114.98     13.72
 SEP    17.02     13.40      6.60    192.00      .10    188.35     16.48
 OCT     9.40      8.50      1.80     94.00      .16    213.76     17.17
 NOV    11.94      4.70     -1.10     34.00      .20    194.79     17.84
 DEC     9.65      2.50     -3.40     12.00      .26    163.60     16.95
 YR     11.37      8.27      2.08    224.33      .17   1868.57    202.97

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                       13:43 :
YTHAN91.dat
WEA:  24   AK  KODIAK WSO

CROP DATA


BASIN  1

OP 1                         CROP 2                       CROP 3
MBER OF CROPS =  1
ANTING DATE =   3/25         PLANTING DATE =   0/ 0       PLANTING DATE =   0/ (
RVE NO PLANTING = 76.0       CURVE NO PLANTING =    .0    CURVE NO PLANTING =
RVEST DATE =   9/30          HARVEST DATE =  0/ 0         HARVEST DATE =   0/ 0
RVE NO HARVEST = 78.0        CURVE NO HARVEST =    .0     CURVE NO HARVEST =
LLAGE OPER =     1           TILLAGE OPER =     0         TILLAGE OPER =     0
T HEAT UNITS=2000. C         POT HEAT UNITS=   0. C       POT HEAT UNITS=   0.
OMASS CONV. =     50.00      BIOMASS CONV. =       .00    BIOMASS CONV. =
TER STRESS FAC =      .01    WATER STRESS FAC =      .00  WATER STRESS FAC =
RVEST INDEX =        .42     HARVEST INDEX =       .00    HARVEST INDEX =
G (1=NO,2=YES) 1             LEG (1=NO,2=YES) 0           LEG (1=NO, 2=YES) 0
E C FACTOR =        .05      AVE C FACTOR =       .00     AVE C FACTOR =

                              FERTILIZER
 1                           CROP 2                      CROP 3
 DATE        N       P       DATE        N        P       DATE        N       P
          (KG/HA) (KG/HA)             (KG/HA)  (KG/HA)             (KG/HA)  (KG/I

  3/15     50.00     .00     0/ 0       .00      .00     0/ 0       .00     .0(
  4/15     77.00     .00     0/ 0       .00      .00     0/ 0       .00     .0(
  0/ 0       .00     .00     0/ 0       .00      .00     0/ 0       .00     .0(
  0/ 0       .00     .00     0/ 0       .00      .00     0/ 0       .00     .0(
  0/ 0       .00     .00     0/ 0       .00      .00     0/ 0       .00     .0(

                               PESTICIDE
         APPLIED  PEST                APPLIED PEST                APPLIED PEST
(KG/HA)  (KG/HA)   NO.                (KG/HA)  NO.                          NO.

  3/15      1.00    1        0/ 0       .00     0        0/ 0       .00     0
  0/ 0      2.00    2        0/ 0       .00     0        0/ 0       .00     0
  0/ 0       .00    0        0/ 0       .00     0        0/ 0       .00     0
  0/ 0       .00    0        0/ 0       .00     0        0/ 0       .00     0
  0/ 0       .00    0        0/ 0       .00     0        0/ 0       .00     0

                               IRRIGATION
         APPLIED                      APPLIED                     APPLIED
          (MM)                         (MM)                        (MM)
```

```
  0/ 0       .00            0/ 0       .00            0/ 0       .00
  0/ 0       .00            0/ 0       .00            0/ 0       .00
  0/ 0       .00            0/ 0       .00            0/ 0       .00
  0/ 0       .00            0/ 0       .00            0/ 0       .00
  0/ 0       .00            0/ 0       .00            0/ 0       .00


                  IRRIGATION DATA
  SUBBASINS         IRRIGATE         WATER STRESS          RUNOFF RATIO
                 (1=YES,0=NO)                         (1 minus fraction that ru


      1              0                     .50                    .90

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                                13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
SUB-BASIN DATA


     SUB-BASIN AREA/BASIN AREA
 1.000

     POND CATCHMENT AREA FRACTION
  .000

     POND SURFACE AREA(HA)
   .00

     MAX POND STORAGE(MM)
    .0

     INTIAL POND STORAGE(MM)
    .0

     INITIAL SED CONC IN PONDS(PPM)
    0.

     NORMAL SED CONC IN PONDS(PPM)
    0.

     SAT CONDUCTIVITY FOR POND BOTTOMS(MM/H)
   .00

     RESERVOIR CATCHMENT AREA FRACTION
  .000

     RESERVOIR SURFACE AREA AT EMERGENCY SPILLWAY(HA)
   .00

     RESERVOIR STORAGE AT EMERGENCY SPILLWAY(MM)
    .0

     RESERVOIR SURFACE AREA AT PRINCIPAL SPILLWAY(HA)
   .00

     RESERVOIR STORAGE AT PRINCIPAL SPILLWAY(MM)
    .0

     INITIAL RESERVOIR STORAGE(MM)
    .0
```

```
    AVE RESERVOIR RELEASE RATES(M**3/S/KM**2)
.00000

    INITIAL SED CONC IN RESERVOIRS(PPM)
 200.

    NORMAL SED CONC IN RESERVOIRS(PPM)
 250.

    SAT CONDUCTIVITY OF RESERVOIR BOTTOMS (MM/H)
  .00

    2 COND CN
 76.0

    SOIL ALBEDO
  .10

    WATER CONTENT OF SNOW COVER (MM)
   .0

    MAIN CHANNEL LENGTH (KM)
73.00     63.00

    CHANNEL SLOPE(M/M)
.0020     .0020

    AVERAGE MAIN CHANNEL WIDTH (M)
 2.50

    HYDR COND OF CHANNEL ALLUVIUM(MM/H)
  .01

    CHANNEL N VALUE
 .010      .050

    OVERLAND FLOW N VALUE
 .090      .600

    TIME OF CONCENTRATION FOR SUB-BASINS(H)
 7.00     23.61

    RET FLO SED CONC (PPM)
 100.

    RET FLO TRAVEL TIME(D)
7.000

    SLOPE LENGTH(M)
  50.      100.

    SLOPE STEEPNESS(M/M)
.1000     .0020

    ERosion CONTROL PRACTICE FACTORS(P)
  .50


    SLOPE LENGTH AND STEEPNESS FACTORS(LS)
 1.89


              ROUTING DATA -- SUB-BASIN TO BASIN OUTLET
```

```
     AVE CHANNEL WIDTH(M)
  2.50

     AVE CHANNEL DEPTH(M)
   .30

     CHANNEL SLOPE(M/M)
   .00

     CHANNEL LENGTH(KM)
  1.00

     CHANNEL N VALUE
   .03

     HYDR COND OF CHANNEL ALLUVIUM(MM/H)
   .01

     USLE SOIL FACTOR K FOR CHANNEL
  .320

     USLE SOIL FACTOR C FOR CHANNEL
  .050

             PESTICIDE DATA


   TOTAL NO OF PESTICIDES SIMULATED =    0
                                                 ---HALF LIFE---
                                     WASH OFF     ON       IN        APPL.
             PEST            KOC       FRAC.    FOLIAGE   SOIL        EFF

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                  13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO

SOILS DATA


           LAYER                 15 BAR    .3 BAR    AVAIL     INITIAL   SA
    ST     DEPTH    POROSITY      SW        SW        W ST      W ST     CC
    NO      (MM)     (MM/MM)   (MM/MM)   (MM/MM)     (MM)      (MM)     (MM
      SUBBASIN    1     TYPIC ARIGIAQUO
     1      10.0      .40       .06       .24       1.80      1.80      3
     2     203.2      .40       .06       .24      34.78     34.78      3
     3     685.8      .40       .06       .24      86.87     86.87      3
     4    1524.0      .40       .13       .31     150.88    150.88      1
TOTALS                                            274.3     274.3


     INITIAL COMPOSITE ST =   274.3 MM

               SOIL SURFACE LAYER

                                                            ORG
                                                             N
                                                           (G/M3)
UB-BASIN    CLAY           SILT         SAND        K
   1         .10            .32          .58       .20    1000.00
```

```
                          SEDIMENT SIZE DISTRIBUTION
    SUB-BASIN                        SIZE(MM)

                SAND        SILT       CLAY     SM AG       L AG
                 .20         .01       .002       .03        .50

        1       .446        .042       .020      .200       .292

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                       13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
                        SUB    WATER  PERCO           SED          ORGANIC ORGANIC
      R        SURQ    SURQ    YIELD  LATE    ET     YIELD    SW      N       P
     (MM)      (MM)    (MM)     (MM)  (MM)   (MM)   (T/HA)   (MM)
1   29.10       .35   15.55   15.90   2.87   6.37      .02 273.24     .01     .00
2   86.10     13.08   14.11   27.19   3.63  18.68      .25 292.00    1.23     .30
3   69.50      4.66   49.09   53.76   3.28  56.71      .15 259.70     .59     .14
4   32.40       .06    9.87    9.93   1.35  37.16      .01 252.97     .01     .00
5   22.80       .00    1.82    1.82   1.20  27.62      .00 246.40     .00     .00
6   98.80       .72    1.49    2.22   2.98  79.84      .03 259.43     .17     .04
7   40.30       .25    2.07    2.33   1.57  53.47      .01 242.79     .03     .01
8   20.50       .00     .86     .86    .92  52.25      .00 209.77     .00     .00
9   23.70       .00     .14     .14    .42  57.15      .00 175.90     .00     .00
10  98.70      5.87    2.02    7.89   1.56  24.23      .30 236.55    1.56     .38
11 107.40      4.17   36.04   40.21   4.15   9.46      .31 274.87    1.48     .35
12  25.40       .44   26.07   26.51   2.50   3.27      .06 274.98     .19     .04

1  654.70     29.62  159.13  188.74  26.41 426.20     1.15 274.98    5.27    1.27


SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                       13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
FINAL VALUES

-BASIN                     SOIL WATER FOR LAYER NO
O

   1     2     3     4
  1.4  35.1  87.1 151.4

  TOTAL SOIL WATER
1     275.0

     FINAL COMPOSITE ST =    275.0 MM
     MIN INDIVIDUAL WATER ST =         .0 MM


                  FINAL CONTENTS
      -----PONDS-----     ---RESERVOIRS---
      WATER      SED        WATER     SED
-BASIN VOL      CONC         VOL     CONC
O      (MM)     (PPM)        (MM)    (PPM)
1       .0         .0          .0    200.0
     FINAL COMPOSITE POND ST =      .00 MM
     FINAL COMPOSITE RESERVOIR ST =      .00 MM


                 IRRIGATION - AVE. ANNUAL
```

```
SUB-BASIN        NO.OF              VOLUME
   NO.        APPLICATIONS        APPLIED(MM)

    1              0                  .000

SOIL WATER BALANCE =       .100516E-01 MM

POND BALANCE
Q =        .000000E+00 MM      Y =       .000000E+00 T/HA

RESERVOIR BALANCE
Q =        .000000E+00 MM      Y =       .000000E+00 T/HA
```

```
SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                     13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
SUB-BASIN STATISTICS

             AVE ANNUAL VALUES
                             SUB
BASIN RAIN       SUR Q      SUR Q        Y           TOTAL BIOMASS(KG/HA)
O    (MM)        (MM)       (MM)       (T/HA)       CROP 1     CROP 2     CROP
1    654.7       29.6       171.8        1.2        4008.3



             AVE MONTHLY BASIN VALUES
               SNOW                  SUB       WATER
O      R       FALL       SUR Q     SUR Q      YIELD       ET         Y
|     (MM)     (MM)       (MM)      (MM)       (MM)       (MM)      (T/HA)
1     29.10     1.50        .35     15.55      15.90       6.37       .02
2     89.18     7.25      13.54     14.62      28.16      19.35       .26
3     69.50      .00       4.66     49.09      53.76      56.71       .15
4     32.40      .00        .06      9.87       9.93      37.16       .01
5     22.80      .00        .00      1.82       1.82      27.62       .00
6     98.80      .00        .72      1.49       2.22      79.84       .03
7     40.30      .00        .25      2.07       2.33      53.47       .01
8     20.50      .00        .00       .86        .86      52.25       .00
9     23.70      .00        .00       .14        .14      57.15       .00
0     98.70     1.40       5.87      2.02       7.89      24.23       .30
1    107.40      .00       4.17     36.04      40.21       9.46       .31
2     25.40      .00        .44     26.07      26.51       3.27       .06


BASIN STATISTICS

     CN--MEAN = 85.970       MAX = 98.372       MIN = 72.787

     PRED PK FLOW
          MEAN =       1.474 M**3/S       ST DEV =       1.630 M**3/S
          NO PKS =          18
          MAX =        5.731 M**3/S

     PRED MO WATER YLD
          MEAN =    15.73 MM
          ST DEV =    17.60 MM

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                     13:43
YTHAN91.dat
```

```
WEA:` 24   AK  KODIAK WSO
     AVE ANNUAL BASIN VALUES

          PRECIP =     654.7 MM
          SNOW FALL =     9.90 MM
          SNOW MELT =     4.05 MM
          PRED SURFACE Q =     29.62 MM
          SUB-SUR Q =  159.13 MM
          PRED H20 YLD =    188.74 MM
          DEEP PERC =   26.41 MM
          ET =     426.2 MM
          TRANS LOSSES =      .00 MM
          TOTAL SUB-BASIN SED YLD =      1.176 T/HA
          BASIN SED YLD =    1.152 T/HA
          POND BUDGET
               EVAPORATION =      .000 MM
               SEEPAGE =     .000 MM
               RAINFALL ON POOL =    .000 MM
               INFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
               OUTFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
          RESERVOIR BUDGET
               EVAPORATION =      .000 MM
               SEEPAGE =     .000 MM
               RAINFALL ON POOL =     .000 MM
               INFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
               OUTFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
          YIELD LOSS FROM PONDS
               Q =    .000 MM
               Y =    .000 T/HA
          YIELD LOSS FROM RESERVOIRS
               Q =    .000 MM
               Y =    .000 T/HA

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                      13:43
YTHAN91.dat  .
WEA:  24   AK  KODIAK WSO
          AVE ANNUAL BASIN VALUES


          NUTRIENTS
               ORGANIC N =      5.27 (KG/HA)
               ORGANIC P =      1.27 (KG/HA)
               NO3 YIELD (SQ) =      3.69 (KG/HA)
               NO3 YIELD (SSQ) =    33.17 (KG/HA)
               SOL P YIELD =      .05 (KG/HA)
               NO3 LEACHED =      .75 (KG/HA)
               N UPTAKE =    99.11 (KG/HA)


YTHAN CATCHMENT                                                      13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
```

```
  MONTHLY AND ANNUAL WATER STATISTICS
       MONTHLY STATISTICS

      PRED       OBS       ERR
 1    15.90      29.98     -14.08
 2    27.19      38.34     -11.15
 3    53.76      75.09     -21.33
 4     9.93      33.49     -23.56
 5     1.82      21.24     -19.42
 6     2.22      21.30     -19.08
 7     2.33      18.24     -15.91
 8      .86      13.17     -12.31
 9      .14      11.01     -10.87
10     7.89      15.78      -7.89
11    40.21      60.34     -20.13
12    26.51      31.62      -5.11

 1   188.74     369.60     -48.93


     MEAN MEAS      =      .308000E+02     R**2       =       .915
     MEAN PRED      =      .157287E+02     REG SLOPE =      1.058
     STD DEV MEAS =        .194635E+02     SUM ER**2 =       .309066E+04
     STD DEV PRED =        .176013E+02     NUM OBS =      12


    J      F      M      A      M      J      J      A      S      O      N      D

D 15.90  27.19  53.76   9.93   1.82   2.22   2.33    .86    .14   7.89  40.21  26.51
  29.98  38.34  75.09  33.49  21.24  21.30  18.24  13.17  11.01  15.78  60.34  31.62


      BEGINNING TIME: 20:35:31.18
      ENDING    TIME: 20:35:38.48
      ----------------------------
      TOTAL RUN TIME:        7.30
```

```
SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                     13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
     NO YRS =    1
     BASIN AREA =   523.000 KM**2
     AVE A RAINFALL/AVE A FOR GAGE
       SUBBASIN
          1    1.00
     BASEFLOW FACTOR =    1.000
     BASIN LAG TIME =   15.00 D
     GENERATOR CYCLES =     0
     WATER STATS =  1
     SEDIMENT STATS =  0


     GENERATOR SEEDS
              9  98 915  92
            135  28 203  85
             43  54 619  33
            645   9 948  65
            885  41 696  62
             51  78 648   0
            227  57 929  37
             20  90 215  31
            320  73 631  49

     TP-40 RAINFALL AMOUNTS (10 YR FREQ) FOR DUR
          0.5 H =  46.74 MM
          6H= 66.29 MM

     NO YRS RECORD MAX.5H RAIN= 11.0

     LATITUDE= 57.75 DEG

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                     13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
CLIMATE DATA

     RAINFALL DATA USED IN THIS RUN ARE:
      **MEASURED SINGLE RAINGAGE**

     TEMPERATURE DATA USED IN THIS RUN ARE;
      **MEASURED FOR ENTIRE BASIN**

                 -MO RAIN PROB--      -MO STATS FOR DAILY RAIN-
                  W/D        W/W       MEAN       ST DV      SKW CF
                  .350       .800     11.430     12.700       .310
                  .310       .800      9.140     12.190      1.910
                  .450       .660      6.600      6.860      -.300
                  .320       .690      6.350      6.600       .170
                  .440       .810      9.400     12.450      2.130
                  .250       .700      7.370      9.400      1.100
                  .330       .660      5.840      8.890      1.940
                  .270       .660      8.380     12.450      2.320
                  .390       .680     11.430     12.950       .210
                  .360       .710     12.450     14.480      1.020
                  .440       .700     10.920     12.700       .650
                  .350       .710      9.650     11.430      1.180
```

```
        R5MX       TMX       TMN        RA       CVT     RAIN      DAYP     AL
 JAN     8.89      2.20     -2.80     26.00      .30   225.48     19.73
 FEB     8.64      2.10     -3.70     84.00      .29   161.11     17.63
 MAR     7.11      4.10     -1.90    232.00      .21   116.54     17.66
 APR     7.37      6.80       .60    363.00      .15    96.76     15.24
 MAY     8.64      9.40      3.60    445.00      .11   203.52     21.65
 JUN    12.95     13.40      6.60    477.00      .11   100.50     13.64
 JUL    12.70     15.70      9.30    418.00      .09    89.17     15.27
 AUG    22.10     16.40      9.30    315.00      .09   114.98     13.72
 SEP    17.02     13.40      6.60    192.00      .10   188.35     16.48
 OCT     9.40      8.50      1.80     94.00      .16   213.76     17.17
 NOV    11.94      4.70     -1.10     34.00      .20   194.79     17.84
 DEC     9.65      2.50     -3.40     12.00      .26   163.60     16.95
 YR     11.37      8.27      2.08    224.33      .17  1868.57    202.97

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                   13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO

CROP DATA


BASIN  1

OP 1                       CROP 2                     CROP 3
MBER OF CROPS =  1
ANTING DATE =  3/25        PLANTING DATE =  0/ 0      PLANTING DATE =  0/
RVE NO PLANTING = 76.0     CURVE NO PLANTING =    .0  CURVE NO PLANTING =
RVEST DATE =  9/30         HARVEST DATE =  0/ 0       HARVEST DATE =  0/ 0
RVE NO HARVEST = 78.0      CURVE NO HARVEST =    .0   CURVE NO HARVEST =
LLAGE OPER =     1         TILLAGE OPER =     0       TILLAGE OPER =     0
T HEAT UNITS=2000. C       POT HEAT UNITS=   0. C     POT HEAT UNITS=   0.
OMASS CONV. =     50.00    BIOMASS CONV. =      .00   BIOMASS CONV. =
TER STRESS FAC =      .01  WATER STRESS FAC =     .00 WATER STRESS FAC =
RVEST INDEX =      .42     HARVEST INDEX =      .00   HARVEST INDEX =
G (1=NO,2=YES) 1           LEG (1=NO,2=YES) 0         LEG (1=NO, 2=YES) 0
E C FACTOR =       .05     AVE C FACTOR =      .00    AVE C FACTOR =

                              FERTILIZER
P 1                         CROP 2                    CROP 3
  DATE        N        P     DATE       N        P     DATE         N        P
           (KG/HA)  (KG/HA)          (KG/HA)  (KG/HA)            (KG/HA)   (KG/

   3/15    50.00      .00    0/ 0      .00      .00    0/ 0        .00      .0
   4/15    77.00      .00    0/ 0      .00      .00    0/ 0        .00      .0
   0/ 0      .00      .00    0/ 0      .00      .00    0/ 0        .00      .0
   0/ 0      .00      .00    0/ 0      .00      .00    0/ 0        .00      .0
   0/ 0      .00      .00    0/ 0      .00      .00    0/ 0        .00      .0

                              PESTICIDE
          APPLIED  PEST             APPLIED  PEST               APPLIED  PEST
(KG/HA)   (KG/HA)   NO.             (KG/HA)   NO.                         NO.

   3/15     1.00     1     0/ 0       .00     0      0/ 0         .00     0
   0/ 0     2.00     2     0/ 0       .00     0      0/ 0         .00     0
   0/ 0      .00     0     0/ 0       .00     0      0/ 0         .00     0
   0/ 0      .00     0     0/ 0       .00     0      0/ 0         .00     0
   0/ 0      .00     0     0/ 0       .00     0      0/ 0         .00     0

                              IRRIGATION
          APPLIED                   APPLIED                     APPLIED
           (MM)                      (MM)                        (MM)
```

```
  0/ 0        .00               0/ 0        .00               0/ 0        .00
  0/ 0        .00               0/ 0        .00               0/ 0        .00
  0/ 0        .00               0/ 0        .00               0/ 0        .00
  0/ 0        .00               0/ 0        .00               0/ 0        .00
  0/ 0        .00               0/ 0        .00               0/ 0        .00


                 IRRIGATION DATA
  SUBBASINS         IRRIGATE          WATER STRESS           RUNOFF RATIO
                  (1=YES,0=NO)                          (1 minus fraction that ru


      1               0                   .50                     .90

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                           13:43
YTHAN91.dat
WEA:   24    AK   KODIAK WSO
SUB-BASIN DATA


    SUB-BASIN AREA/BASIN AREA
 1.000

    POND CATCHMENT AREA FRACTION
  .000

    POND SURFACE AREA(HA)
   .00

    MAX POND STORAGE(MM)
    .0

    INTIAL POND STORAGE(MM)
    .0

    INITIAL SED CONC IN PONDS(PPM)
    0.

    NORMAL SED CONC IN PONDS(PPM)
    0.

    SAT CONDUCTIVITY FOR POND BOTTOMS(MM/H)
   .00

    RESERVOIR CATCHMENT AREA FRACTION
  .000

    RESERVOIR SURFACE AREA AT EMERGENCY SPILLWAY(HA)
   .00

    RESERVOIR STORAGE AT EMERGENCY SPILLWAY(MM)
    .0

    RESERVOIR SURFACE AREA AT PRINCIPAL SPILLWAY(HA)
   .00

    RESERVOIR STORAGE AT PRINCIPAL SPILLWAY(MM)
    .0

    INITIAL RESERVOIR STORAGE(MM)
    .0
```

```
    AVE RESERVOIR RELEASE RATES(M**3/S/KM**2)
.00000

    INITIAL SED CONC IN RESERVOIRS(PPM)
 200.

    NORMAL SED CONC IN RESERVOIRS(PPM)
 250.

    SAT CONDUCTIVITY OF RESERVOIR BOTTOMS (MM/H)
  .00

    2 COND CN
 76.0

    SOIL ALBEDO
  .10

    WATER CONTENT OF SNOW COVER (MM)
   .0

    MAIN CHANNEL LENGTH (KM)
73.00     63.00

    CHANNEL SLOPE(M/M)
.0020     .0020

    AVERAGE MAIN CHANNEL WIDTH (M)
 2.50

    HYDR COND OF CHANNEL ALLUVIUM(MM/H)
  .01

    CHANNEL N VALUE
 .010      .050

    OVERLAND FLOW N VALUE
 .090      .600

    TIME OF CONCENTRATION FOR SUB-BASINS(H)
 7.00     23.61

    RET FLO SED CONC (PPM)
 100.

    RET FLO TRAVEL TIME(D)
7.000

    SLOPE LENGTH(M)
  50.      100.

    SLOPE STEEPNESS(M/M)
.1000     .0020

    EROSION CONTROL PRACTICE FACTORS(P)
  .50


    SLOPE LENGTH AND STEEPNESS FACTORS(LS)
 1.89


            ROUTING DATA -- SUB-BASIN TO BASIN OUTLET
```

```
     AVE CHANNEL WIDTH(M)
  2.50

     AVE CHANNEL DEPTH(M)
   .30

     CHANNEL SLOPE(M/M)
   .00

     CHANNEL LENGTH(KM)
  1.00

     CHANNEL N VALUE
   .03

     HYDR COND OF CHANNEL ALLUVIUM(MM/H)
   .01

     USLE SOIL FACTOR K FOR CHANNEL
  .320

     USLE SOIL FACTOR C FOR CHANNEL
  .050

               PESTICIDE DATA


   TOTAL NO OF PESTICIDES SIMULATED =    0
                                                  ---HALF LIFE---
                                        WASH OFF   ON        IN          APPL.
               PEST           KOC         FRAC.   FOLIAGE    SOIL         EFF

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                      13:43 :
YTHAN91.dat
WEA:  24   AK  KODIAK WSO

SOILS DATA


          LAYER                15 BAR    .3 BAR     AVAIL      INITIAL    SA
    ST    DEPTH     POROSITY     SW        SW       W ST        W ST      CO
    NO     (MM)     (MM/MM)   (MM/MM)   (MM/MM)     (MM)        (MM)     (MM
      SUBBASIN    1       TYPIC ARIGIAQUO
     1     10.0       .40       .06       .24       1.80        1.80      3
     2    203.2       .40       .06       .24      34.78       34.78      3
     3    685.8       .40       .06       .24      86.87       86.87      3
     4   1524.0       .40       .13       .31     150.88      150.88      1
TOTALS                                            274.3       274.3


     INITIAL COMPOSITE ST =    274.3 MM

                SOIL SURFACE LAYER

                                                                ORG
                                                                 N
                                                               (G/M3)
UB-BASIN     CLAY          SILT         SAND          K
   1          .10           .32          .58         .20      1000.00
```

```
                                SEDIMENT SIZE DISTRIBUTION
    SUB-BASIN                              SIZE(MM)

                     SAND          SILT        CLAY     SM AG       L AG
                      .20           .01        .002       .03        .50

          1          .446          .042        .020      .200       .292

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                              13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
                       SUB     WATER   PERCO           SED             ORGANIC ORGANIC
      R        SURQ   SURQ     YIELD   LATE    ET     YIELD     SW        N       P
     (MM)      (MM)   (MM)      (MM)   (MM)   (MM)    (T/HA)   (MM)
1  29.10        .35  15.55   15.90    2.87    6.37     .02 273.24      .01     .00
2  86.10    13.08  14.11   27.19    3.63   18.68     .25 292.00     1.23     .30
3  69.50     4.66  49.09   53.76    3.28   56.71     .15 259.70      .59     .14
4  32.40      .06   9.87    9.93    1.35   37.16     .01 252.97      .01     .00
5  22.80      .00   1.82    1.82    1.20   27.62     .00 246.40      .00     .00
6  98.80      .72   1.49    2.22    2.98   79.84     .03 259.43      .17     .04
7  40.30      .25   2.07    2.33    1.57   53.47     .01 242.79      .03     .01
8  20.50      .00    .86     .86     .92   52.25     .00 209.77      .00     .00
9  23.70      .00    .14     .14     .42   57.15     .00 175.90      .00     .00
0  98.70     5.87   2.02    7.89    1.56   24.23     .30 236.55     1.56     .38
1 107.40     4.17  36.04   40.21    4.15    9.46     .31 274.87     1.48     .35
2  25.40      .44  26.07   26.51    2.50    3.27     .06 274.98      .19     .04

1 654.70    29.62 159.13 188.74   26.41 426.20    1.15 274.98     5.27    1.27


SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                              13:43
YTHAN91.dat
WEA:  24   AK  KODIAK WSO
FINAL VALUES

-BASIN                          SOIL WATER FOR LAYER NO
O


    1      2      3     4
   1.4   35.1   87.1 151.4

  TOTAL SOIL WATER
1     275.0

      FINAL COMPOSITE ST =   275.0 MM
      MIN INDIVIDUAL WATER ST =        .0 MM


                    FINAL CONTENTS
        -----PONDS-----     ---RESERVOIRS---
        WATER       SED        WATER     SED
-BASIN VOL         CONC         VOL      CONC
O        (MM)      (PPM)        (MM)     (PPM)
          .0          .0          .0     200.0
      FINAL COMPOSITE POND ST =      .00 MM
      FINAL COMPOSITE RESERVOIR ST =      .00 MM


                  IRRIGATION - AVE. ANNUAL
```

```
     SUB-BASIN        NO.OF              VOLUME
        NO.       APPLICATIONS       APPLIED(MM)

         1              0                   .000

     SOIL WATER BALANCE =        .100516E-01 MM

     POND BALANCE
     Q =        .000000E+00 MM      Y =       .000000E+00 T/HA

     RESERVOIR BALANCE
     Q =        .000000E+00 MM      Y =       .000000E+00 T/HA

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                   13:43
 YTHAN91.dat
 WEA:  24   AK  KODIAK WSO
 SUB-BASIN STATISTICS

              AVE ANNUAL VALUES
                             SUB
-BASIN RAIN       SUR Q     SUR Q        Y            TOTAL BIOMASS(KG/HA)
O       (MM)      (MM)      (MM)       (T/HA)      CROP 1     CROP 2     CROP
1      654.7      29.6     171.8        1.2        4008.3


              AVE MONTHLY BASIN VALUES
                 SNOW               SUB       WATER
O     R          FALL     SUR Q    SUR Q      YIELD      ET          Y
    (MM)         (MM)     (MM)     (MM)       (MM)      (MM)       (T/HA)
1   29.10        1.50      .35    15.55      15.90      6.37         .02
2   89.18        7.25    13.54    14.62      28.16     19.35         .26
3   69.50         .00     4.66    49.09      53.76     56.71         .15
4   32.40         .00      .06     9.87       9.93     37.16         .01
5   22.80         .00      .00     1.82       1.82     27.62         .00
6   98.80         .00      .72     1.49       2.22     79.84         .03
7   40.30         .00      .25     2.07       2.33     53.47         .01
8   20.50         .00      .00      .86        .86     52.25         .00
9   23.70         .00      .00      .14        .14     57.15         .00
10  98.70        1.40     5.87     2.02       7.89     24.23         .30
11 107.40         .00     4.17    36.04      40.21      9.46         .31
12  25.40         .00      .44    26.07      26.51      3.27         .06


 BASIN STATISTICS

     CN--MEAN = 85.970      MAX = 98.372      MIN = 72.787

     PRED PK FLOW
          MEAN =        1.474 M**3/S      ST DEV =       1.630 M**3/S
          NO PKS =         18
          MAX =         5.731 M**3/S

     PRED MO WATER YLD
          MEAN =    15.73 MM
          ST DEV =    17.60 MM

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                   13:43
 YTHAN91.dat
```

```
WEA:  24   AK   KODIAK WSO
     AVE ANNUAL BASIN VALUES

          PRECIP =    654.7 MM
          SNOW FALL =    9.90 MM
          SNOW MELT =     4.05 MM
          PRED SURFACE Q =    29.62 MM
          SUB-SUR Q =  159.13 MM
          PRED H20 YLD =   188.74 MM
          DEEP PERC =   26.41 MM
          ET =    426.2 MM
          TRANS LOSSES =       .00 MM
          TOTAL SUB-BASIN SED YLD =     1.176 T/HA
          BASIN SED YLD =    1.152 T/HA
          POND BUDGET
               EVAPORATION =     .000 MM
               SEEPAGE =     .000 MM
               RAINFALL ON POOL =    .000 MM
               INFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
               OUTFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
          RESERVOIR BUDGET
               EVAPORATION =     .000 MM
               SEEPAGE =     .000 MM
               RAINFALL ON POOL =     .000 MM
               INFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
               OUTFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
          YIELD LOSS FROM PONDS
               Q =    .000 MM
               Y =    .000 T/HA
          YIELD LOSS FROM RESERVOIRS
               Q =    .000 MM
               Y =    .000 T/HA

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                    13:43
YTHAN91.dat
WEA:  24   AK   KODIAK WSO
          AVE ANNUAL BASIN VALUES


          NUTRIENTS
               ORGANIC N =     5.27 (KG/HA)
               ORGANIC P =     1.27 (KG/HA)
               NO3 YIELD (SQ) =     3.69 (KG/HA)
               NO3 YIELD (SSQ) =   33.17 (KG/HA)
               SOL P YIELD =     .05 (KG/HA)
               NO3 LEACHED =     .75 (KG/HA)
               N UPTAKE =   99.11 (KG/HA)


YTHAN CATCHMENT                                                    13:43
YTHAN91.dat
WEA:  24   AK   KODIAK WSO
```

```
    MONTHLY AND ANNUAL WATER STATISTICS
         MONTHLY STATISTICS

      PRED          OBS          ERR
 1    15.90         29.98       -14.08
 2    27.19         38.34       -11.15
 3    53.76         75.09       -21.33
 4     9.93         33.49       -23.56
 5     1.82         21.24       -19.42
 6     2.22         21.30       -19.08
 7     2.33         18.24       -15.91
 8      .86         13.17       -12.31
 9      .14         11.01       -10.87
10     7.89         15.78        -7.89
11    40.21         60.34       -20.13
12    26.51         31.62        -5.11

91   188.74        369.60       -48.93

     MEAN MEAS     =     .308000E+02     R**2      =      .915
     MEAN PRED     =     .157287E+02     REG SLOPE =     1.058
     STD DEV MEAS  =     .194635E+02     SUM ER**2 =      .309066E+04
     STD DEV PRED  =     .176013E+02     NUM OBS =      12

   J     F     M     A     M     J     J     A     S     O     N     D

ED 15.90 27.19 53.76  9.93  1.82  2.22  2.33   .86   .14  7.89 40.21 26.51
S  29.98 38.34 75.09 33.49 21.24 21.30 18.24 13.17 11.01 15.78 60.34 31.62

      BEGINNING TIME: 20:35:31.18
      ENDING    TIME: 20:35:38.48
      ----------------------------
      TOTAL RUN TIME:         7.30
```

```
SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                     13:43
YTHAN90.dat
WEA:  24   AK  KODIAK WSO
     NO YRS =     1
     BASIN AREA =   523.000 KM**2
     AVE A RAINFALL/AVE A FOR GAGE
       SUBBASIN
          1    1.00
     BASEFLOW FACTOR =    1.000
     BASIN LAG TIME =   15.00 D
     GENERATOR CYCLES =     0
     WATER STATS =  1
     SEDIMENT STATS =  0


     GENERATOR SEEDS
               9   98 915   92
             135   28 203   85
              43   54 619   33
             645    9 948   65
             885   41 696   62
              51   78 648    0
             227   57 929   37
              20   90 215   31
             320   73 631   49

     TP-40 RAINFALL AMOUNTS (10 YR FREQ) FOR DUR
          0.5 H =  46.74 MM
          6H= 66.29 MM

     NO YRS RECORD MAX.5H RAIN= 11.0

     LATITUDE= 57.75 DEG

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                     13:43
YTHAN90.dat
WEA:  24   AK  KODIAK WSO
CLIMATE DATA

     RAINFALL DATA USED IN THIS RUN ARE:
      **MEASURED SINGLE RAINGAGE**

     TEMPERATURE DATA USED IN THIS RUN ARE;
      **MEASURED FOR ENTIRE BASIN**

                 -MO RAIN PROB--      -MO STATS FOR DAILY RAIN-
                  W/D         W/W     MEAN        ST DV       SKW CF
                  .350        .800    11.430      12.700       .310
                  .310        .800     9.140      12.190      1.910
                  .450        .660     6.600       6.860      -.300
                  .320        .690     6.350       6.600       .170
                  .440        .810     9.400      12.450      2.130
                  .250        .700     7.370       9.400      1.100
                  .330        .660     5.840       8.890      1.940
                  .270        .660     8.380      12.450      2.320
                  .390        .680    11.430      12.950       .210
                  .360        .710    12.450      14.480      1.020
                  .440        .700    10.920      12.700       .650
                  .350        .710     9.650      11.430      1.180
```

```
         R5MX        TMX        TMN         RA         CVT       RAIN       DAYP       AL
 JAN      8.89       2.20      -2.80      26.00        .30     225.48      19.73
 FEB      8.64       2.10      -3.70      84.00        .29     161.11      17.63
 MAR      7.11       4.10      -1.90     232.00        .21     116.54      17.66
 APR      7.37       6.80        .60     363.00        .15      96.76      15.24
 MAY      8.64       9.40       3.60     445.00        .11     203.52      21.65
 JUN     12.95      13.40       6.60     477.00        .11     100.50      13.64
 JUL     12.70      15.70       9.30     418.00        .09      89.17      15.27
 AUG     22.10      16.40       9.30     315.00        .09     114.98      13.72
 SEP     17.02      13.40       6.60     192.00        .10     188.35      16.48
 OCT      9.40       8.50       1.80      94.00        .16     213.76      17.17
 NOV     11.94       4.70      -1.10      34.00        .20     194.79      17.84
 DEC      9.65       2.50      -3.40      12.00        .26     163.60      16.95
 YR      11.37       8.27       2.08     224.33        .17    1868.57     202.97

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                            13:43
YTHAN90.dat
WEA:  24    AK  KODIAK WSO

CROP DATA


BASIN  1

OP 1                       CROP 2                      CROP 3
MBER OF CROPS =  1
ANTING DATE =  3/25        PLANTING DATE =  0/ 0       PLANTING DATE =  0/
RVE NO PLANTING = 76.0     CURVE NO PLANTING =    .0   CURVE NO PLANTING =
RVEST DATE =  9/30         HARVEST DATE =  0/ 0        HARVEST DATE =  0/ 0
RVE NO HARVEST = 78.0      CURVE NO HARVEST =   .0     CURVE NO HARVEST =
LLAGE OPER =    1          TILLAGE OPER =    0         TILLAGE OPER =    0
T HEAT UNITS=2000. C       POT HEAT UNITS=   0. C      POT HEAT UNITS=   0.
OMASS CONV. =    50.00     BIOMASS CONV. =     .00     BIOMASS CONV. =
TER STRESS FAC =     .01   WATER STRESS FAC =     .00  WATER STRESS FAC =
RVEST INDEX =       .42    HARVEST INDEX =      .00    HARVEST INDEX =
G (1=NO,2=YES) 1           LEG (1=NO,2=YES) 0          LEG (1=NO, 2=YES) 0
E C FACTOR =       .05     AVE C FACTOR =      .00     AVE C FACTOR =

                              FERTILIZER
P 1                         CROP 2                        CROP 3
. DATE       N        P     DATE        N        P        DATE        N        P
          (KG/HA)  (KG/HA)           (KG/HA)  (KG/HA)              (KG/HA)  (KG/

1   3/15   50.00      .00    0/ 0       .00      .00      0/ 0        .00      .0
2   4/15   77.00      .00    0/ 0       .00      .00      0/ 0        .00      .0
3   0/ 0     .00      .00    0/ 0       .00      .00      0/ 0        .00      .0
4   0/ 0     .00      .00    0/ 0       .00      .00      0/ 0        .00      .0
5   0/ 0     .00      .00    0/ 0       .00      .00      0/ 0        .00      .0

                               PESTICIDE
          APPLIED  PEST                 APPLIED PEST                 APPLIED PEST
(KG/HA)   (KG/HA)   NO.                 (KG/HA)  NO.                          NO.

    3/15    1.00     1       0/ 0       .00      0        0/ 0        .00      0
    0/ 0    2.00     2       0/ 0       .00      0        0/ 0        .00      0
    0/ 0     .00     0       0/ 0       .00      0        0/ 0        .00      0
    0/ 0     .00     0       0/ 0       .00      0        0/ 0        .00      0
    0/ 0     .00     0       0/ 0       .00      0        0/ 0        .00      0

                               IRRIGATION
          APPLIED                       APPLIED                      APPLIED
           (MM)                          (MM)                         (MM)
```

```
   0/ 0       .00              0/ 0      .00              0/ 0      .00
   0/ 0       .00              0/ 0      .00              0/ 0      .00
   0/ 0       .00              0/ 0      .00              0/ 0      .00
   0/ 0       .00              0/ 0      .00              0/ 0      .00
   0/ 0       .00              0/ 0      .00              0/ 0      .00


                 IRRIGATION DATA
   SUBBASINS       IRRIGATE         WATER STRESS          RUNOFF RATIO
                 (1=YES,0=NO)                        (1 minus fraction that ru


       1              0                   .50                     .90
SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                    13:43
YTHAN90.dat
WEA:   24    AK   KODIAK WSO
SUB-BASIN DATA


     SUB-BASIN AREA/BASIN AREA
 1.000

     POND CATCHMENT AREA FRACTION
  .000

     POND SURFACE AREA(HA)
   .00

     MAX POND STORAGE(MM)
    .0

     INTIAL POND STORAGE(MM)
    .0

     INITIAL SED CONC IN PONDS(PPM)
    0.

     NORMAL SED CONC IN PONDS(PPM)
    0.

     SAT CONDUCTIVITY FOR POND BOTTOMS(MM/H)
   .00

     RESERVOIR CATCHMENT AREA FRACTION
  .000

     RESERVOIR SURFACE AREA AT EMERGENCY SPILLWAY(HA)
   .00

     RESERVOIR STORAGE AT EMERGENCY SPILLWAY(MM)
    .0

     RESERVOIR SURFACE AREA AT PRINCIPAL SPILLWAY(HA)
   .00

     RESERVOIR STORAGE AT PRINCIPAL SPILLWAY(MM)
    .0

     INITIAL RESERVOIR STORAGE(MM)
    .0
```

```
    AVE RESERVOIR RELEASE RATES(M**3/S/KM**2)
.00000

    INITIAL SED CONC IN RESERVOIRS(PPM)
 200.

    NORMAL SED CONC IN RESERVOIRS(PPM)
 250.

    SAT CONDUCTIVITY OF RESERVOIR BOTTOMS (MM/H)
  .00

    2 COND CN
 76.0

    SOIL ALBEDO
  .10

    WATER CONTENT OF SNOW COVER (MM)
   .0

    MAIN CHANNEL LENGTH (KM)
73.00     63.00

    CHANNEL SLOPE(M/M)
.0020     .0020

    AVERAGE MAIN CHANNEL WIDTH (M)
 2.50

    HYDR COND OF CHANNEL ALLUVIUM(MM/H)
  .01

    CHANNEL N VALUE
 .010      .050

    OVERLAND FLOW N VALUE
 .090      .600

    TIME OF CONCENTRATION FOR SUB-BASINS(H)
 7.00     23.61

    RET FLO SED CONC (PPM)
 100.

    RET FLO TRAVEL TIME(D)
7.000

    SLOPE LENGTH(M)
  50.      100.

    SLOPE STEEPNESS(M/M)
.1000     .0020

    EROSION CONTROL PRACTICE FACTORS(P)
  .50


    SLOPE LENGTH AND STEEPNESS FACTORS(LS)
 1.89


              ROUTING DATA -- SUB-BASIN TO BASIN OUTLET
```

```
    AVE CHANNEL WIDTH(M)
 2.50

    AVE CHANNEL DEPTH(M)
  .30

    CHANNEL SLOPE(M/M)
  .00

    CHANNEL LENGTH(KM)
 1.00

    CHANNEL N VALUE
  .03

    HYDR COND OF CHANNEL ALLUVIUM(MM/H)
  .01

    USLE SOIL FACTOR K FOR CHANNEL
 .320

    USLE SOIL FACTOR C FOR CHANNEL
 .050

            PESTICIDE DATA

   TOTAL NO OF PESTICIDES SIMULATED =    0
                                                    ---HALF LIFE---
                                        WASH OFF     ON        IN        APPL.
            PEST               KOC        FRAC.    FOLIAGE    SOIL        EFF

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                      13:43
YTHAN90.dat
WEA:  24   AK  KODIAK WSO

SOILS DATA


          LAYER                  15 BAR    .3 BAR     AVAIL     INITIAL    SA
   ST     DEPTH     POROSITY      SW        SW        W ST       W ST      CO
   NO      (MM)     (MM/MM)    (MM/MM)    (MM/MM)     (MM)       (MM)      (MM
     SUBBASIN     1.      TYPIC ARIGIAQUO
    1      10.0       .40        .06        .24       1.80       1.80       3
    2     203.2       .40        .06        .24      34.78      34.78       3
    3     685.8       .40        .06        .24      86.87      86.87       3
    4    1524.0       .40        .13        .31     150.88     150.88       1
TOTALS                                              274.3      274.3


     INITIAL COMPOSITE ST =    274.3 MM

                SOIL SURFACE LAYER

                                                             ORG
                                                              N
                                                            (G/M3)      (
UB-BASIN     CLAY          SILT         SAND         K
   1          .10           .32          .58         .20    1000.00
```

```
                              SEDIMENT SIZE DISTRIBUTION
    SUB-BASIN                          SIZE(MM)

                  SAND       SILT       CLAY     SM AG      L AG
                   .20        .01       .002       .03       .50

          1       .446       .042       .020      .200      .292

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                       13:43
 YTHAN90.dat
 WEA:  24    AK  KODIAK WSO
                      SUB     WATER  PERCO          SED          ORGANIC ORGANIC
      R        SURQ  SURQ     YIELD  LATE   ET     YIELD   SW       N       P
     (MM)      (MM)  (MM)     (MM)   (MM)  (MM)   (T/HA)  (MM)
 1   39.40    4.56  10.33   14.89   2.74    6.92    .07 276.98    .30     .07
 2   60.90    1.47  27.79   29.25   3.28   21.66    .04 276.80    .11     .02
 3   12.20     .00  19.81   19.81   1.10   32.05    .02 252.15    .00     .00
 4   35.90     .00   3.05    3.05   1.70   35.49    .00 250.10    .00     .00
 5   48.00     .46   1.38    1.84   1.62   41.27    .01 253.19    .06     .01
 6   83.80    3.12   1.32    4.45   2.55   66.66    .12 263.56    .59     .14
 7   33.80     .27   1.22    1.49   1.42   49.68    .01 245.14    .05     .01
 8   73.20    3.61   1.09    4.70   1.95   71.51    .02 239.87    .08     .02
 9   73.80    1.77   1.16    2.93   1.82   49.99    .00 256.89    .01     .00
10  112.40   21.66  19.06   40.71   3.94   29.48   2.39 281.14  12.12    2.97
11   80.70    9.05  54.86   63.91   4.40    9.51   1.10 276.13   5.43    1.32
12   48.00     .43  45.30   45.72   3.78    3.28    .08 274.90    .24     .05

90  702.10   46.39 186.36  232.75  30.29  417.52   3.86 274.90  18.99    4.63
```

```
 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                       13:43
 YTHAN90.dat
 WEA:  24    AK  KODIAK WSO
 FINAL VALUES

B-BASIN                      SOIL WATER FOR LAYER NO
NO


     1     2     3     4
1    .6  35.2  87.5 151.5

   TOTAL SOIL WATER
 1      274.9

      FINAL COMPOSITE ST =    274.9 MM
      MIN INDIVIDUAL WATER ST =        .0 MM


                FINAL CONTENTS
      -----PONDS-----      ---RESERVOIRS---
      WATER      SED        WATER      SED
B-BASIN VOL      CONC        VOL       CONC
NO      (MM)     (PPM)       (MM)      (PPM)
1        .0        .0         .0      200.0
      FINAL COMPOSITE POND ST =       .00 MM
      FINAL COMPOSITE RESERVOIR ST =      .00 MM


               IRRIGATION - AVE. ANNUAL
```

```
     SUB-BASIN         NO.OF           VOLUME
        NO.        APPLICATIONS     APPLIED(MM)

         1              0                .000

     SOIL WATER BALANCE =      .114215E-01 MM

     POND BALANCE
     Q =       .000000E+00 MM      Y =      .000000E+00 T/HA

     RESERVOIR BALANCE
     Q =       .000000E+00 MM      Y =      .000000E+00 T/HA

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                      13:43
 YTHAN90.dat
 WEA:  24   AK  KODIAK WSO
 SUB-BASIN STATISTICS

              AVE ANNUAL VALUES
                             SUB
B-BASIN RAIN        SUR Q    SUR Q       Y            TOTAL BIOMASS(KG/HA)
NO       (MM)       (MM)     (MM)      (T/HA)      CROP 1     CROP 2     CROP
 1      702.1       46.4     207.3       3.9       2110.3



              AVE MONTHLY BASIN VALUES
                SNOW                SUB      WATER
MO      R       FALL      SUR Q    SUR Q     YIELD      ET         Y
       (MM)     (MM)      (MM)     (MM)      (MM)      (MM)      (T/HA)
 1    39.40      .00      4.56     10.33     14.89      6.92       .07
 2    63.08      .00      1.52     28.78     30.29     22.44       .05
 3    12.20      .00       .00     19.81     19.81     32.05       .02
 4    35.90      .00       .00      3.05      3.05     35.49       .00
 5    48.00      .00       .46      1.38      1.84     41.27       .01
 6    83.80      .00      3.12      1.32      4.45     66.66       .12
 7    33.80      .00       .27      1.22      1.49     49.68       .01
 8    73.20      .00      3.61      1.09      4.70     71.51       .02
 9    73.80      .00      1.77      1.16      2.93     49.99       .00
10   112.40      .00     21.66     19.06     40.71     29.48      2.39
11    80.70      .00      9.05     54.86     63.91      9.51      1.10
12    48.00      .00       .43     45.30     45.72      3.28       .08


 BASIN STATISTICS

     CN--MEAN = 87.923      MAX = 92.061      MIN = 82.288

     PRED PK FLOW
          MEAN =      2.370 M**3/S      ST DEV =      2.964 M**3/S
          NO PKS =        21
          MAX =     10.996 M**3/S

     PRED MO WATER YLD
          MEAN =    19.40 MM
          ST DEV =    21.00 MM

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                      13:43
 YTHAN90.dat
```

```
WEA:  24   AK  KODIAK WSO
     AVE ANNUAL BASIN VALUES

          PRECIP =    702.1 MM
          SNOW FALL =     .00 MM
          SNOW MELT =      .00 MM
          PRED SURFACE Q =    46.39 MM
          SUB-SUR Q =  186.36 MM
          PRED H20 YLD =   232.75 MM
          DEEP PERC =   30.29 MM
          ET =    417.5 MM
          TRANS LOSSES =      .00 MM
          TOTAL SUB-BASIN SED YLD =     3.918 T/HA
          BASIN SED YLD =    3.863 T/HA
          POND BUDGET
               EVAPORATION =     .000 MM
               SEEPAGE =     .000 MM
               RAINFALL ON POOL =    .000 MM
               INFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
               OUTFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
          RESERVOIR BUDGET
               EVAPORATION =     .000 MM
               SEEPAGE =     .000 MM
               RAINFALL ON POOL =     .000 MM
               INFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
               OUTFLOW
                    Q =     .000 MM
                    Y =     .000 T/HA
          YIELD LOSS FROM PONDS
               Q =    .000 MM
               Y =    .000 T/HA
          YIELD LOSS FROM RESERVOIRS
               Q =    .000 MM
               Y =    .000 T/HA

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                     13:43
YTHAN90.dat
WEA:  24   AK  KODIAK WSO
          AVE ANNUAL BASIN VALUES


          NUTRIENTS
               ORGANIC N =    18.99 (KG/HA)
               ORGANIC P =     4.63 (KG/HA)
               NO3 YIELD (SQ) =      .54 (KG/HA)
               NO3 YIELD (SSQ) =   79.60 (KG/HA)
               SOL P YIELD =     .08 (KG/HA)
               NO3 LEACHED =     3.50 (KG/HA)
               N UPTAKE =    55.23 (KG/HA)


YTHAN CATCHMENT                                                     13:43
YTHAN90.dat
WEA:  24   AK  KODIAK WSO
```

```
        MONTHLY AND ANNUAL WATER STATISTICS
              MONTHLY STATISTICS

        PRED          OBS           ERR
 1      14.89         14.49           .40
 2      29.25         22.06          7.19
 3      19.81         22.43         -2.62
 4       3.05         15.10        -12.05
 5       1.84         12.99        -11.15
 6       4.45         13.70         -9.25
 7       1.49         10.19         -8.70
 8       4.70         10.10         -5.40
 9       2.93          9.15         -6.22
10      40.71         26.59         14.12
11      63.91         67.88         -3.97
12      45.72         44.17          1.55

90     232.75        268.85        -13.43


       MEAN MEAS      =     .224042E+02     R**2       =       .874
       MEAN PRED      =     .193958E+02     REG SLOPE  =       .773
       STD DEV MEAS   =     .173626E+02     SUM ER**2  =       .775151E+03
       STD DEV PRED   =     .210043E+02     NUM OBS  =      12


     J      F      M      A      M      J      J      A      S      O      N      D

ED  14.89  29.25  19.81   3.05   1.84   4.45   1.49   4.70   2.93  40.71  63.91  45.72
S   14.49  22.06  22.43  15.10  12.99  13.70  10.19  10.10   9.15  26.59  67.88  44.17

        BEGINNING TIME: 20:40:32.99
        ENDING    TIME: 20:40:46.61
        ----------------------------
        TOTAL RUN TIME:       13.62
```

```
SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                       13:43
YTHAN93.dat
WEA:  24   AK  KODIAK WSO
     NO YRS =    1
     BASIN AREA =   523.000 KM**2
     AVE A RAINFALL/AVE A FOR GAGE
       SUBBASIN
          1    1.00
     BASEFLOW FACTOR =    1.000
     BASIN LAG TIME =   15.00 D
     GENERATOR CYCLES =    0
     WATER STATS =  1
     SEDIMENT STATS =  0


     GENERATOR SEEDS
              9  98 915  92
            135  28 203  85
             43  54 619  33
            645   9 948  65
            885  41 696  62
             51  78 648   0
            227  57 929  37
             20  90 215  31
            320  73 631  49

     TP-40 RAINFALL AMOUNTS (10 YR FREQ) FOR DUR
          0.5 H =  46.74 MM
          6H= 66.29 MM

     NO YRS RECORD MAX.5H RAIN= 11.0

     LATITUDE= 57.75 DEG

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                       13:43
YTHAN93.dat
WEA:  24   AK  KODIAK WSO
CLIMATE DATA

     RAINFALL DATA USED IN THIS RUN ARE:
      **MEASURED SINGLE RAINGAGE**

     TEMPERATURE DATA USED IN THIS RUN ARE;
      **MEASURED FOR ENTIRE BASIN**

                 -MO RAIN PROB--     -MO STATS FOR DAILY RAIN-
                  W/D        W/W     MEAN      ST DV     SKW CF
                  .350       .800    11.430    12.700     .310
                  .310       .800     9.140    12.190    1.910
                  .450       .660     6.600     6.860    -.300
                  .320       .690     6.350     6.600     .170
                  .440       .810     9.400    12.450    2.130
                  .250       .700     7.370     9.400    1.100
                  .330       .660     5.840     8.890    1.940
                  .270       .660     8.380    12.450    2.320
                  .390       .680    11.430    12.950     .210
                  .360       .710    12.450    14.480    1.020
                  .440       .700    10.920    12.700     .650
                  .350       .710     9.650    11.430    1.180
```

```
        R5MX       TMX       TMN        RA       CVT      RAIN    DAYP     AL
  JAN    8.89      2.20     -2.80     26.00      .30    225.48   19.73
  FEB    8.64      2.10     -3.70     84.00      .29    161.11   17.63
  MAR    7.11      4.10     -1.90    232.00      .21    116.54   17.66
  APR    7.37      6.80       .60    363.00      .15     96.76   15.24
  MAY    8.64      9.40      3.60    445.00      .11    203.52   21.65
  JUN   12.95     13.40      6.60    477.00      .11    100.50   13.64
  JUL   12.70     15.70      9.30    418.00      .09     89.17   15.27
  AUG   22.10     16.40      9.30    315.00      .09    114.98   13.72
  SEP   17.02     13.40      6.60    192.00      .10    188.35   16.48
  OCT    9.40      8.50      1.80     94.00      .16    213.76   17.17
  NOV   11.94      4.70     -1.10     34.00      .20    194.79   17.84
  DEC    9.65      2.50     -3.40     12.00      .26    163.60   16.95
  YR    11.37      8.27      2.08    224.33      .17   1868.57  202.97

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                      13:43
 YTHAN93.dat
 WEA:  24   AK  KODIAK WSO

 CROP DATA


BBASIN  1

ROP 1                          CROP 2                         CROP 3
UMBER OF CROPS =  1
LANTING DATE =  3/25           PLANTING DATE =  0/ 0          PLANTING DATE =  0/
URVE NO PLANTING = 76.0        CURVE NO PLANTING =    .0      CURVE NO PLANTING =
ARVEST DATE =  9/30            HARVEST DATE =  0/ 0           HARVEST DATE =  0/ 0
URVE NO HARVEST = 78.0         CURVE NO HARVEST =    .0       CURVE NO HARVEST =
ILLAGE OPER =    1             TILLAGE OPER =    0            TILLAGE OPER =    0
OT HEAT UNITS=2000. C          POT HEAT UNITS=   0. C         POT HEAT UNITS=   0.
IOMASS CONV. =      50.00      BIOMASS CONV. =      .00       BIOMASS CONV. =
ATER STRESS FAC =     .01      WATER STRESS FAC =     .00     WATER STRESS FAC =
ARVEST INDEX =      .42        HARVEST INDEX =      .00       HARVEST INDEX =
EG (1=NO,2=YES) 1              LEG (1=NO,2=YES) 0             LEG (1=NO, 2=YES) 0
VE C FACTOR =      .05         AVE C FACTOR =      .00        AVE C FACTOR =

                               FERTILIZER
OP 1                            CROP 2                      CROP 3
P. DATE        N        P       DATE       N        P       DATE        N        P
            (KG/HA)  (KG/HA)            (KG/HA)  (KG/HA)             (KG/HA)  (KG/

1   3/15     50.00      .00      0/ 0       .00      .00     0/ 0       .00      .0
2   4/15     77.00      .00      0/ 0       .00      .00     0/ 0       .00      .0
3   0/ 0       .00      .00      0/ 0       .00      .00     0/ 0       .00      .0
4   0/ 0       .00      .00      0/ 0       .00      .00     0/ 0       .00      .0
5   0/ 0       .00      .00      0/ 0       .00      .00     0/ 0       .00      .0

                                PESTICIDE
          APPLIED   PEST             APPLIED PEST                 APPLIED PEST
 (KG/HA)  (KG/HA)    NO.             (KG/HA)  NO.                          NO.

    3/15     1.00     1      0/ 0       .00    0          0/ 0       .00    0
    0/ 0     2.00     2      0/ 0       .00    0          0/ 0       .00    0
    0/ 0      .00     0      0/ 0       .00    0          0/ 0       .00    0
    0/ 0      .00     0      0/ 0       .00    0          0/ 0       .00    0
    0/ 0      .00     0      0/ 0       .00    0          0/ 0       .00    0

                                IRRIGATION
          APPLIED                    APPLIED                      APPLIED
           (MM)                       (MM)                         (MM)
```

```
   0/ 0       .00             0/ 0      .00            0/ 0      .00
   0/ 0       .00             0/ 0      .00            0/ 0      .00
   0/ 0       .00             0/ 0      .00            0/ 0      .00
   0/ 0       .00             0/ 0      .00            0/ 0      .00
   0/ 0       .00             0/ 0      .00            0/ 0      .00


                 IRRIGATION DATA
   SUBBASINS       IRRIGATE          WATER STRESS           RUNOFF RATIO
                 (1=YES,0=NO)                          (1 minus fraction that ru


       1              0                   .50                      .90

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

YTHAN CATCHMENT                                                          13:43
YTHAN93.dat
WEA:  24   AK  KODIAK WSO
SUB-BASIN DATA


     SUB-BASIN AREA/BASIN AREA
 1.000

     POND CATCHMENT AREA FRACTION
  .000

     POND SURFACE AREA(HA)
   .00

     MAX POND STORAGE(MM)
    .0

     INTIAL POND STORAGE(MM)
    .0

     INITIAL SED CONC IN PONDS(PPM)
    0.

     NORMAL SED CONC IN PONDS(PPM)
    0.

     SAT CONDUCTIVITY FOR POND BOTTOMS(MM/H)
   .00

     RESERVOIR CATCHMENT AREA FRACTION
  .000

     RESERVOIR SURFACE AREA AT EMERGENCY SPILLWAY(HA)
   .00

     RESERVOIR STORAGE AT EMERGENCY SPILLWAY(MM)
    .0

     RESERVOIR SURFACE AREA AT PRINCIPAL SPILLWAY(HA)
   .00

     RESERVOIR STORAGE AT PRINCIPAL SPILLWAY(MM)
    .0

     INITIAL RESERVOIR STORAGE(MM)
    .0
```

```
    AVE RESERVOIR RELEASE RATES(M**3/S/KM**2)
.00000

    INITIAL SED CONC IN RESERVOIRS(PPM)
 200.

    NORMAL SED CONC IN RESERVOIRS(PPM)
 250.

    SAT CONDUCTIVITY OF RESERVOIR BOTTOMS (MM/H)
  .00

    2 COND CN
 76.0

    SOIL ALBEDO
  .10

    WATER CONTENT OF SNOW COVER (MM)
   .0

    MAIN CHANNEL LENGTH (KM)
73.00     63.00

    CHANNEL SLOPE(M/M)
.0020     .0020

    AVERAGE MAIN CHANNEL WIDTH (M)
 2.50

    HYDR COND OF CHANNEL ALLUVIUM(MM/H)
  .01

    CHANNEL N VALUE
 .010      .050

    OVERLAND FLOW N VALUE
 .090      .600

    TIME OF CONCENTRATION FOR SUB-BASINS(H)
 7.00     23.61

    RET FLO SED CONC (PPM)
 100.

    RET FLO TRAVEL TIME(D)
7.000

    SLOPE LENGTH(M)
  50.      100.

    SLOPE STEEPNESS(M/M)
.1000     .0020

    EROSION CONTROL PRACTICE FACTORS(P)
  .50


    SLOPE LENGTH AND STEEPNESS FACTORS(LS)
 1.89


               ROUTING DATA -- SUB-BASIN TO BASIN OUTLET
```

```
     AVE CHANNEL WIDTH(M)
  2.50

     AVE CHANNEL DEPTH(M)
   .30

     CHANNEL SLOPE(M/M)
   .00

     CHANNEL LENGTH(KM)
  1.00

     CHANNEL N VALUE
   .03

     HYDR COND OF CHANNEL ALLUVIUM(MM/H)
   .01

     USLE SOIL FACTOR K FOR CHANNEL
  .320

     USLE SOIL FACTOR C FOR CHANNEL
  .050

             PESTICIDE DATA


   TOTAL NO OF PESTICIDES SIMULATED =    0
                                                  ---HALF LIFE---
                                       WASH OFF    ON        IN        APPL.
             PEST             KOC       FRAC.    FOLIAGE   SOIL        EFF

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                      13:43
 YTHAN93.dat
 WEA:  24   AK  KODIAK WSO

 SOILS DATA


           LAYER                15 BAR    .3 BAR     AVAIL     INITIAL    SA
    ST     DEPTH     POROSITY     SW        SW        W ST      W ST      CO
    NO      (MM)     (MM/MM)   (MM/MM)   (MM/MM)      (MM)      (MM)     (MM
     SUBBASIN     1        TYPIC ARIGIAQUO
     1      10.0       .40       .06       .24       1.80      1.80       3
     2     203.2       .40       .06       .24      34.78     34.78       3
     3     685.8       .40       .06       .24      86.87     86.87       3
     4    1524.0       .40       .13       .31     150.88    150.88       1
 TOTALS                                           274.3     274.3


      INITIAL COMPOSITE ST =    274.3 MM

                SOIL SURFACE LAYER

                                                              ORG
                                                               N
                                                             (G/M3)       (
SUB-BASIN      CLAY          SILT         SAND         K
    1           .10           .32          .58        .20    1000.00
```

```
                               SEDIMENT SIZE DISTRIBUTION
     SUB-BASIN                            SIZE(MM)

                   SAND          SILT        CLAY     SM AG       L AG
                    .20           .01        .002       .03        .50

          1        .446          .042        .020      .200       .292

 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                               13:43
 YTHAN93.dat
 WEA:  24    AK   KODIAK WSO
                          SUB     WATER  PERCO          SED            ORGANIC ORGANIC
       R        SURQ   SURQ     YIELD   LATE   ET      YIELD    SW        N        P
      (MM)      (MM)   (MM)     (MM)    (MM)  (MM)    (T/HA)   (MM)
 1   54.10     2.86   19.09    21.95    3.43   6.84      .06  275.61     .23      .06
 2   21.80      .00   18.91    18.91    1.66  21.83      .02  271.63     .00      .00
 3   33.30      .06    3.58     3.64    1.25  34.22      .00  268.74     .00      .00
 4   60.00     2.86    3.41     6.27    2.46  62.74      .09  257.27     .44      .11
 5   72.60     5.22    2.31     7.53    2.15  58.70      .19  261.62     .98      .24
 6   51.30     1.46    1.57     3.03    2.05  56.16      .06  252.00     .31      .08
 7   96.00     5.38    1.32     6.71    2.65  71.33      .16  266.19     .79      .20
 8   85.00     3.37   12.98    16.35    2.96  76.66      .07  253.51     .32      .08
 9   43.30     1.46    3.40     4.86    1.24  43.49      .01  249.92     .06      .01
10  101.10     9.85   31.53    41.38    4.22  27.34     1.06  266.25    5.31     1.29
11   55.30     4.43   20.57    24.99    3.10   7.96      .35  281.89    1.78      .41
12   99.60    32.58   50.06    82.64    4.73   2.71     2.46  284.51   13.10     3.02

93  773.40    69.53  168.73   238.26   31.90 469.98     4.54  284.51   23.33     5.49
```

```
 SWRRBWQ 07/06/92 IBM PC  VERSION 1.0

 YTHAN CATCHMENT                                                               13:43
 YTHAN93.dat
 WEA:  24    AK   KODIAK WSO
 FINAL VALUES

B-BASIN                        SOIL WATER FOR LAYER NO
NO


     1     2     3     4
1   1.7  41.0  90.0 151.9

   TOTAL SOIL WATER
 1      284.5

      FINAL COMPOSITE ST =    284.5 MM
      MIN INDIVIDUAL WATER ST =        .0 MM


                  FINAL CONTENTS
      -----PONDS-----      ---RESERVOIRS---
      WATER       SED          WATER     SED
B-BASIN VOL      CONC          VOL      CONC
NO       (MM)     (PPM)         (MM)     (PPM)
1         .0        .0           .0     200.0
      FINAL COMPOSITE POND ST =      .00 MM
      FINAL COMPOSITE RESERVOIR ST =      .00 MM


                 IRRIGATION - AVE. ANNUAL
```

```
    SUB-BASIN        NO.OF            VOLUME
       NO.        APPLICATIONS      APPLIED(MM)

        1             0                  .000

    SOIL WATER BALANCE =      .224434E-01 MM

    POND BALANCE
    Q =       .000000E+00 MM     Y =       .000000E+00 T/HA

    RESERVOIR BALANCE
    Q =       .000000E+00 MM     Y =       .000000E+00 T/HA

SWRRBWQ 07/06/92 IBM PC  VERSION 1.0
```