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A semi-distributed integrated flow and nitrogen model for multiple source assessment in catchments (INCA): Part II—application to large river basins in south Wales and eastern England

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Abstract

The integrated nitrogen in catchments (INCA) model is applied to two large river basins, the River Tywi in south Wales and the Great Ouse in eastern England. These two catchments have contrasting hydrogeology, land use and climatic regimes and provide an interesting test of the INCA model. The model is calibrated and validated against hydrological and chemical data for the rivers and a sensitivity analysis used to investigate parametric uncertainty. The annual loads estimated by the model are also compared with experimental data taken from nitrogen experiments around the world. Finally, scenario analysis is used to investigate impacts of changes in nitrogen deposition patterns and land use change in upland and lowland river systems. © 1998 Elsevier Science B.V.

Keywords: INCA model; River Tywi; Catchments; Great Ouse; Nitrogen; GIS; Water quality

1. Introduction

The INCA model has been described in article I (Whitehead et al., 1997) which gives full details of the hydrological and biochemical process equations used to simulate nitrogen transportation and transport through terrestrial systems into rivers. In part II of the article we illustrate the application of INCA to two contrasting river basins, the River Tywi in south Wales and the Great Ouse in eastern England. The River Tywi is an upland forest and moorland catchment whereas the Great Ouse is a lowland agricultural catchment. The INCA model was developed to

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explore changing land use, deposition patterns and climatic regimes and these two catchments, with their contrasting characteristics, illustrating the versatility of INCA. The model is calibrated and validated against flow and chemistry data from the rivers and a number of scenario runs are undertaken to illustrate the model behaviour under changed land use, deposition and hydrological patterns.

2. The River Tywi catchment application

The River Tywi system in south Wales (Fig. 1) is 78 km in length and drains southwest towards Camarthen from the upland areas surrounding Llyn Brianne.

Details of the river network and catchment relief derived from a Digital Terrain Model are shown in Fig. 2. The catchment area is 1090 km^2 and covers a range of land class from coniferous forests (Sitka spruce and Lodgepole pine) and moorland in the upper reaches to pasture and some arable in the lower reaches (Fig. 3). The bedrock in the upper region consists of Ordovician and Silurian shales, grits and mudstones, overlain by peats and ferric stagnopodzols on the upper slopes and brown podzolic soils on the lower slopes. Further down the system the soils become brown earths and stagnogleys and the river is significantly less acidic due to high pH waters draining calcite-rich sub-catchments. The River Tywi is an ideal test catchment for applying INCA due to the variation in land use. Moreover there is a considerable quantity of flow and water chemistry data available for the Tywi from the Environment Agency and from acidification studies in the Llyn Brianne area (Edwards et al., 1990). Nitrogen deposition is an issue of concern in the region and a number of the plantation forests are thought to be 'nitrogen-saturated' in that they are leaching nitrate in excess of plant

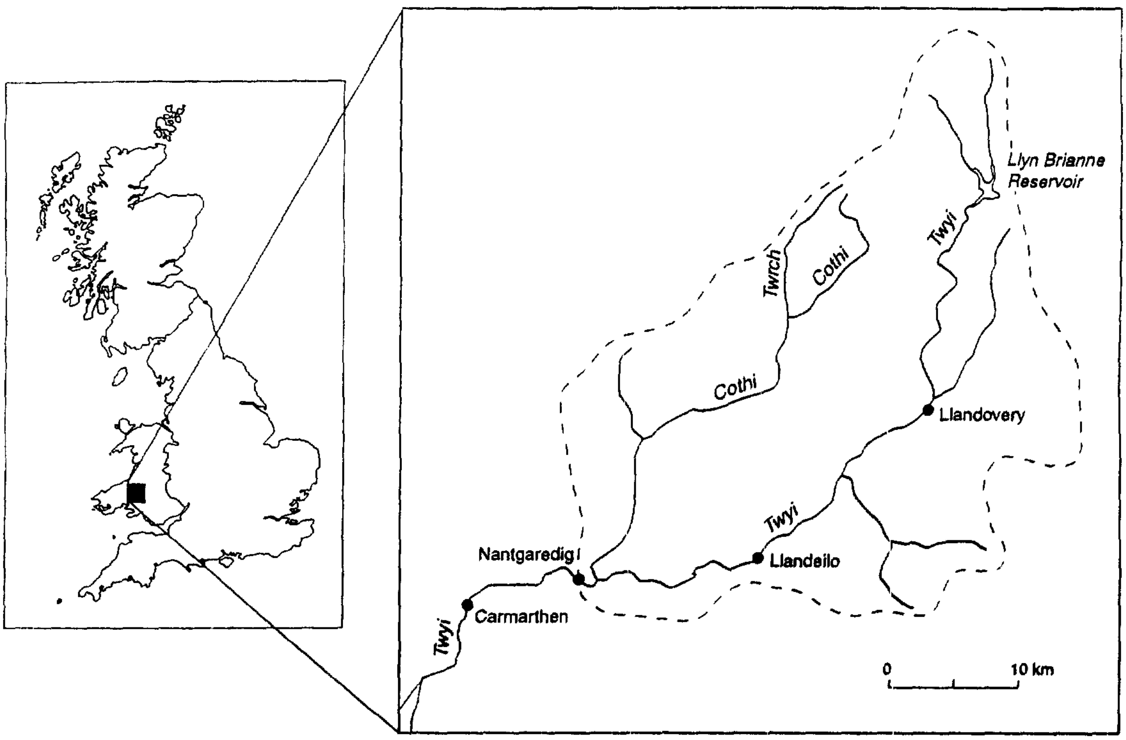


Fig. 1. River Tywi system in south Wales.

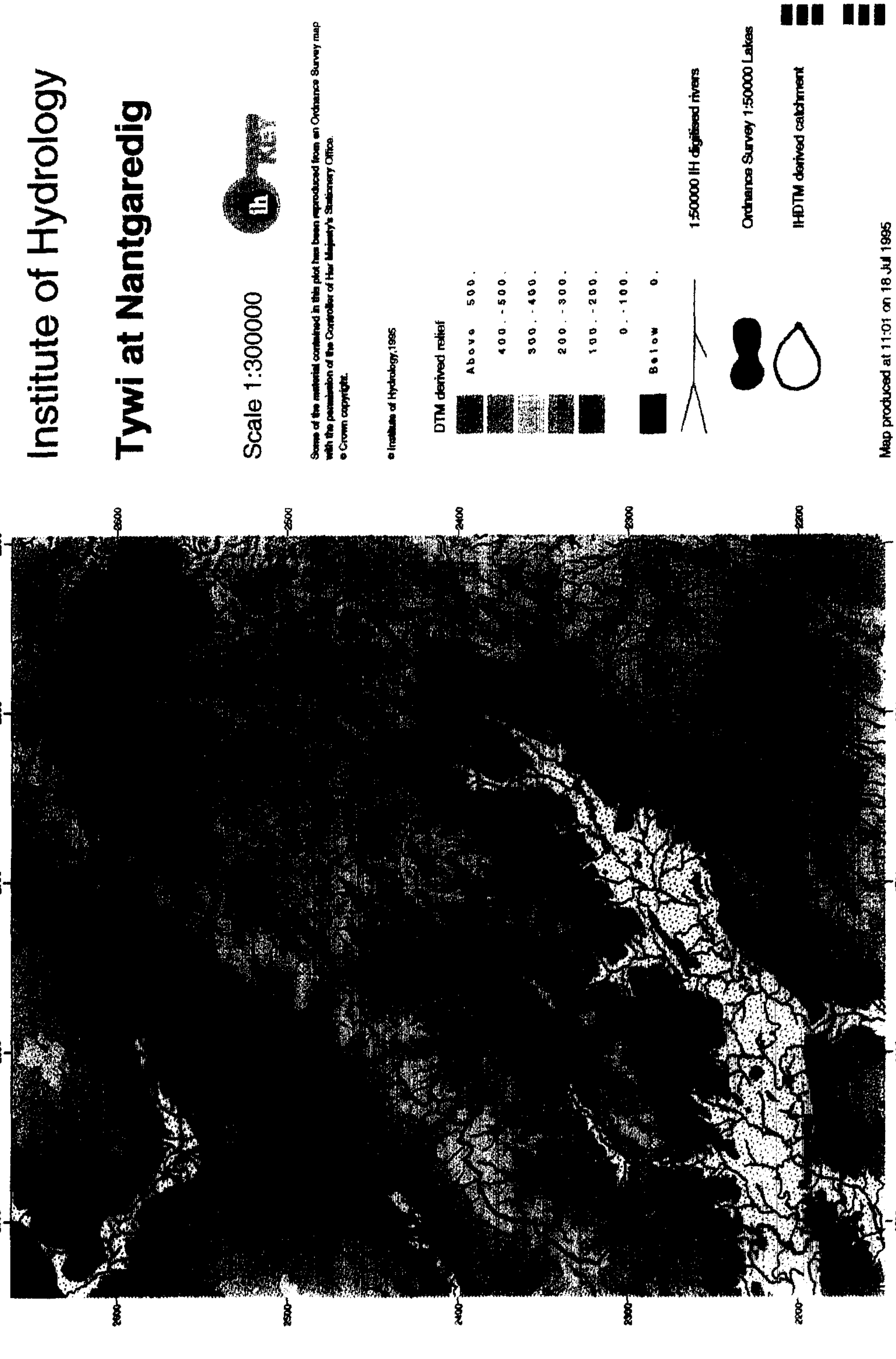


Fig. 2. Digital terrain and river channel flow patterns for the River Tywi.

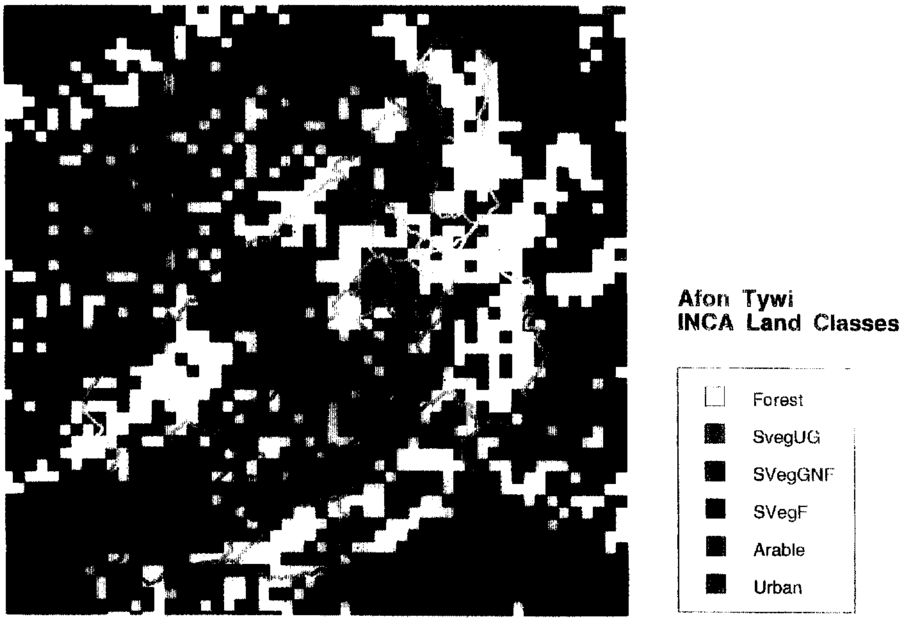


Fig. 3. Land use in the River Tywi catchment.

Table 1
River reach and sub-catchment land use information for the River Tywi

Reach Boundary		Reach length (m)	Sub-catchment area (km^2)	Land use class percentages					
				Forest (%)	SvegUG (%)	SVegGNF (%)	SVegF (%)	Arable (%)	Urban (%)
1	Source	10 000	39	69	0	31	0	0	0
2	Tywi	5000	46	46	2	50	2	0	0
3	Brianne	3000	53	28	0	72	0	0	0
4	Doethie	1000	2	100	0	0	0	0	0
5	Galltybere	1250	2	50	0	50	0	0	0
6	Gwenffrwd	2500	20	55	5	40	0	0	0
7	Rhandirmyn	5000	16	38	0	31	31	0	0
8	Rhydwydd	2000	18	11	0	56	33	0	0
9	Gwenlas	3250	19	26	0	6	68	0	0
10	Dolachirian	3750	126	55	1	13	28	0	0
11	Abbran	2500	7	0	14	86	0	0	0
12	Dolgarreg	6000	63	29	0	10	61	0	0
13	Sawdde	2250	138	33	0	22	42	0	1
14	Glanrhyd	5500	18	11	0	0	83	6	0
15	Pontbren	5000	98	37	0	9	54	0	0
16	Llandeilo	5750	28	29	0	0	71	0	0
17	Cilsen	6500	12	42	0	0	58	0	0
18	Dryslwyn	8500	63	12	0	33	83	2	0
19	Nantgoredig	1250	301	33	2	13	52	0	0

The six land uses are forest, short vegetation ungrazed (SVegUG), short vegetation grazed not fertilised (SVegGNF), short vegetation fertilised (SVegF), arable and urban areas.

Table 2
Sub-catchment wet and dry oxidised N and ammonium deposition rates (kg N Ha^{-1} $year^{-1}$)

Reach	Oxidised N		Reduced N	
	Dry	Wet	Dry	Wet
1	6.6	4.0	5.8	3.4
2	7.0	4.1	7.3	4.6
3	7.3	4.[illegible]	7.1	5.2
4	5.7	4.1	7.1	4.6
5	6.8	4.[illegible]	7.1	4.6
6	6.6	4.[illegible]	7.1	4.6
7	6.7	4.1	7.1	4.6
8	7.3	4.0	7.0	4.9
9	6.7	3.9	6.5	5.9
10	6.9	4.2	7.4	5.2
11	7.1	3.9	6.5	6.1
12	6.7	3.9	6.5	6.0
13	6.9	3.9	6.6	5.9
14	6.8	3.9	6.5	6.1
15	6.9	4.0	6.6	5.6
16	6.5	3.9	6.5	5.8
17	5.9	3.6	6.3	5.7
18	6.2	3.7	6.3	5.6
19	6.3	3.9	6.7	5.2

and microbial demand (Emmett et al., 1995). Also forests in the uplands above Llyn Brianne are reaching maturity and clear felling may lead to changes in N fluxes.

In order to run INCA it is necessary to provide two data files, a catchment description and process parameter file and a hydrological daily time series file.

2.1. The catchment description and process parameter data file

The catchment and parameter file consists of the following information:

2.1.1. Reach structure, land class percentages and base flow characteristics

Table 1 shows the reach structure selected for the River Tywi system together with information on reach length, sub-catchment area and the percentage of INCA land use classes obtained from a GIS-INCA interface. The reach boundaries defined in Table 1 have been derived from an analysis of the DTM information in Fig. 2 making use of catchment boundary algorithms developed at the Institute of Hydrology (Morris, personal communication, 1997). Similar algorithms are available in GIS systems such as ARC-INFO. Reach boundaries reflect not only sub-catchment streams joining the main river but other key factors controlling flow and water quality such as the location of effluent discharges, flow gauges and water

Table 3
Parameter values for the six land classes

Parameters	Forest	SVegVG	SVegGNF	SVegF	Arable	Urban
1	0.008	0.010	0.002	0.001	0.001	0.001
2	0.002	0.002	0.002	0.002	0.002	0.000
3	0.100	0.080	0.100	0.025	0.025	0.080
4	70.000	40.000	45.000	105.000	95.000	70.000
5	0.000	0.000	0.000	30.000	50.000	0.000
6	0.800	0.800	0.800	0.800	0.800	0.000
7	0.080	0.080	0.090	0.090	0.140	0.000
8	0.100	0.100	0.100	0.100	0.100	0.100
9	0.000	0.000	0.000	30.000	50.000	0.000
10	0.100	0.080	0.090	0.080	0.120	0.080
11	70.000	70.000	70.000	70.000	70.000	70.000
12	366.000	366.000	366.000	150.000	120.000	366.000
13	0.000	0.000	0.000	120.000	120.000	0.000
14	0.000	0.000	0.000	130.000	130.000	0.000
15	80.000	80.000	80.000	80.000	80.000	80.000
16	4.500	4.500	4.500	4.500	4.500	4.500
17	2.30	2.30	2.30	2.30	2.30	2.30
18	23.00	23.00	23.00	23.00	23.00	23.00

Table 4
Velocity flow information for the River Tywi

Percentile flow	10	20	30	40	50	60	70	80	90
Flow $m^3 s^{-1}$	90	60	40	30	23.8	17	13	9	6
Mean velocity $m s^{-1}$	0.92	0.65	0.50	0.41	0.35	0.30	0.26	0.23	0.21

quality monitoring sites. The areas given in Table 1 are also derived from the DTM analysis via Institute of Hydrology algorithms. The land use percentages in Table 1 are obtained from the ITE land class data summarised, as described in part I of the article, as the six key land classes. Note that the Tywi catchment is dominated by forest and moorland (i.e. surface vegetation grazed not fertilised) in the upper reaches and fertilised grassland (SVegF) in the lower reaches (see Fig. 3).

In addition to the sub-catchment land use information it is required to define the hydrological routing in the sub-catchments. As discussed in

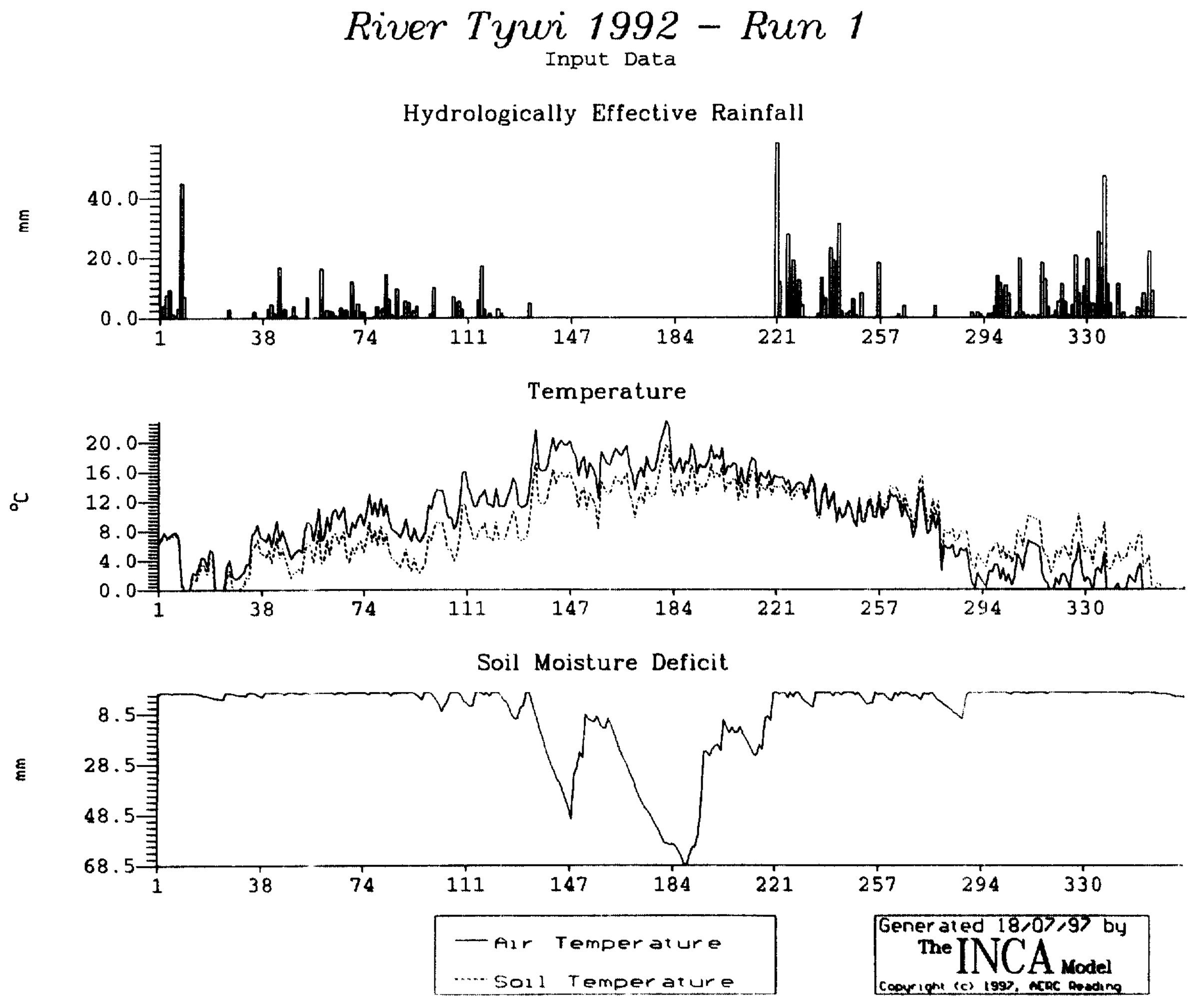


Fig. 4. River Tywi 1992 hydrologically effective rainfall, air and soil temperature and soil moisture deficit.

Table 5
Literature values of N fluxes for the processes specified in the land phase model of INCA

Process	Value (kg N ha^{-1} $year^{-1}$)	Vegetation / ecosystem	INCA land class	Literature source
N uptake into tree biomass	23–66	Coniferous forest (NITREX sites across Europe. Values include an estimated 10 kg N ha^{-1} $year^{-1}$ uptake into roots. Value for Welsh site is 63 kg N ha^{-1} $year^{-1}$)	Forest (1)	Reynolds et al., 1997 Gundersen et al., in press
	17–69	Coniferous forest (range for *Pinus* spp. across Scotland)		Miller, 1981
	5.1 (±2.2)	Boreal coniferous forest (International Biological Programme data)		Cole, 1981
	47.4 (±17.3)	Temperate deciduous forest (International Biological Programme data)		Cole, 1981
	75.4 (±18.2)	Temperate coniferous (International Biological Programme data)		
	60	Missisippi pine (20-year-old stand)		Waring and Schlesinger, 1985
	30–50	Coniferous forest (range of sites)		Gosz, 1981
	50–100	Deciduous forest (range of sites)		Gosz, 1981
	72–153			Melillo, 1981
N uptake by vegetation	42	Heather moorland	Short vegetation, ungrazed (2)	Miller, 1981
	35	Unimproved grassland (Aber, N Wales, sheep-grazed grassland)	Short vegetation, grazed, not fertilised (3)	Emmett et al., in press
	162	Unimproved grassland (Snowdonia)		Heal and Perkins, 1978
	30–42	Unimproved grassland (Calcareous grassland)		Wilson et al., 1995
	105	Improved grassland	Short vegetation, fertilised (4)	Miller, 1981
N uptake into crop	95	Winter wheat	Arable (5)	Miller, 1981
Denitrification	< 0.01–4	Coniferous forests across Europe (NITREX sites), temperate coniferous forests (range of soil types)	Forest (1)	Reynolds et al., 1997 Hornung et al., 1995
	1	Upland riparian	Short vegetation, ungrazed (2)	Schipper et al., 1993
	1	Unimproved grassland (N Wales)	Short vegetation, grazed, not fertilised (3)	Emmett et al., in press
	3.4–4.4	Unimproved grassland (grass-clover / herballey)		Ruzjerez et al., 1994
	19	Fertilised (400 kg N ha^{-1} $year^{-1}$ urea) grass	Short vegetation, fertilised (4)	Ruzjerez et al., 1994

Table 5 (*Continued*)

Process	Value (kg N ha^{-1} $year^{-1}$)	Vegetation/ecosystem	INCA land class	Literature source
Mineralisation	10–292	Sitka spruce forest, N Wales (net mineralisation, forest floor)	Forest (1)	Emmett et al., 1993
	68 (±16.5)	Aber Forest (Sitka spruce), N Wales (net mineralisation, organic horizon)		Emmet et al., 1995
	30–50	Typical coniferous forests		Gosz, 1981
	25–149	Typical deciduous forests		Melillo, 1981
	44	Corsican pine, UK		Miller, 1981
	35–105	Norway spruce, acid soil		Persson and Wiren, 1995
	38–53	Pine, New Jersey		Poovarodom et al., 1988
	45	Bracken, acid soil	Short vegetation, ungrazed/short vegetation, grazed, not fertilised (2/3)	K.A Brown, pers. commun.
	20–60	Semi-natural vegetation/ acidic upland grass		INDITE, 1994
	1–35	Welsh, upland grass		
	73	Welsh, upland grass, grazed		Emmett et al., 1993
	7	Calcareous grassland, peak district		Heal and Perkins, 1978 Morecroft et al., 1994
	44-126	Dutch heathland		Van Vuuren et al., 1992
	40–50	Acid and calcareous grassland, peak district	Short vegetation, fertilised (4)	Morecroft et al., 1994
	62		Arable (5)	
Nitrification	15	Welsh spruce forests	Forest (1)	Stevens et al., 1994
	1–35	Dutch coniferous forests		Tietema, 1993
	3–54	Dutch heathland	Short vegetation, ungrazed/ short vegetation, grazed, not fertilised (2/3)	Van Vuuren et al., 1992
Inorganic N leaching	0–30	Welsh spruce forests	Forest (1)	Emmett et al., 1993
	< 1	Natural coniferous forests		INDITE, 1994
	2–3	Natural deciduous forests		
	0.1–43	Coniferous forests across Europe (NITREX sites) Includes highly N saturated Dutch sites		Tietema and Beier, 1995
	1.8–5.3	Welsh mooreland	Short vegetation, ungrazed/ short vegetation, grazed not fertilised (2/3)	Stevens et al., 1994
	19–84	Winter wheat	Arable (5)	Powlson et al., 1992
	40–41	(Fertilised with 96–192 kg N ha^{-1} year)		Addiscott and Powlson, 1989

part I this base flow index governs the transfer of water from the soil reactive zone to the groundwater. In the Tywi this index can be derived from the application of time series analysis techniques such as IHACRES (Jakeman et al., 1993), as discussed in part I or obtained from the Institute of Hydrology Catchment Characteristics and Hydrology year books. An IHACRES analysis of all five gauged catchments for the Tywi gives a mean base flow index of 0.45 and this compares with 0.43 from the IH year books. This is a remarkably close agreement and surprising given the completely independent methods of analysis. It does reflect however, the similarity of the hydrological response around the Tywi region (with a relatively small groundwater component) compared to other catchments. In the River Tywi the average of the IHACRES and IH year book values has been used, i.e. 0.44, so that 44% of the water flows through the groundwater on average and 56% flow through the surface soil zone.

2.1.2. Deposition data

Table 2 shows the atmospheric wet and dry nitrogen deposition in the sub-catchments. These atmospheric inputs have been derived using the model MATADORN (see part I, this volume) using 1992 meteorological and emission data.

2.1.3. Land process parameters

In part I of this article the catchment N transformations are described in detail. Associated with each of these processes are parameters which control the dynamic response. The following

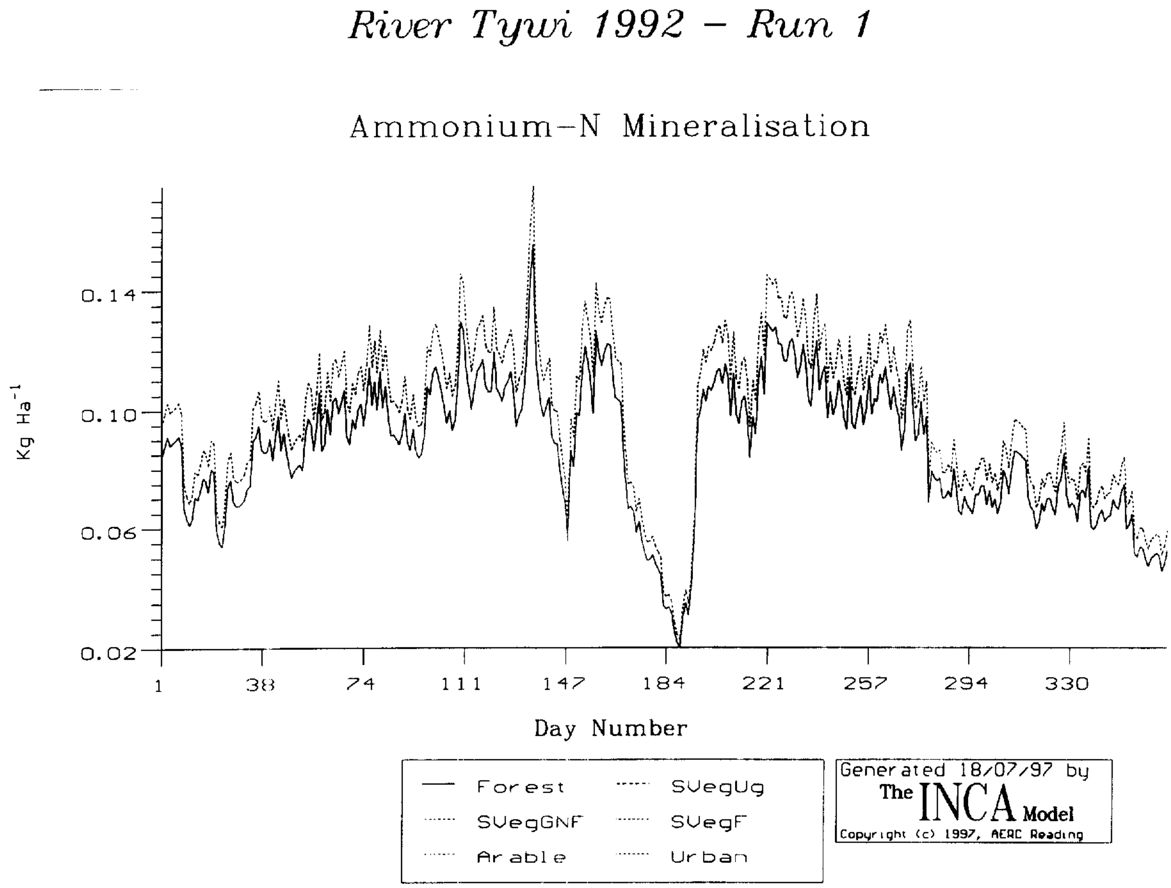


Fig. 5. Daily simulated flux for mineralization over 1992.

parameters need to be defined in INCA for each land class:

1. Denitrification rate (day^{-1});
2. Nitrogen fixation rate ($mg\ l^{-1}\ day^{-1}$);
3. Plant uptake rate — nitrate (day^{-1});
4. Maximum nitrogen uptake ($kg\ ha^{-1}\ year^{-1}$);
5. Nitrate (fertiliser/livestock) addition rate ($kg\ ha^{-1}\ year^{-1}$);
6. Ammonium nitrification rate (day^{-1});
7. Ammonium mineralisation rate (day^{-1});
8. Ammonium immobilisation rate (day^{-1});
9. Ammonium (fertiliser/livestock) addition rate ($kg\ ha^{-1}\ year^{-1}$);
10. Plant uptake rate — ammonium (day^{-1});
11. Plant growth start day;
12. Plant growth period (days);
13. Fertiliser addition start day;
14. Fertiliser addition period (days);
15. Soil moisture deficit maximum (mm);
16. Maximum temperature difference (air–soil)°C;
17. Soil reactive zone time constant (days); and
18. Groundwater zone time constant (days).

Table 3 shows the parameter set used to simulate the River Tywi catchment for the six land classes.

2.1.4. River data and parameters

The river data consists of information on reach lengths (as shown in Table 1), velocity-flow information and sewage inputs. Velocity-flow information has been derived from a set of tracer experiments conducted by the Welsh Region of the

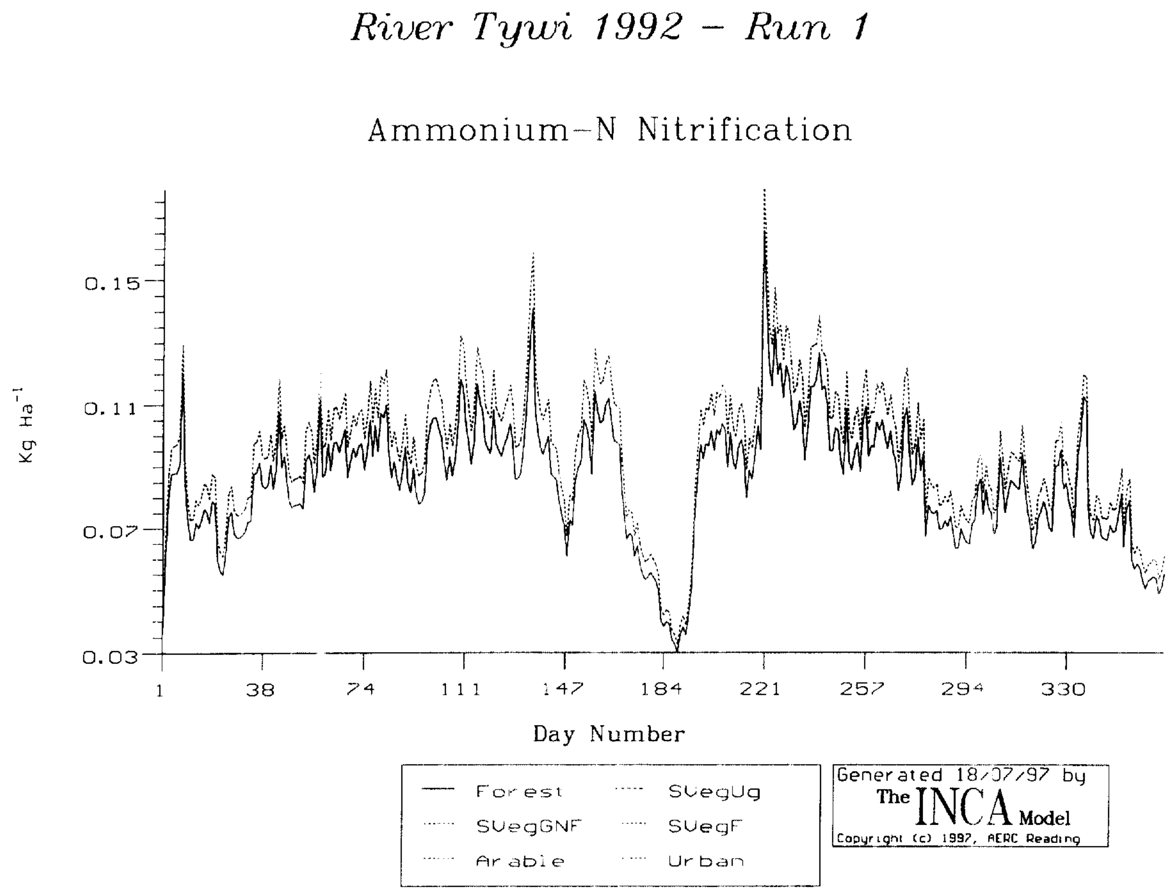


Fig. 6. Daily simulated flux for nitrification over 1992.

Table 6
Annual process and leaching fluxes in kg ha^{-1} $year^{-1}$ for 1991 — River Tywi catchment principal land classes

	Forest	SVegUG	SVegGNF	SVegF	Arable
Nitrate N leaching	10.48	11.40	11.14	30.51	53.06
Ammonium N leaching	0.69	0.78	0.75	0.90	1.25
Nitrate N uptake	33.01	32.71	37.59	60.02	69.41
Ammonium N uptake	4.07	3.53	4.06	4.62	9.67
Mineralisation	31.97	31.97	35.31	63.97	94.69
Nitrification	31.85	34.59	35.31	63.97	94.69
Dentrification	3.52	5.27	1.01	2.16	3.69
Fixation	0.93	0.93	0.93	0.93	0.93
Immobilisation	3.98	4.32	4.41	8.00	11.84

Environment Agency (unpublished data supplied by Lloyd of the EA) and Table 4 gives the relevant velocity flow information for the Tywi area.

The following velocity flow relationship has been derived from the Tywi from these data.

$$v = 0.04Q^{0.67}$$

This equation is similar in form to velocity flow relationships for a range of rivers (Whitehead et al., 1986).

The sewage discharges directly impact the river water quality and flow, nitrate and ammonium data are supplied to INCA as annual mean flows and concentrations, respectively, for each discharge. These data are available from the Environment Agency.

In addition to these input data, initial nitrate and ammonium concentrations have to be specified for the water draining the soil zone and the groundwater zone. These values are normally derived from observed data so that realistic initial conditions are used for the model run.

The model also requires the user to specify the parameters that control nitrification and denitrification processes occurring in the river. These processes are particularly important during low flow summer conditions when residence times and temperatures are high. Whitehead and Williams (1982) have applied nitrogen process models to several river systems and these two parameters are included in the model INCA as temperature dependent rate coefficients.

2.1.5. Input time series data file

The input data required to run INCA consists of daily time series of hydrologically effective rainfall, soil moisture deficit and temperature. These time series data have been derived using MORECS (Meteorological Office, 1981) with meteorological data from the UK Met. Office. The catchment average rainfall is calculated together with evapotranspiration and soil moisture deficit to give a net rainfall or hydrologically effective rainfall. Fig. 4 shows the 1992 data for the River Tywi. As shown, the lack of rainfall in the summer months leads to a significant soil moisture deficit which has a major bearing on nitrogen fluxes. Note that in the summer of 1992 on day 221 a major storm occured and this replenished the soil to maximum wetness conditions. The temperature patterns show the air temperature varying seasonally and the calculated soil temperature for the forest giving higher temperatures in winter and lower temperatures in summer reflecting the damping effect of the forest.

2.1.6. Observed data file

The final data set consists of observed flow and water quality for the river at any reach boundary.

2.2. INCA output information

There are easy to use menu options within the INCA program for altering river and terrestrial parameter sets, river configuration, land use percentages, nitrogen deposition rates, initial conditions and graphical scales. Model outputs can be displayed in many forms as time series, probability distributions, river profiles, 2D and 3D graphs and tables of statistics on flow, water quality and process and leaching fluxes.

3. Model calibration and River Tywi simulation

3.1. Flux simulation results

A key aspect of process based models such as INCA is the need to provide calibration results. There are two levels of calibration possible with INCA. Firstly it is necessary to arrive at process parameters that generate sensible annual fluxes for catchment processes such as net-mineralization, denitrification, fixation, etc. Table 5 shows the range of N fluxes for the major transformations taken from experimental and field studies in the literature. This list is not intended to be exhaustive but these values provide a useful check and balance on the overall performance of the model. Since most N transformations are dependent on soil properties and climatic conditions, we can expect a large degree of variation in annual fluxes between sites. In addition, the daily pattern of N fluxes will vary according to hydrology, soil moisture, temperature and nitrogen input. Figs. 5 and 6, for example, show mineralization and nitrification changing over time as soil moisture decreases and increases.

The statistical routines in INCA provide a summary of the annual fluxes of these different processes under different land uses, as shown in Table 6 and Fig. 7 and these can be compared

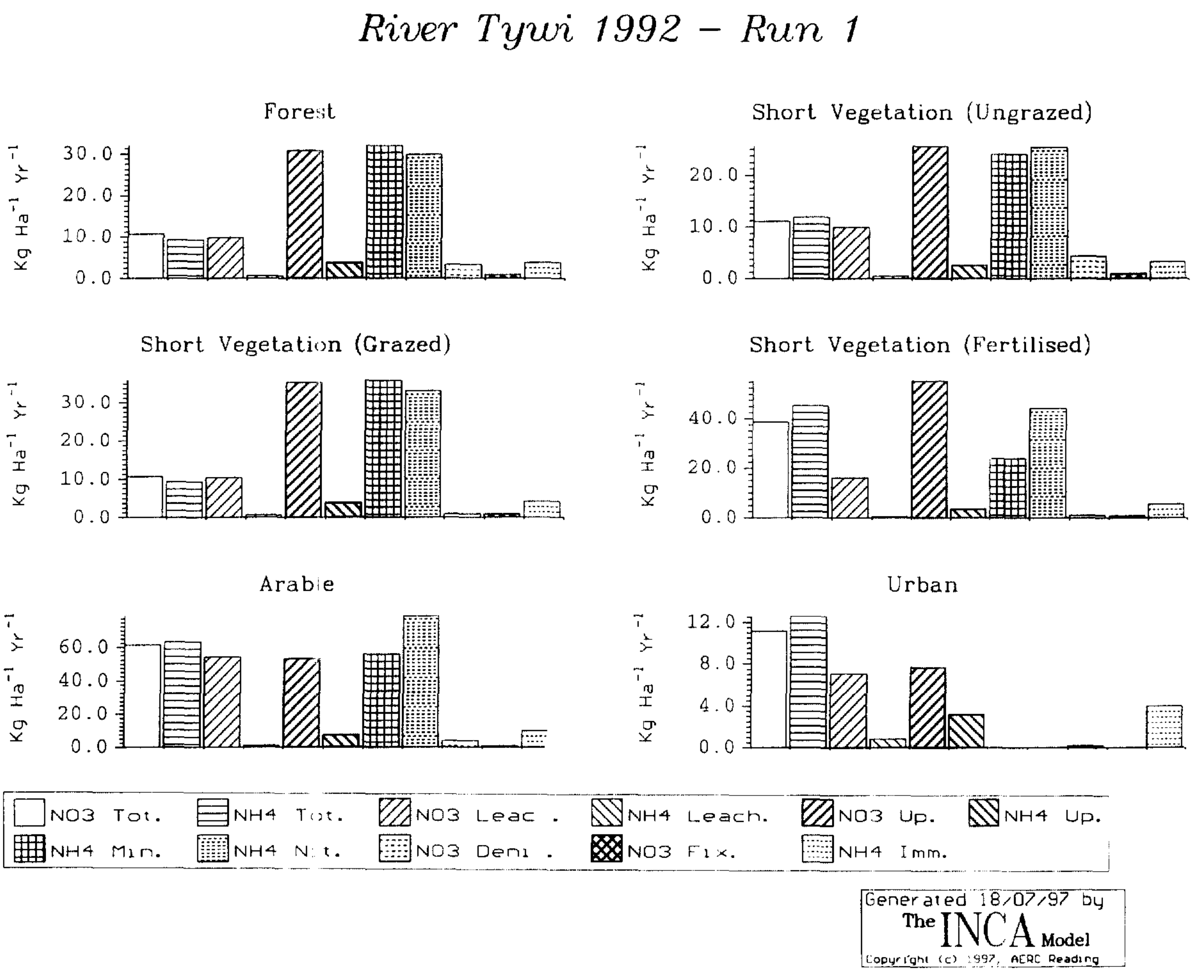


Fig. 7. Annual loads in kg Ha^{-1} $year^{-1}$ for each process and land use.

with Table 5 values. In general the fluxes from INCA lie within the ranges of fluxes shown in Table 5.

3.2. Flow and nitrogen daily simulation results

The principal objective of INCA is to simulate the observed behaviour of river systems and Fig. 8 shows a successful daily simulation of flow, nitrate and ammonium concentrations over the year 1992. The model generates daily simulations at any of the 19 reaches and the match between simulated and observed flow and quality for Nantgoredig (reach 19), as shown in Fig. 8, is excellent. Concentrations in the river are lower in the summer and then rise as soon as the soils wet and nitrogen is flushed from the catchment system. The lower concentrations in summer reflect the lower flows and the increased residence times which provides more time for instream denitrification to occur.

The model results can be presented either as a distribution, as shown in Fig. 9, or as a profile down the river, as shown in Fig. 10. Fig. 9 provides information on the statistical nature of the

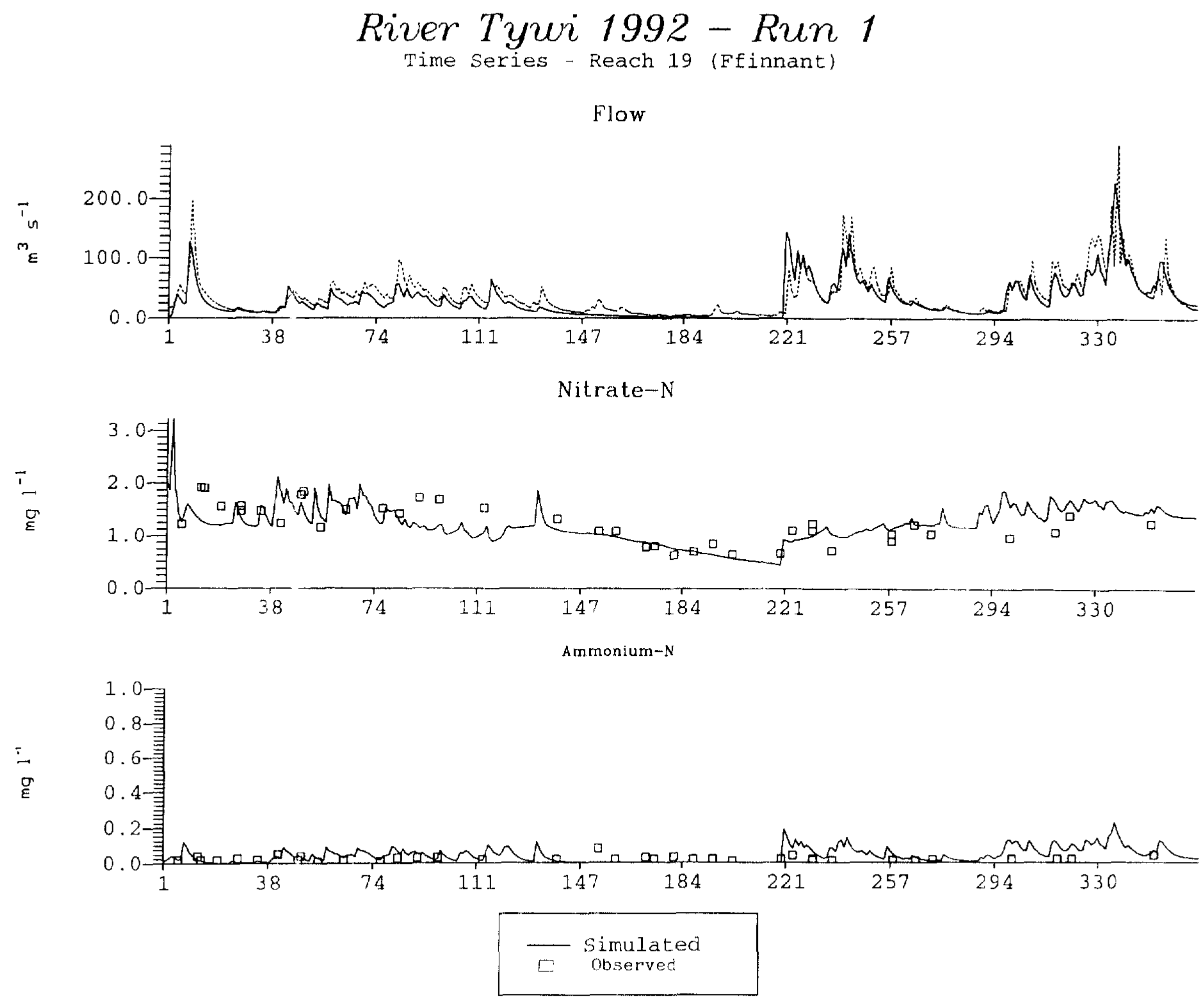


Fig. 8. Simulated and observed flow, nitrate and ammonium, River Tywi at reach 19, 1992.

flow and quality and can give information on the extremes of behaviour. For example, INCA can provide information on 95 percentile levels which are frequently used by the Environment Agency for river quality classification or for setting consent levels. Fig. 10 shows the profile along the river on a selected day and can be used to assess the build up of pollution along the river or the impact of a particular discharge or sub-catchment entering the river. A statistical summary of the reach simulation outputs are given in Table 7.

3.3. Scenario analysis

INCA was designed to address policy issues by investigating alternative scenarios for N deposition, land use change, etc. As an illustration two such scenarios are demonstrated here, a change in nitrogen deposition and a change in land use.

Fig. 12 shows the simulation given an increase in N deposition of 20%. As can be seen, the effect on nitrogen in the stream water is minimal and this reflects the ability of vegetation to take up the additional nitrogen deposited on the catchment. It is well known that as nitrogen deposition increases a point is reached when the vegetation sink is insufficient to prevent leaching. This nitrogen 'breakthrough' is currently being investigated using INCA as a tool to study the mechanisms controlling nitrogen release under a range of hydrochemical conditions.

By contrast Fig. 11 shows the land use change scenario in which it is assumed that in the upper reaches of the Tywi the 31% unfertilised short vegetation (GNF) is converted to fertilised short vegetation. The results indicate that the nitrogen balance would be significantly affected, raising peak nitrogen values and also, increasing nitrogen levels in wet conditions.

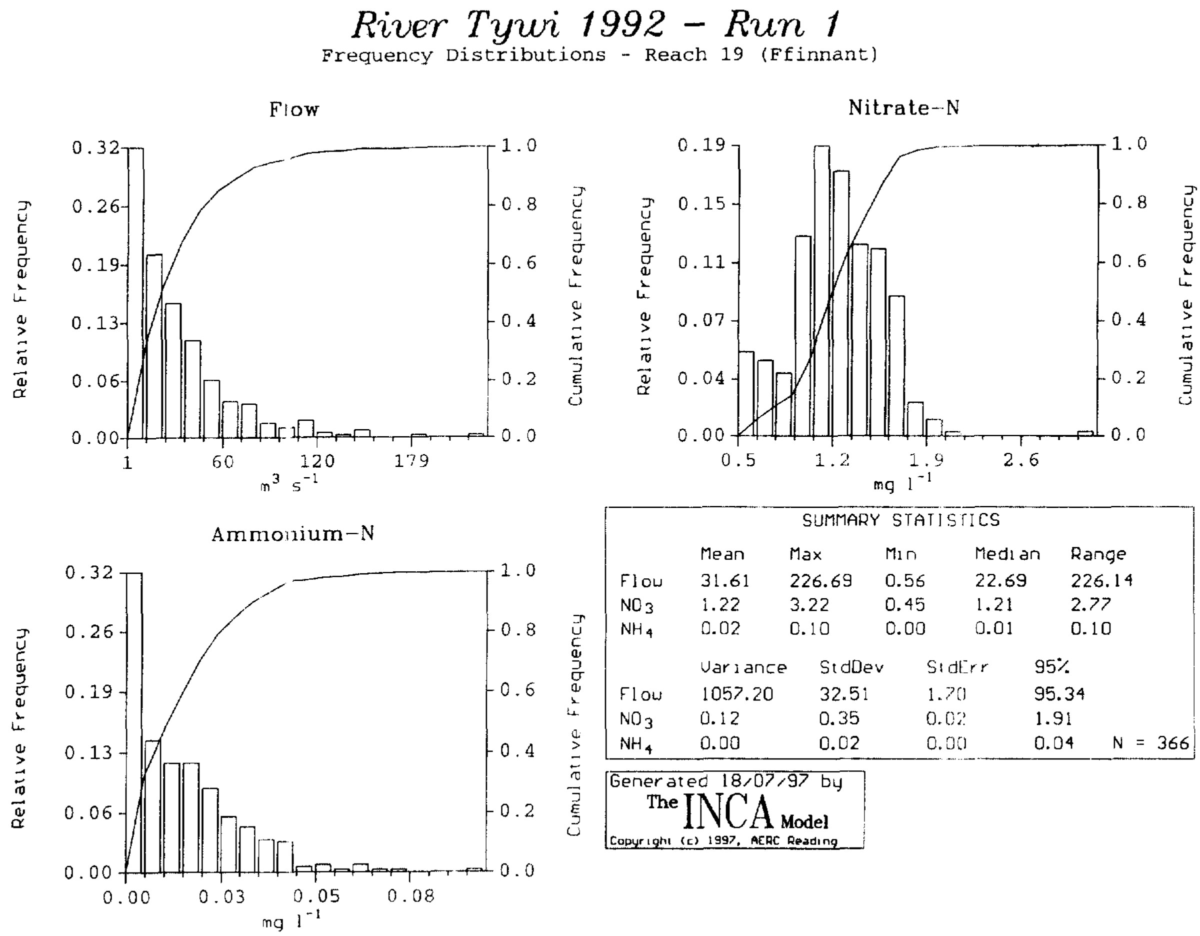
These are just some examples of the types of scenarios that can be performed with INCA. More detailed policy issues are currently being addressed to predict the effects on river nitrate quality. These will be reported in future articles.

4. Application to the Great Ouse

The River Great Ouse in eastern England (see Fig. 13) has a catchment of 8380 km^2, including most of Cambridgeshire and Bedfordshire and part of seven other counties. Two major river systems, the Bedford Ouse and the Ely Ouse,

Table 7
Nitrate N statistics from the 1992 River Tywi simulation

Reach	Mean	Max.	Min.	S.D.	95%ile
1	0.71	2.11	0.05	0.32	1.34
2	0.78	1.56	0.09	0.29	1.34
3	0.81	1.40	0.14	0.26	1.31
4	1.31	3.60	0.45	0.48	2.26
5	1.29	3.48	0.40	0.47	2.21
6	1.28	3.35	0.39	0.45	2.17
7	1.26	3.34	0.29	0.48	2.19
8	1.09	1.36	0.90	0.08	1.25
9	1.08	1.36	0.71	0.10	1.28
10	1.07	1.36	0.57	0.13	1.33
11	1.12	1.45	0.52	0.16	1.44
12	1.12	1.57	0.41	0.21	1.52
13	1.17	1.97	0.41	0.25	1.66
14	1.17	2.02	0.34	0.28	1.71
15	1.20	2.30	0.34	0.32	1.82
16	1.32	3.01	0.85	0.32	1.95
17	1.31	3.09	0.69	0.36	2.01
18	1.31	3.20	0.54	0.40	2.09
19	1.31	3.20	0.54	0.40	2.09



SUMMARY STATISTICS

	Mean	Max	Min	Median	Range
Flow	31.61	226.69	0.56	22.69	226.14
NO_3	1.22	3.22	0.45	1.21	2.77
NH_4	0.02	0.10	0.00	0.01	0.10

	Variance	StdDev	StdErr	95%
Flow	1057.20	32.51	1.70	95.34
NO_3	0.12	0.35	0.02	1.91
NH_4	0.00	0.02	0.00	0.04

N = 366

Fig. 9. Distributions for flow, nitrate and ammonium River Tywi, reach 19.

converge at Denver in Norfolk, releasing an average of 38.5 m^3 s^{-1} of freshwater into the Great Ouse estuary and The Wash at King's Lynn. Details of the river network and catchment relief derived from the IH Digital Terrain Map (IHDTM) are shown in Fig. 14. The resident population of the catchment is approximately 1.6 million, resulting in effluent discharges from over 500 sewage and industrial treatment plants, including those serving the major conurbations of Milton Keynes, Cambridge, Bedford and King's Lynn.

The river and its tributaries are used for public water supply from six separate intakes and in addition large quantities of water are transferred into neighbouring catchments for potable water supplies using the Ely Ouse-Essex water transfer scheme. The rivers have a high recreational value, being navigable for much of their length and are highly regarded by boating enthusiasts and anglers alike.

This study is concerned with the Bedford Ouse river system which rises to the north of Brackley and flows north-eastwards across the Oolitic and Cornbrash limestones to Newport Pagnell. Below Newport Pagnell the geology becomes impermeable clays (Ampthill, Kimmeridge and Oxford) which persist until Oxford where the geology becomes dominated by chalk. The river continues to flow in a north-eastwards direction to Brownshill Staunch which forms the downstream boundary of the Bedford Ouse river system in this study.

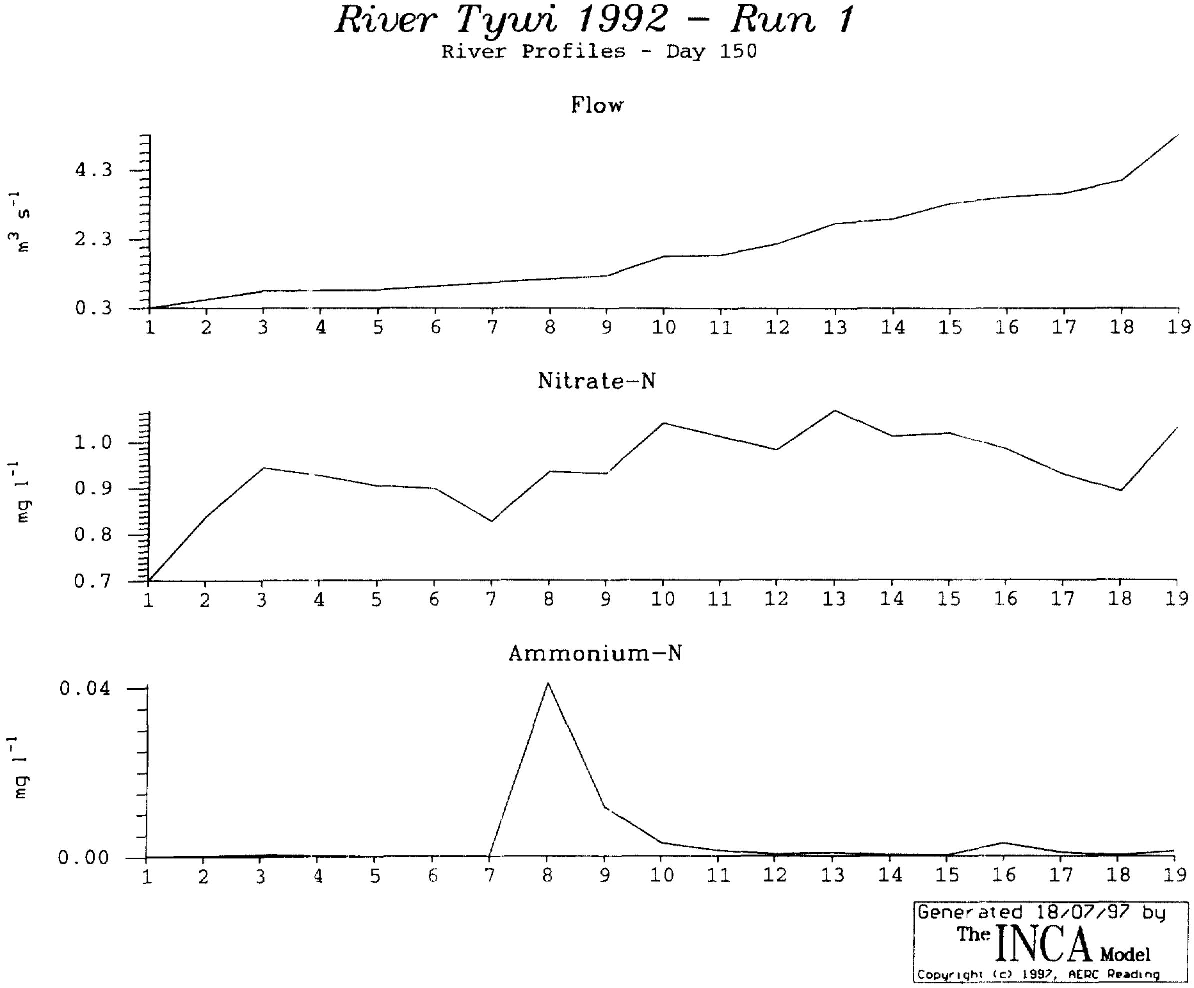


Fig. 10. Profiles of flow, nitrate and ammonium along the River Tywi on day 150.

Land use in the Bedford Ouse catchment is strongly dominated by arable but with large urban centres located at Milton Keynes and Bedford. Grazing land and fertilised grassland are also found in the upper reaches, as shown in the land use map in Fig. 15.

4.1. Reach structure

Table 8 shows the reach structure selected for the Bedford Ouse together with information on reach length, sub-catchment area and the land use percentages obtained from the GIS-INCA interface. Reach boundaries for the river system are selected at the confluence of tributaries, at the location of effluent discharges, at weirs and at points where water quality and flow monitoring stations are located (Fig. 16), thereby allowing model simulations to be compared to observed data at specific sites down the river. These reach boundaries are used to derive the sub-catchment boundaries using the IHDTM as shown in Fig. 14.

4.2. Effluent discharges

Over 500 sewage treatment works (STW) discharge into the catchment of the River Great

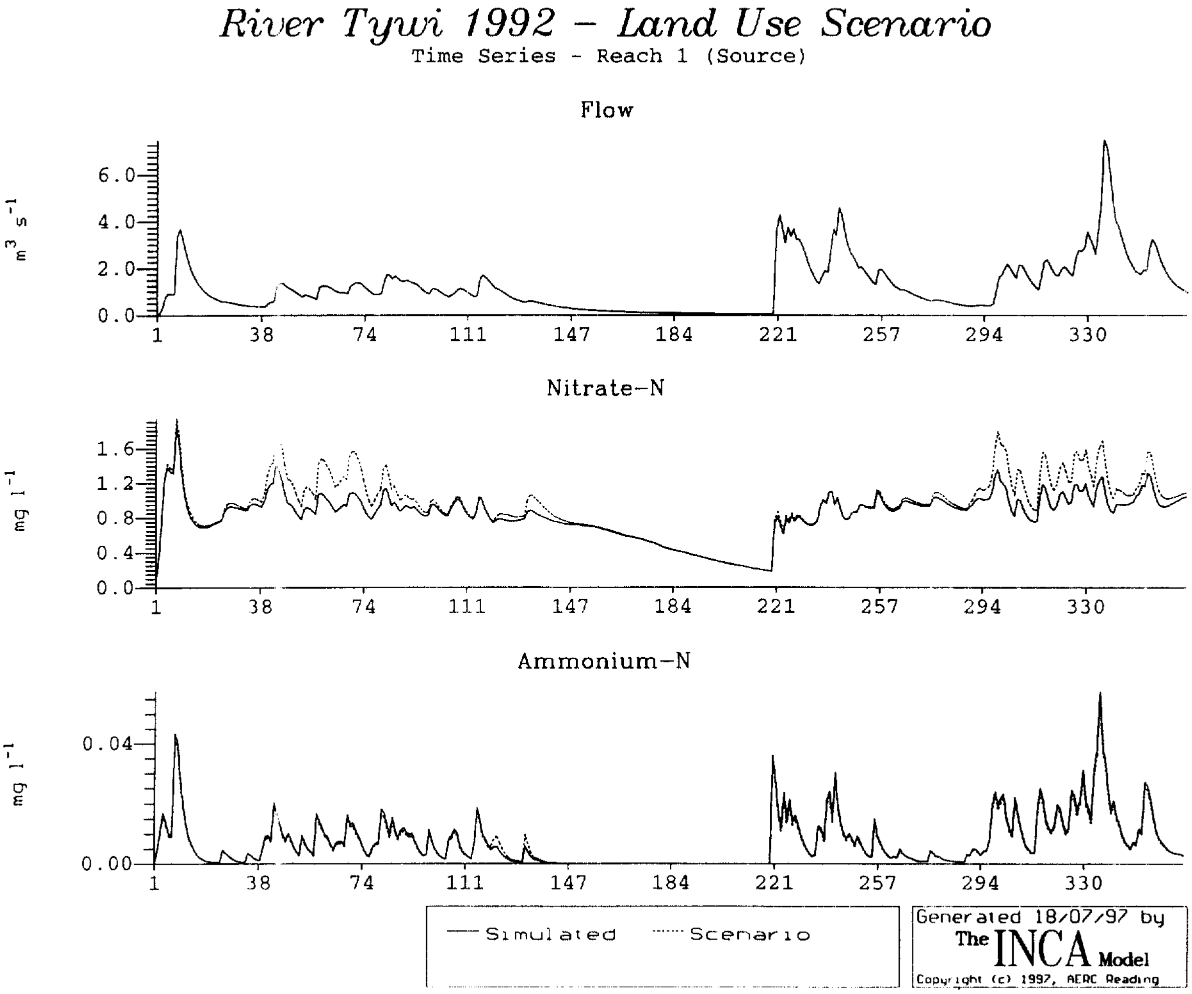


Fig. 11. Effects of changing land use from s.v. grazed not fertilised to fertilised.

Ouse. Of these, eight major STW discharge into the Bedford Ouse between its source and Brownshill Staunch (Fig. 16).

4.3. Velocity-discharge relationship

Velocity-discharge information for the Bedford Ouse has been derived from a set of tracer experiments conducted by Whitehead et al. (1986).

The following relationship has been derived from the field data:

$$v = 0.046Q^{0.64}$$

4.4. Base flow index

Table 9 shows the base flow index (BFI) for a number of reaches along the Bedford Ouse and which have been obtained from an IH Hydrometric Register and Statistics year book. The BFI determines the transfer of water from the soil reactive zone to the groundwater. The variation in Table 9 therefore reflects the variation in geology with the highest BFIs being associated with the chalk and the lowest with the clay lithologies. Where reaches contain no flow guaging moni-

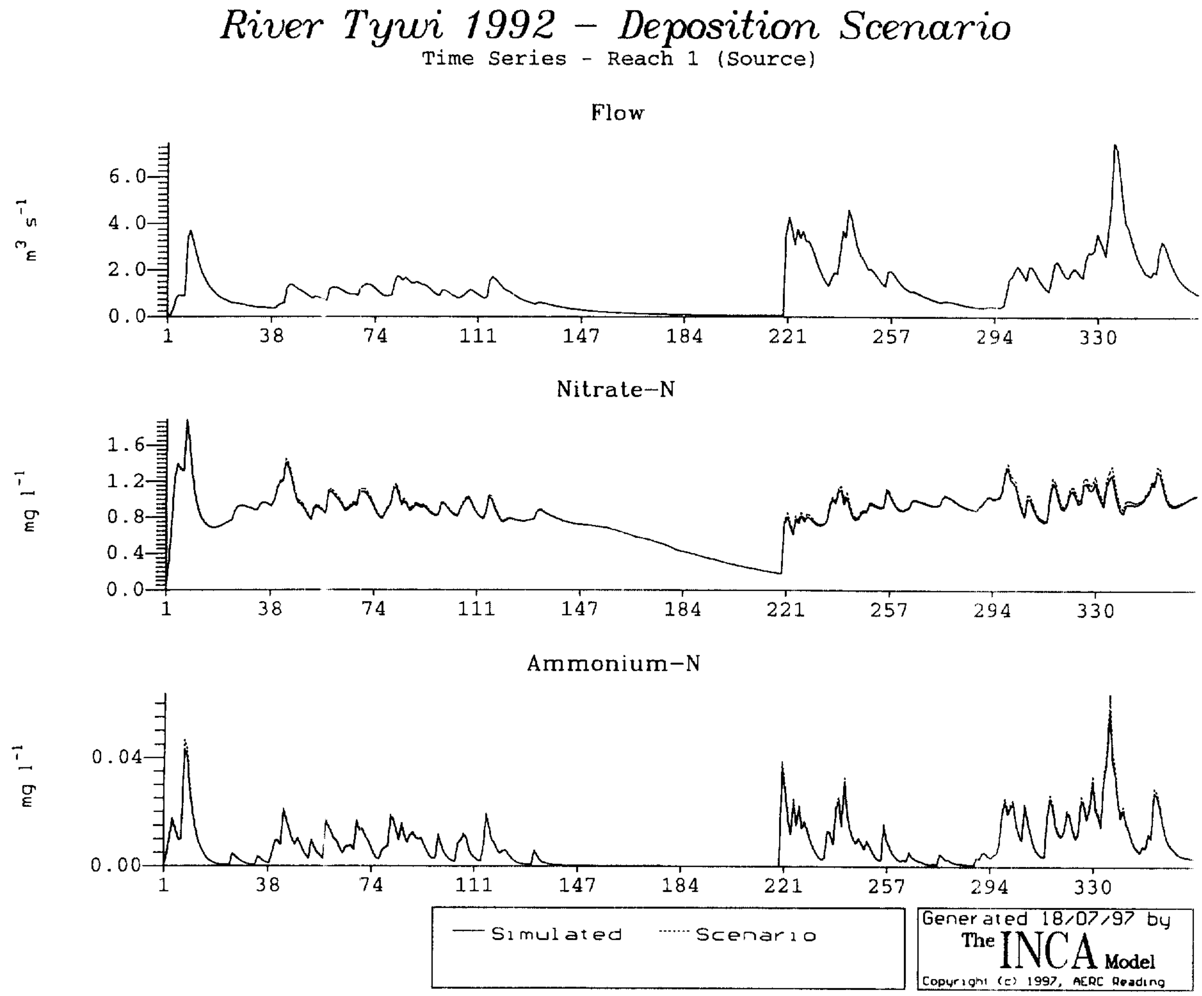


Fig. 12. Effects of increasing N-deposition, River Tywi at reach 1, 1992

toring stations BFIs have been determined by extrapolating a known BFI downstream until a monitoring station is encountered and the new BFI used.

4.5. Model calibration and sensitivity analysis

A parameter sensitivity analysis has been undertaken to evaluate how simulation errors of nitrate prediction vary with parameter value. Fig. 17 shows a plot of parameter values against the root mean square error. In each case a well defined minimum is obtained and the optimal parameter set have been used to simulate the Bedford Ouse System.

The model has been tested against observed data for the years 1974 and 1993 and Fig. 18 shows the simulated vs. observed data for 1993. Here the flow simulation is good except for periods following dry conditions. This discrepancy is a result of the MORECS model which underestimates the hydrologically effective rainfall and hence generates too little flow in the model. In a further development of INCA a new hydrological model will be created to improve on the MORECS

Fig. 13. Map of Bedford Ouse River system, eastern England.

model. The nitrate and ammonia simulations are close to the observed showing particularly high nitrate compared to the River Tywi. These high nitrates are above the EU limits of 11.3 mg N l^{-1} and hence, are of concern to the water industry. The high nitrates are derived largely from the agricultural runoff and reflect the high concentrations in the groundwater.

5. Conclusions

INCA has proved to be an extremely interesting tool for simulating catchment behaviour. It appears to reproduce the observed patterns of behaviour and changes in land use, hydrology and deposition generate reasonable and acceptable results. The internal budgeting of the model processes enables the user to investigate nitrogen dynamics and the interactions between physical, chemical and biological behaviour in a totally new manner. This unique development in dynamic biochemical models has yet to be explored or exploited in detail and is clearly an area for further research. INCA provides a new approach to dynamic modelling taking advantage of recent computing power to generate rapid results on internal mechanisms and overall river catchment behaviour. The understanding of process interactions will lead to increased confidence in model results especially when management options are being investigated. A full range of scenarios detailing changed emission strategies can be evalu-

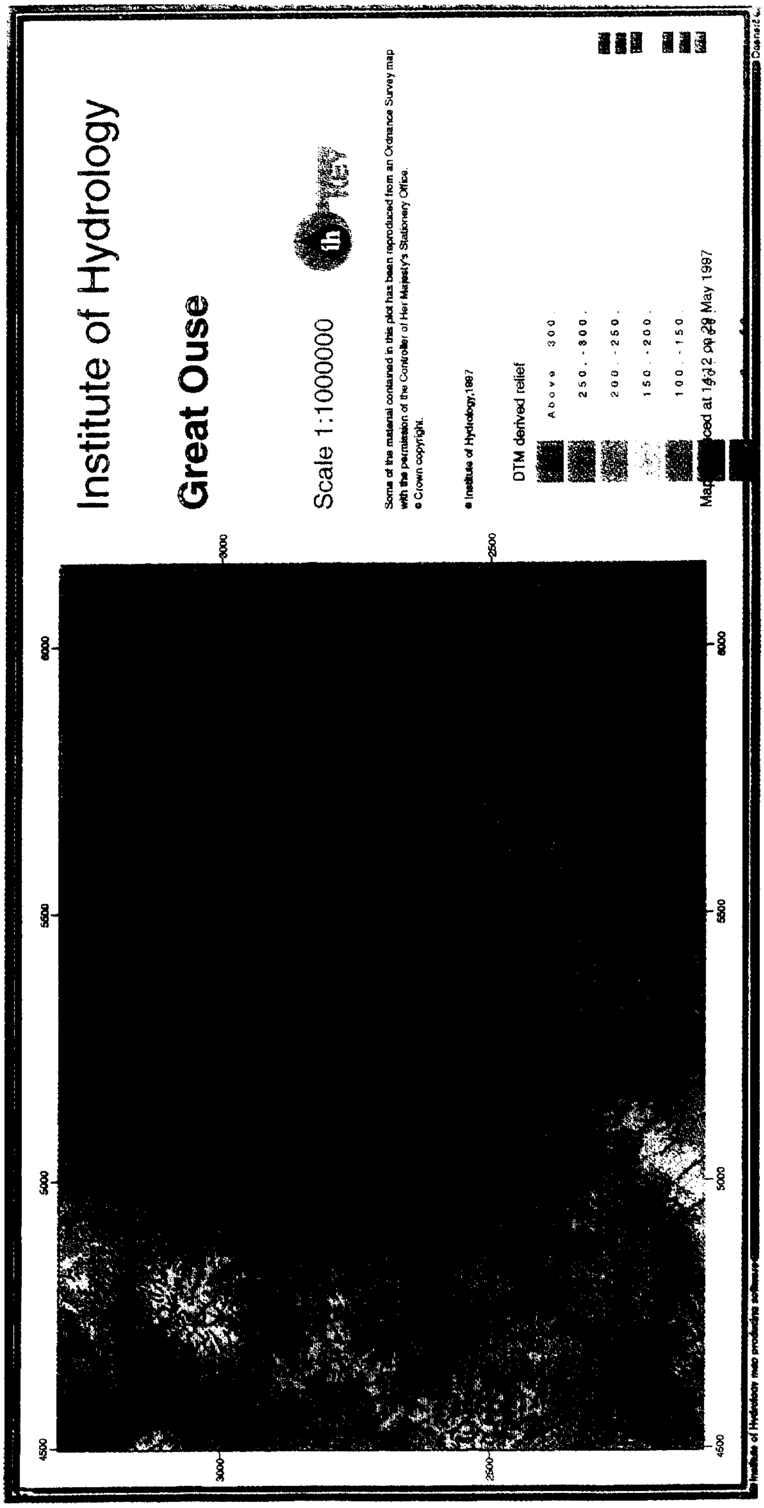


Fig. 14. Digital terrain and river channel network for Bedford Ouse River system.

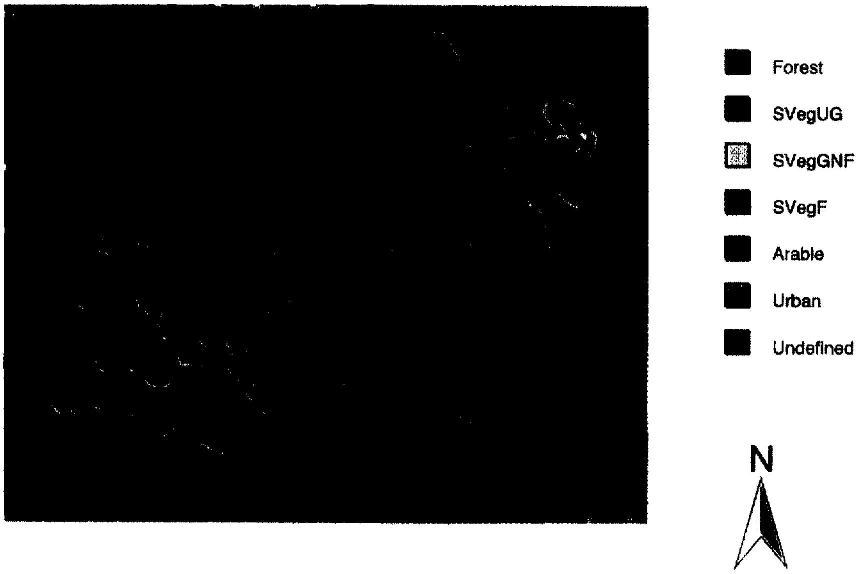
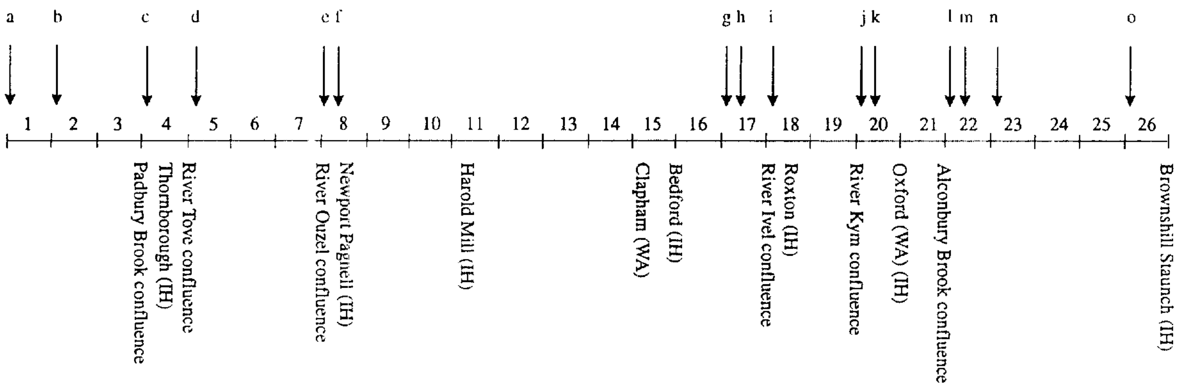


Fig. 15. Land use map for Bedford Ouse area.

Table 8
Reach and land use information for the Bedford Ouse

Reach number	Reach length (m)	Area km^2	Forest (%)	SVegUG (%)	SvegGNF (%)	SVegF (%)	Arable (%)	Urban (%)
1	17750	102	3	0	11	10	75	1
2	10000	51	0	0	20	15	59	6
3	1250	238	1	0	17	20	62	0
4	6500	56	4	0	12	13	71	0
5	6500	290	4	0	7	7	81	0
6	6500	50	0	0	24	12	42	22
7	6000	384	2	0	16	3	71	8
8	9250	74	1	0	10	0	88	1
9	5500	37	0	0	10	3	84	3
10	8000	33	0	0	9	0	91	0
11	7000	31	0	0	0	0	100	0
12	7000	30	0	0	10	0	90	0
13	7000	15	0	0	0	0	100	0
14	7000	14	0	0	0	0	100	0
15	10000	66	0	0	9	0	80	11
16	3750	12	0	0	17	0	0	83
17	4500	147	0	0	7	1	85	7
18	6750	577	1	0	7	1	83	8
19	9500	325	1	0	5	1	91	2
20	6250	34	0	0	3	0	94	3
21	5750	36	0	0	3	0	94	3
22	4000	13	0	0	8	0	77	15
23	7000	251	0	0	6	3	88	3
24	2750	91	0	0	7	1	91	1
25	2500	38	0	5	11	0	84	0
26	2000	1	0	0	0	0	100	0



a	EFFL	Brackley sewage treatment works	j	EFFL	St Neots sewage treatment works
b	EFFL	Moreton final sediment tank discharge	k	TRIB	River Kym tributary
c	TRIB	Padbury Brook tributary	l	EFFL	Huntingdon sewage treatment works
d	TRIB	River Tove tributary	m	TRIB	Alconbury Brook tributary
e	EFFL	Cotton Valley neck pit discharge	n	EFFL	St Ives sewage treatment works
f	TRIB	River Ouzel tributary	o	EFFL	Uttons Drove sewage treatment works
g	EFFL	Bedford final sediment tank discharge		EFFL	= effluent
h	TRIB	Bedford tributary		TRIB	= tributary
i	TRIB	River Ivel tributary		WA	= water abstraction
				IH	= IH monitoring station

Fig. 16. Modelled reach structure for the Bedford Ouse.

Table 9
Base flow index for the River Great Ouse

Reach number	Flow gauging station (station number)	BFI
4	Thornborough (33 005)	0.5
8	Newport Pagnell (33 037)	0.48
11	Harold Mill (33 009)	0.52
16	Bedford (33 002)	0.51
18	Roxton (33 039)	0.54
21	Oxford (33 026)	0.48
26	Brownshill Staunch (33 001)	0.5

ated and these compared with the impacts of changing land use. INCA can also be calibrated for experimental sites across Europe to explain the data and leaching rates observed.

Finally INCA is available for external users who wish to apply the model to their particular catchment system. The model is also ideal for teaching purposes as the internal mechanisms of nitrogen processes can be evaluated using the menu driven system. Contact Paul Whitehead in Reading to obtain the software.

Acknowledgements

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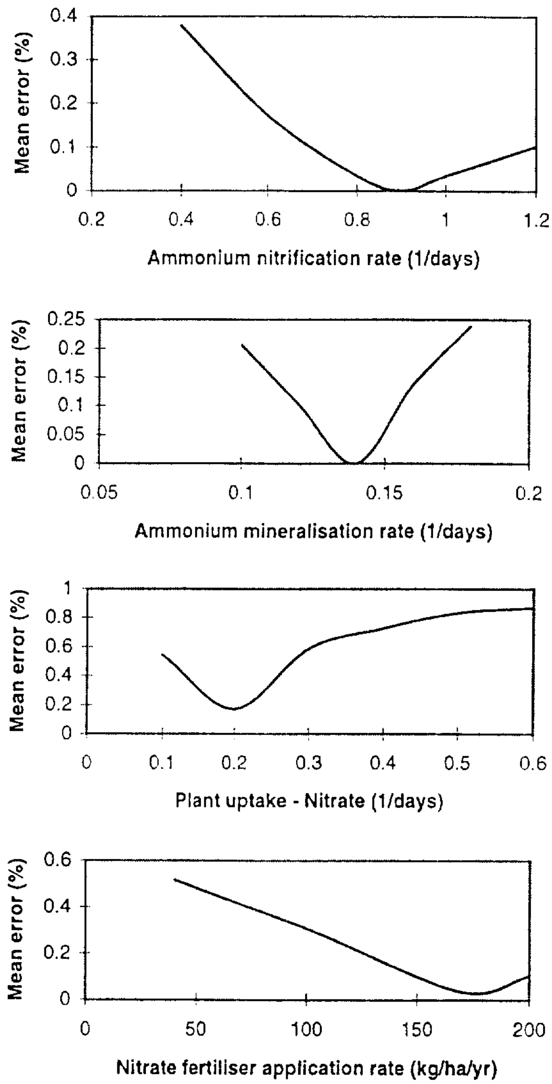

Fig. 17. Sensitivity of errors to changes in model parameters.

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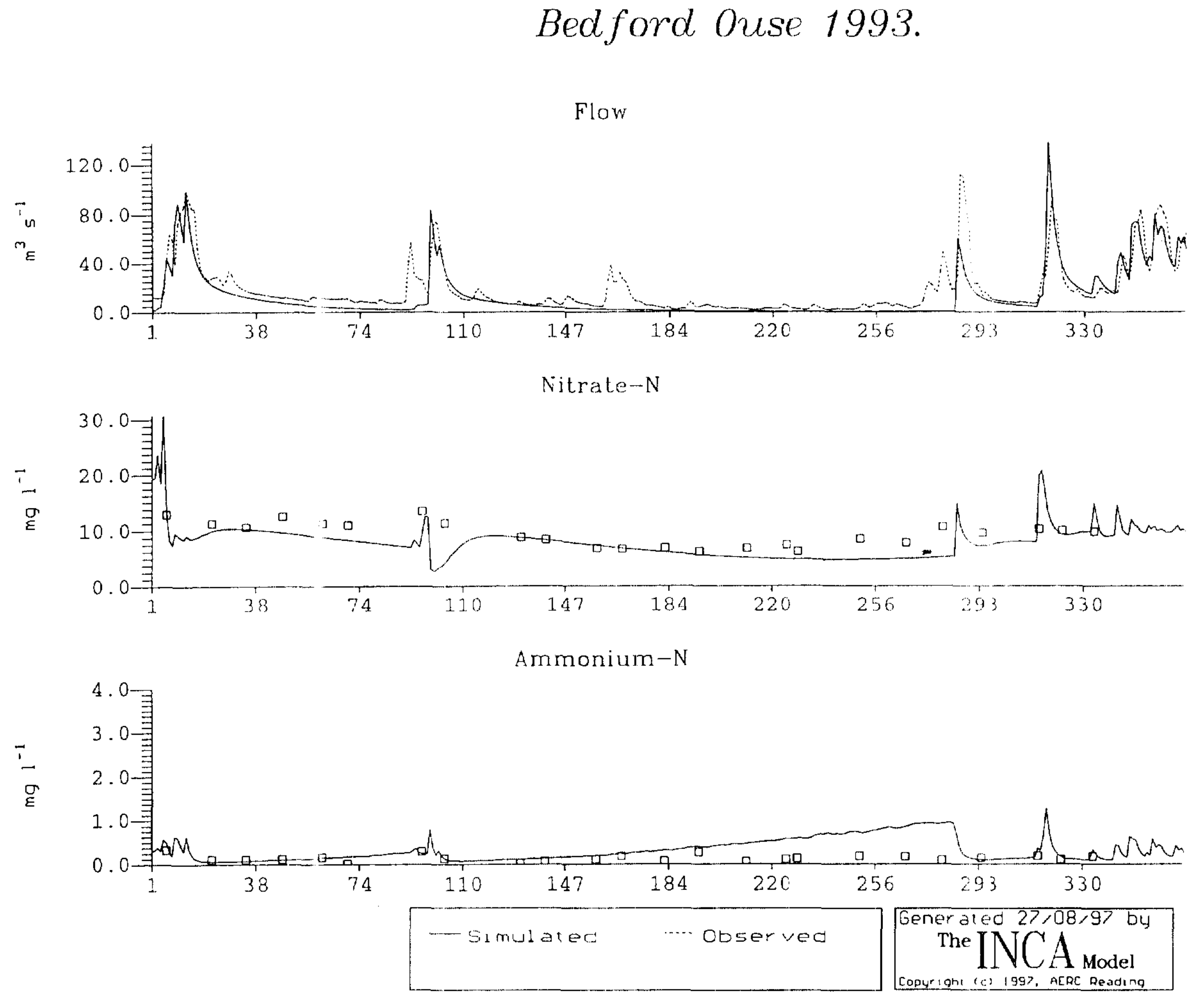

Fig. 18. Observed and simulated daily flow, nitrate and ammonium for the Bedford Ouse for 1993.

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