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Steady state and dynamic modelling of nitrogen in the River Kennet: impacts of land use change since the 1930s

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Abstract

Steady state and dynamic models have been developed and applied to the River Kennet system. Annual nitrogen exports from the land surface to the river have been estimated based on land use from the 1930s and the 1990s. Long term modelled trends indicate that there has been a large increase in nitrogen transport into the river system driven by increased fertiliser application associated with increased cereal production, increased population and increased livestock levels. The dynamic model INCA (Integrated Nitrogen in Catchments) has been applied to simulate the day-to-day transport of N from the terrestrial ecosystem to the riverine environment. This process-based model generates spatial and temporal data and reproduces the observed instream concentrations. Applying the model to current land use and 1930s land use indicates that there has been a major shift in the short term dynamics since the 1930s, with increased river and groundwater concentrations caused by both non-point source pollution from agriculture and point source discharges. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Water quality; River Kennet; Dynamic model; Land use change; Nitrogen

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1. Introduction

There has been much debate about the hydrology, water quality and ecology of chalk streams in the UK and considerable focus on the River Kennet system. The Axford Public Inquiry (Whitehead et al., 1998a) was held to evaluate impacts of groundwater abstraction on the River Kennet and a large number of issues were raised on the history, current management and future of the River Kennet. Local residents, river keepers, land owners, fisheries managers and anglers have perceived a notable decline in the River Kennet water quality, hydrology and ecology. At the time of the public enquiry, they considered that nutrient levels (nitrate and phosphorus) had risen significantly in the last two decades, water levels had visibly fallen, vegetation growth had declined and siltation of the river had increased. Local pressure groups such as Action for the River Kennet (ARK), the Kennet Valley Fisheries Association and the Wiltshire Wildlife Trust brought these issues to the attention of the Environment Agency. The River Kennet Axford Inquiry was perhaps the first public inquiry to address the extremely complex issue of how to separate man-made effects from natural effects in the river systems. The River Kennet has been subject to many influences over the past 50 years, including land-use change, climatic change, increasing fertiliser use, land drainage, dredging for flood mitigation, fish farming and changing river flow management. All of these issues affect stream hydrology, chemistry and ecology. Establishing what is scientific fact from fiction is extremely difficult. Mathematical models provide a means of evaluating impacts of change on river systems and have been used very effectively to study a wide range of problems including acidification, nutrients in rivers, eutrophication in estuary systems, algal growth in lakes and pollution problems in rivers.

In this paper, we make use of two modelling techniques to evaluate the impacts of land use change on the River Kennet. Firstly, we utilise the export coefficient techniques of Johnes (1996) to investigate steady state or annual fluxes in the

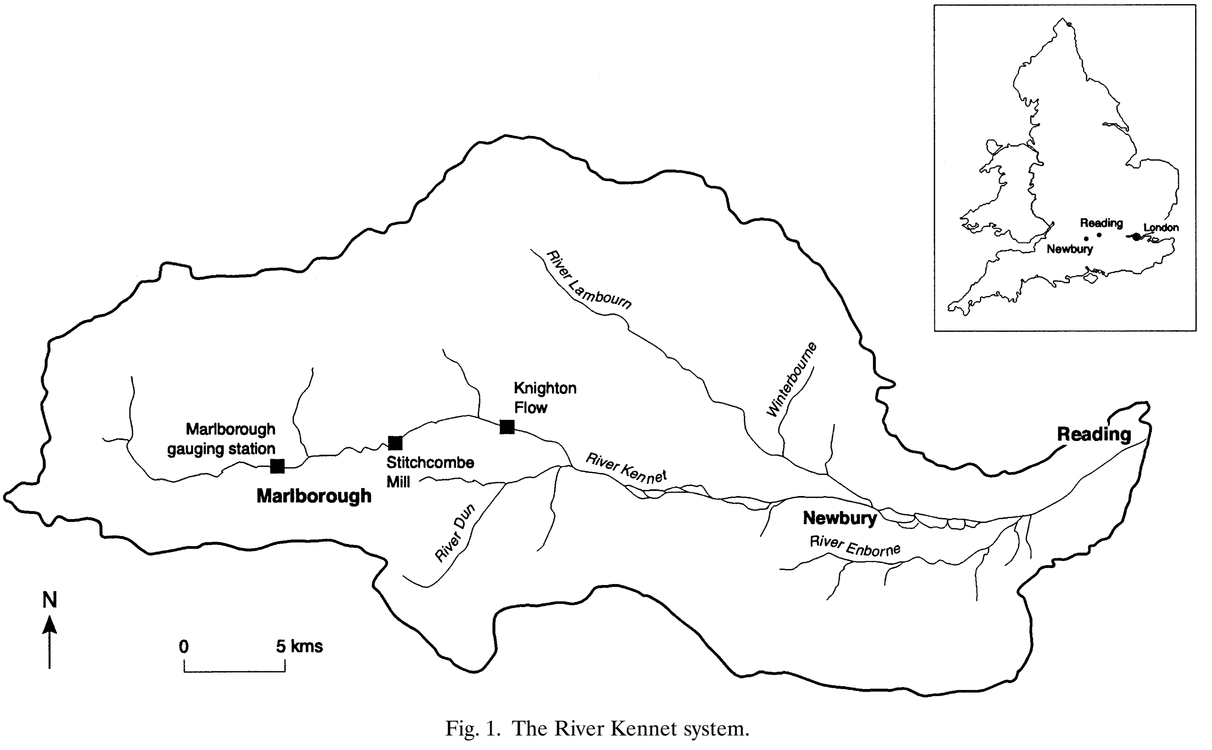


Fig. 1. The River Kennet system.

River Kennet catchment since the 1930s, and secondly, we use the process-based INCA (Integrated Nitrogen in Catchments) model (Whitehead et al., 1998b,c) to evaluate the dynamic behaviour of nitrogen in the River Kennet.

1.1. The River Kennet system

The Kennet catchment, as shown in Fig. 1 extends west of Reading to beyond Marlborough and drains into the 98-km length of the River Kennet through its seven tributaries: the Lambourne, Enbourne, Foudrey Brook, River Dunn, Aldbourne, Shalbourne and the River Og. To the north of the Kennet catchment are the Berkshire Downs, which rise to an average height of 150 m (MOD) in the east and 200 m in the west. The Hampshire Downs to the south of the catchment and the Marlborough Downs to the west have altitudes exceeding 270 and 290 m, respectively. The whole Kennet catchment drains an area of 1164 km^2, whereas the upper Kennet down to the Knighton flow gauge covers an area of 295 km^2.

The geology of the catchment is mainly confined cretaceous Chalk in the west, which is covered by clays and sands at the western end of the London Basin syncline. The Chalk aquifer acts as a large water storage unit, supplying 95% of the water in the Kennet as groundwater. The streamflow hydrograph is characteristically smooth, depicting a slow response to rainfall events and droughts alike. In the north and west of the Kennet catchment, where the aquifer is unconfined, it is recharged directly by rainfall so that the river is largely dependent upon the discharge from the Chalk aquifer. The Kennet hydrological regime is typical of a Chalk stream as it receives a stable base flow component from the groundwater all year round, despite the reduction in rainfall in the summer months. The rainfall and percolation patterns driving the Kennet hydrological regime cause spring peaks and late autumn troughs in water levels.

The River Kennet Catchment Management Plan (Environment Agency, 1994) and the current Local Environment Action Plan (Environment Agency, 2000) describes the Kennet as a 'healthy' river from a water quality viewpoint. The Upper Kennet has a class of 1A, which is the highest classification possible under the current scheme. The high quality and conservation value has been confirmed recently by the designation of part of the River Kennet as a site of special scientific interest. Whilst BOD levels are generally low, there are considerable diurnal variations in DO ranging from 22% to 200% (Whitehead et al., 1998a) saturation and this is indicative of a eutrophic stream dominated by plants and/or algae. Local concerns have been raised about the decline in macrophytes along certain reaches and the increase in epiphytic growth on aquatic plants and bottom algae growth. These eutrophic conditions are stimulated by high nutrient levels in the Kennet below Marlborough. The sewage works at Marlborough acts as a major point source of phosphorus in the Upper Kennet, although phosphorus also enters the river as non-point source runoff from both the agricultural system and the urban area of Marlborough. Wade et al. (2002a,b) describe phosphorus models to assess the impact of Marlborough sewage works on instream phosphorus.

The predominant instream macrophyte species in the Upper Kennet is Water crowfoot, otherwise known as *Ranunculus Penisilatus Variety Calcareous*. This instream vegetation is a core component of the Chalk stream ecology as it provides vital cover to the fish in their fry, parr and juvenile stages. It also raises the water levels in the river to maintain depths preferable to fish. Although the Kennet is heavily stocked with brown trout, one of the main concerns expressed by local residents, anglers and river keepers is the apparent decline in their numbers. A significant decline in *Ranunculus* has also been noted. Some have attributed these problems to the groundwater abstraction at Axford, although an alternative hypothesis is that the increased nutrient loads in the Upper Kennet have caused algal populations to boom, choking the instream vegetation and reducing invertebrate diversity.

The River Kennet channel morphology shows evidence of recent dredging to the river bed. Indeed, since the early 1880s, sections of it have been widened, canalised and re-routed as it has been used to support water meadows and drive water wheels in the many mills established along it. Now managed by a collection of different river keepers, working on behalf of a range of land owners, the river has also experienced considerable change in more recent years. The many sluices, weirs and fords constructed along the reach between Marlborough and Reading are managed and operated independently from one another, impacting local areas of the river by altering depths, velocity distributions and sedimentation rates. Low flows in summer will clearly have a major impact on instream quality and river ecology and there may be evidence that increased frequency of low flows could be partly responsible

Table 1
Land use and nutrient fluxes in the River Kennet from 1931 to 1991

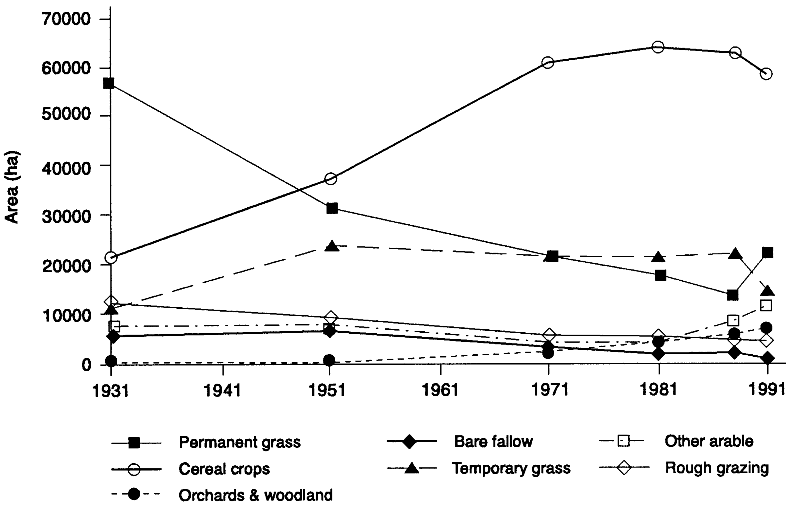
Year	Permanent grass (kg N)	Temporary grass (kg N)	Cereal crops (kg N)	Other arable (kg N)	Rough grazing (kg N)	Woodland and orchards (kg N)	Bare fallow land (kg N)	Cattle (kg N)
Nitrogen exported from nutrient sources in the catchment								
1931	179 540	23 814	32 489	36 266	17	2539	4712	518 417
1951	132 940	70 864	152 523	73 790	17	1775	5364	839 472
1971	158 478	221 898	673 252	86 335	143	1070	2583	892 534
1981	136 615	260 859	978 377	125 883	396	1059	1062	929 362
1988	111 272	241 651	1 178 436	288 581	507	881	1016	700 209
1991	191 471	143 918	1 222 525	393 275	646	760	314	691 352

Year	Permanent grass (kg P)	Temporary grass (kg P)	Cereal crops (kg P)	Other arable (kg P)	Rough grazing (kg P)	Woodland and orchards (kg P)	Bare fallow land (kg P)	Cattle (kg P)
Phosphorus exported from nutrient sources in the catchment								
1931	5452	2655	3704	1915	0	0	0	23 008
1951	14 324	19 573	21 751	3723	0	0	0	37 256
1971	4531	19 865	33 814	3507	0	0	0	39 611
1981	3102	13 411	34 715	3024	0	0	0	41 246
1988	1826	8886	38 468	7138	0	0	0	31 076
1991	2523	3771	38 497	9927	0	0	0	30 683

Year	Pigs (kg N)	Sheep (kg N)	Poultry (kg N)	People (kg N)	Rainfall (kg N)	Total N export rate (kg N ha − 1)	Total N exported (kg N)
Nitrogen exported from nutrient sources in the catchment							
1931	53 945	135 696	31 081	117 414	582 000	14.8	1 717 929
1951	71 823	44 107	37 368	158 600	582 000	18.6	2 170 641
1971	194 074	67 041	58 050	273 502	582 000	27.6	3 210 960
1981	253 260	143 901	48 450	311 466	582 000	32.4	3 772 689
1988	205 679	208 894	36 706	356 692	582 000	33.6	3 912 524
1991	162 172	232 040	52 761	376 076	582 000	34.8	4 049 308

Year	Pigs (kg P)	Sheep (kg P)	Poultry (kg P)	People (kg P)	Rainfall (kg P)	Total P export rate (kg P ha − 1)	Total P exported (kg P)
Phosphorus exported from nutrient sources in the catchment							
1931	2861	3556	1994	43 132	5820	0.8	94 097
1951	3809	1156	2398	58 261	5820	1.4	168 071
1971	10 292	1757	3725	100 469	5820	1.9	223 392
1981	13 431	3771	3109	114 415	5820	2.0	236 045
1988	10 907	5475	2355	131 029	5820	2.1	242 980
1991	8600	6081	3386	138 150	5820	2.1	247 438

(a) Land use



(b) Livestock and people

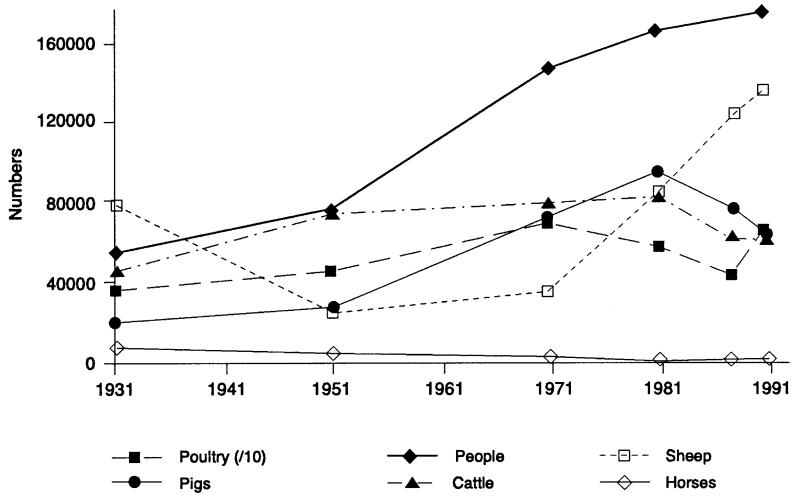


Fig. 2. Land use, livestock and population change in the River Kennet catchment from 1931–1991.

for the perceived environmental degradation. A separate study by Limbrick et al. (2000) has shown that the impacts of climatic change on the low flow regime could be significant in the River Kennet.

2. Steady state modelling of nutrients to assess land use change

The modelling approach used for the steady state analysis is the export coefficient method as described by Johnes (1996). This model makes use of the area of a particular land use type multiplied by an export coefficient. The summation of all of the exports from the different land uses gives an annual flux of nutrient into the river system as follows:

$$L = \sum_{i=1}^{n} E_i[A_i(I_i)] + P \qquad (1)$$

where L is the total loss of nutrients; E is the export coefficient for nutrient source i; A is the area of catchment occupied by a particular land use type i, or number of livestock i, or of people; i is the input of nutrients to the river from that particular source i; and p is the input of nutrient from precipitation.

This technique has been used to generate an annual flux of nitrogen given changes in land use, stocking rates population. A complete summary of these changes and estimated exports of N are given in Table 1, based on MAFF parish data export maps for the Kennet catchment. Fig. 4 shows the export of N from all parishes across the Kennet catchment based on 1931 land use and 1991 land use obtained from the MAFF records (MAFF, 1968). Fig. 2 presents data showing land use change, stocking and population change as a function of time from 1931. The major change that has occurred in the Kennet appears to be a reduction in permanent grass and a corresponding increase in cereal crops. Whilst stock numbers of pigs has also increased, there has been a big increase in the population in the Kennet from 50 000 to 170 000. The switch to cereals has been accompanied by an increased use of fertilisers, thereby increasing non-point source pollution and the population increase has resulted in an increase in the point sources, such as at the Marlborough sewage works. Fig. 3a shows that these changes have produced a rising trend in N fluxes in the catchment and, for comparison, Fig. 3b shows the nitrate concentrations in the Thames at Teddington. These concentrations show a very similar pattern to the N flux for the Kennet, which is not surprising given the fact that similar land use change and population patterns have been seen for the whole of the Thames catchment. Table 1 shows the actual land use data, stocking rates and population data used to calcu-

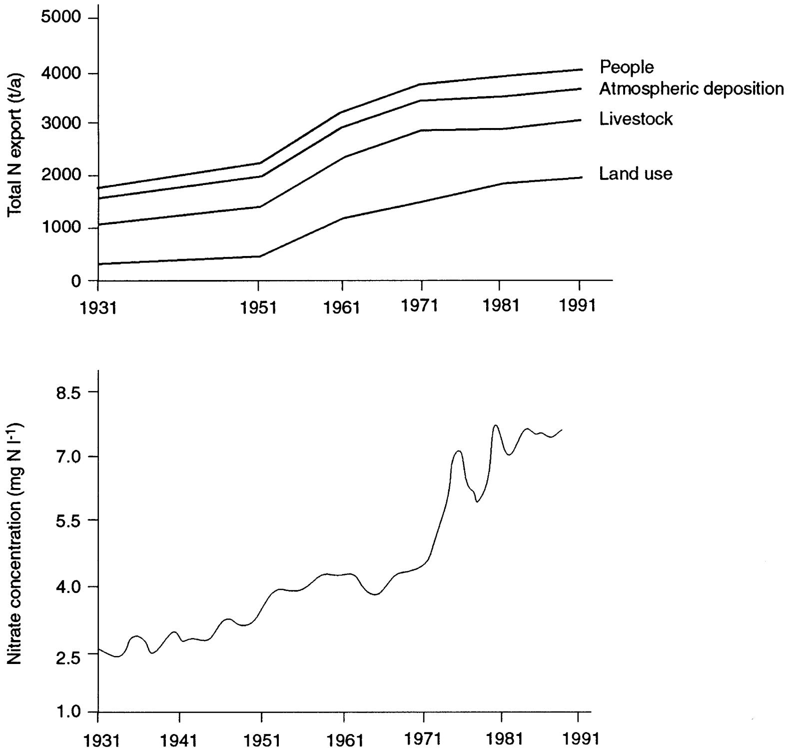
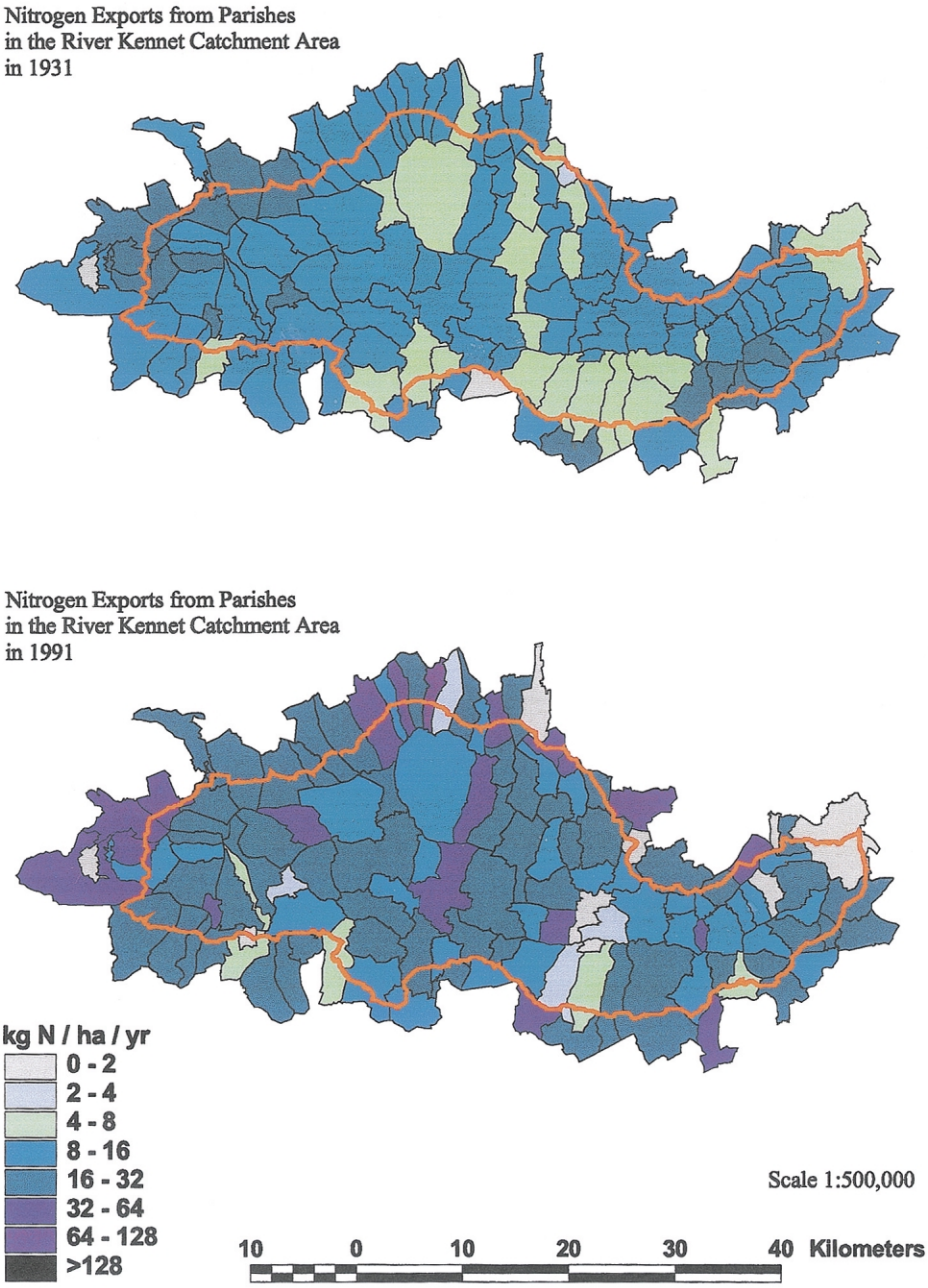


Fig. 3. Total nitrogen export in the River Kennet and nitrate concentrations in the River Thames at Teddington from 1931 to 1991.



Nitrogen Exports from Parishes in the River Kennet Catchment Area in 1931

Nitrogen Exports from Parishes in the River Kennet Catchment Area in 1991

Fig. 4. Spatial patterns of nitrogen export across the Kennet catchment from 1931 to 1991.

late exports from the Kennet. These results confirm the concerns of the local people in the Kennet in that there has been a demonstratable increase in nitrogen in the River Kennet system since the 1930s. The spatial pattern of change across the Kennet system is shown in Fig. 4. Here, fluxes of N loss from all the parishes in the Kennet show a three-fold increase from 1931 to

1991 with export rates increasing to 80 kg ha^{-1} year^{-1} in certain upper catchments.

3. Dynamic modelling of nitrogen using the INCA model

The INCA model has been designed to investigate the fate and distribution of nitrogen in the aquatic and terrestrial environment (Whitehead et al., 1998b,c). The model simulates flow, nitrate–nitrogen and ammonium–nitrogen and tracks the flow paths operating in both the land phase and riverine phase. The model is dynamic in that the day-to-day variations in flow and nitrogen can be investigated following a change in input conditions, such as atmospheric deposition/sewage discharges or fertiliser addition. The model can also be used to investigate a change in land use (e.g. moorland to forest or pasture to arable). Dilution, natural decay and biochemical transformation processes are included in the model, as well as the interactions with plant biomass such as nitrogen uptake by vegetation.

INCA has been designed to be easy to use and fast, with excellent output graphics. The menu system allows the user to specify the semi-distributed nature of a river basin or catchment, to alter reach lengths, rate coefficients, land use, velocity–flow relationships and to vary input nitrogen deposition loads.

INCA provides the following outputs:

- daily time series of flows, nitrate–nitrogen and ammonium–nitrogen concentrations at selected sites along the river;
- profiles of flow or nitrogen along the river at selected times;
- cumulative frequency distributions of flow and nitrogen at selected sites;
- table of statistics for all sites; and
- daily and annual nitrogen loads for all land uses and all processes.

4. Nitrogen process equations

The hydrological model as shown in Figs. 5 and 6 provides information on the flow moving through

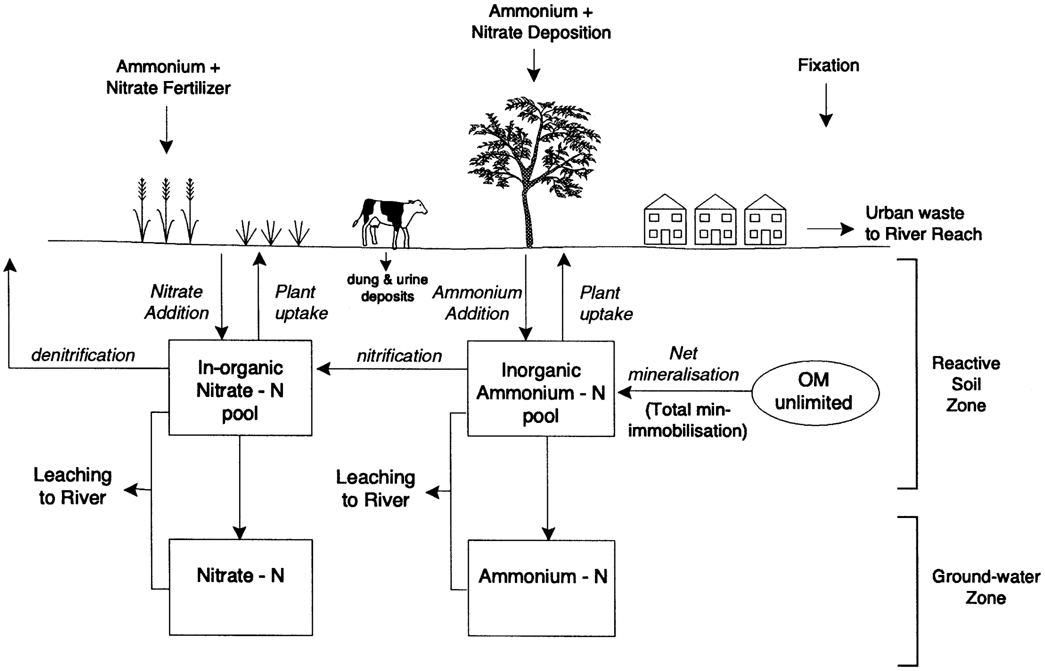


Fig. 5. Nitrogen input, processes and outputs in the soil and groundwater system.

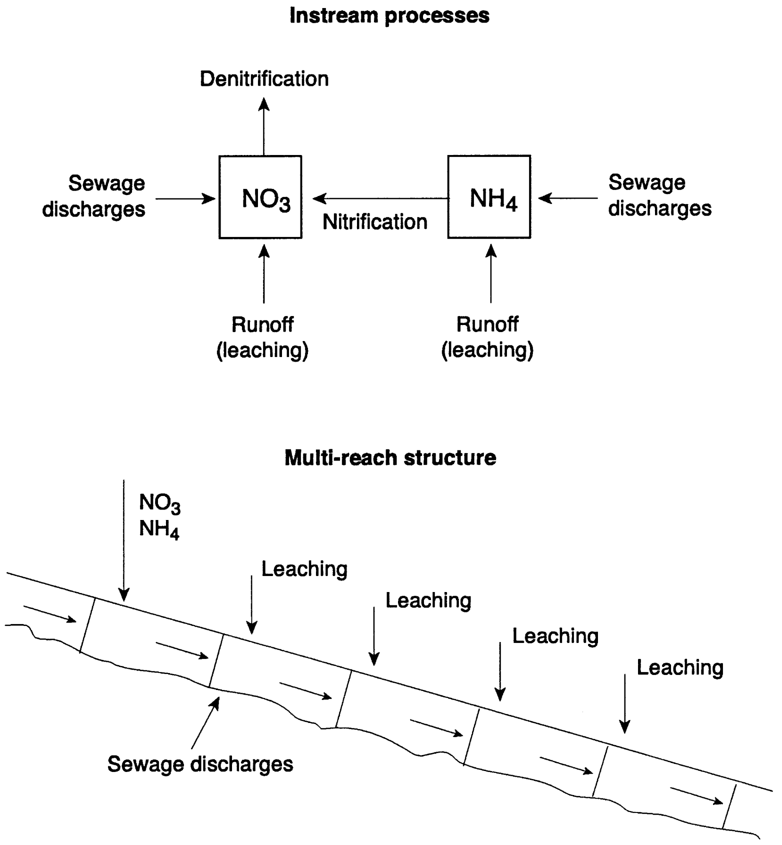


Fig. 6. Nitrogen inputs, processes and outputs in the river system.

the soil zone, the groundwater zone and the river system. Simultaneously, whilst solving the flow equations, it is necessary to solve the mass balance equations for both nitrate–nitrogen and ammonium–nitrogen in both the soil and groundwater zones. The key processes that require modelling in the soil zone, as shown in Fig. 5, are plant uptake for NH_4–N and NO_3–N, ammonia nitrification, denitrification of NO_3–N, ammonia mineralisation, ammonia immobilisation and N fixation. All of these processes will vary from land use to land use and a generalised set of equations is required for which parameter sets can be derived for different land uses. The land phase model must also account for all the inputs affecting each land use, including dry and wet deposition of NH_4–N and NO_3–N and fertiliser addition for both NH_4–N and NO_3–N (e.g. as ammonium nitrate). Also, temperature and soil moisture will control certain processes so that, for example, nitrification reaction kinetics are temperature dependent and denitrification and mineralisation are both temperature and soil moisture dependent.

In the groundwater zone, it is assumed that no biochemical reactions occur and that there is mass balance for NH_4–N and NO_3–N. The equations used in INCA are as follows:

NITRATE–N

$$\text{Soil zone } \frac{dx_3}{dt} = \frac{1}{V_1}(U_3 - x_1 x_3) - C_3 U_7 x_3 + C_6 x_5 - C_1 U_5 x_3 + C_2 \qquad (2)$$

$$\text{Groundwater}\ \frac{\mathrm{d}x_4}{\mathrm{d}t} = \frac{1}{V_2}(x_3 x_1 U_8 - x_2 x_4) \qquad (3)$$

AMMONIUM–N

$$\text{Soil zone}\ \frac{\mathrm{d}x_5}{\mathrm{d}t} = \frac{1}{V_1}(U_4 - x_1 x_5) - C_{10} U_7 x_5 - C_6 x_5 + C_7 U_6 + C_8 x_5 \qquad (4)$$

$$\text{Groundwater}\ \frac{\mathrm{d}x_6}{\mathrm{d}t} = \frac{1}{V_2}(x_5 x_1 U_8 - x_2 x_6) \qquad (5)$$

where x_3 and x_4 are the daily NO_3–N concentrations, (mg/l), in the soil zone and groundwater zone, respectively; and x_5 and x_6 are the daily NH_4–N concentrations, (mg/l), in the soil zone and groundwater zone, respectively.

U_8 is the baseflow index and C_3, C_6, C_1, C_2, C_{10}, C_7, C_8 are rate coefficients (per day) for, respectively, plant uptake of nitrate, ammonia nitrification, nitrate denitrification, nitrate fixation, plant uptake of ammonia, ammonia mineralisation and ammonia immobilisation. U_3 and U_4 are the daily nitrate–nitrogen and ammonium–nitrogen loads entering the soil zone and constitute the additional dry and wet deposition and agricultural inputs (e.g. fertiliser addition). All rate coefficients are temperature dependent using the equation:

$$C_n = C_n 1.047^{(\theta_s - 20)}$$

where θ_s is soil temperature estimated from a seasonal relationship dependent on air temperature, as follows:

$$\text{Soil temperature} = \text{Air temperature} + C_{16} \sin\left(\frac{3}{2}\pi \frac{\text{day no.}}{365}\right) \qquad (6)$$

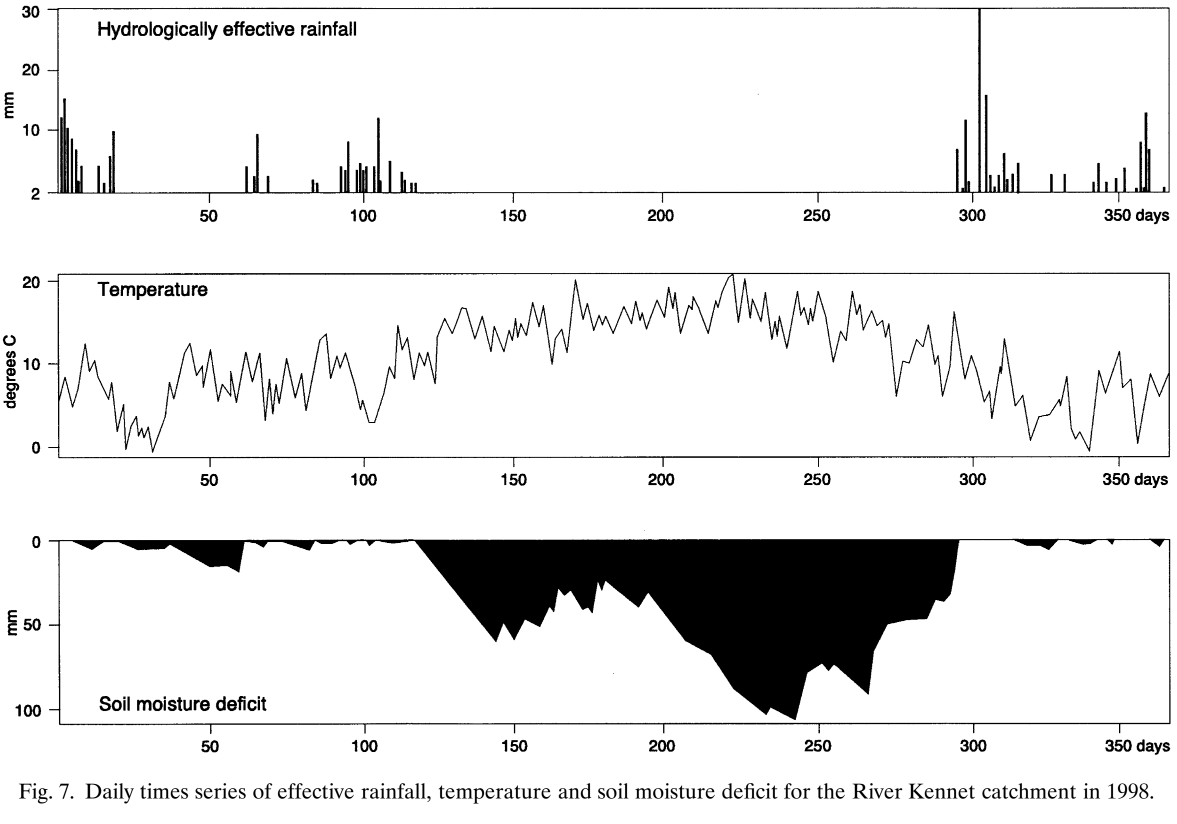


Fig. 7. Daily times series of effective rainfall, temperature and soil moisture deficit for the River Kennet catchment in 1998.

Table 2
River reach and sub-catchment area and land use for River Kennet

Reach boundary	Reach length (m)	Sub-catchment area (km^2)	Land use class percentages					
			Forest (%)	SvegUG (%)	SVegGNF (%)	SvegF (%)	Arable (%)	Urban (%)
1 Source	6250	24	0	0	13	4	83	0
2 Avebury	4500	34	0	0	0	3	97	0
3 Fyfield	8000	51	2	0	0	10	88	0
4 Clatford	1750	5	0	0	0	0	100	0
5 Marlborough	3000	24	13	0	4	13	62	8
6 Glebe House	2250	77	1	0	0	4	92	3
7 Mildenhall	500	1	0	0	0	0	100	0
8 Stichcombe	1500	2	0	0	0	50	50	0
9 Axford	1000	2	0	0	0	50	50	0
10 Ramsbury	4000	24	4	0	0	4	88	4
11 Knighton	2500	57	2	0	0	4	92	2
12 Chilton	3500	13	0	0	8	0	92	0
13 Hungerford	1750	6	0	0	0	17	83	0
14 Hampstead	10 000	208	12	0	7	7	73	1
15 Newbury-GS	4000	18	0	0	17	33	22	28
16 Newbury	1750	266	4	0	8	3	88	2
17 Thatcham	4500	18	11	0	17	17	22	33
18 Woolhampton	5000	12	8	0	8	25	59	0
19 Padworth	4000	159	17	0	21	18	43	1
20 Ufton Bridge	3000	13	0	0	77	8	15	0
21 Theale	3250	23	13	0	35	9	39	4
22 Burghfield	3250	5	0	0	20	0	20	60
23 Fobney	2000	2	0	0	0	0	0	100
24 Berkerley-Rd	2250	95	8	0	40	4	31	17
25 Thames Confl	2250	3	0	0	0	0	0	100

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

where C_{16} is the maximum temperature (°C), difference between summer and winter conditions.

U_7 is a seasonal plant growth index where:

$$U_7 = 0.66 + 0.34\sin\left(2\pi\frac{[\text{day no.} - C_{11}]}{365}\right) \qquad (7)$$

where C_{11} is the day number associated with the start of the growing season; and U_5 is a soil moisture threshold below which denitrification will not occur. Denitrification generally will only be significant when soil moisture levels are high. Similarly, U_6 is a soil moisture control for mineralisation which permits mineralisation when the soil water content is above a threshold level.

4.1. Nitrogen process equation: river system

In the river, the key processes are denitrification of NO_3–N, nitrification of NH_4–N and mass balance. The reach mass balance needs to include the upstream NO_3–N and NH_4–N together with inputs from both the soil zone and groundwater zone, as well as direct effluent discharges, as shown in Fig. 6.

The equations for the flow NO_3–N and NH_4–N river reaches are then:

$$\text{Flow}\ \frac{\mathrm{d}x_7}{\mathrm{d}t} = \frac{1}{T_3}(U_9 - x_7) \qquad (8)$$

$$\text{Nitrate } \frac{dx_8}{dt} = \frac{1}{V_3}(U_{10}U_9 - x_7x_8) - C_{17}x_8 + C_{14}x_9 \qquad (9)$$

$$\text{Ammonia } \frac{dx_9}{dt} = \frac{1}{V_3}(U_{11}U_9 - x_7x_9) - C_{14}U_3x_9 \qquad (10)$$

where $T_3 = L/v = L/(aQ^b)$ is a non-linear velocity flow relationship; U_9 is the upstream flow (m^3/S); U_{10} is the upstream NO_3–N (mg/l); U_{11} is the upstream NH_4–N (mg/l); T_3 is the reach time constant (or residence time) which varies from day to day; x_7 is the estimated downstream flow rate (m^3/S); x_8 and x_9 are the downstream (i.e. reach output) concentrations of nitrate and ammonia, respectively; and C_{17} and C_{18} are temperature-dependent rate parameters for denitrification and nitrification, respectively. Temperature effects are introduced related to river water temperature σ as follows:

$$C_8 = C_8 1.047^{(\sigma - 20)} \qquad (11)$$

The equations are solved using a fourth order Runga Kutta method of solution with a Merson variable step length integration routine. This enables stable numerical integration of the equations and minimises numerical problems. The advantage of this scheme is that scientific effort can be directed to ensuring correct process formulation and interaction rather than numerical stability problems. Full details of the model and its application to river catchments are given by Whitehead et al. (1998b,c).

4.2. Application to the River Kennet

The model has been applied to the whole of

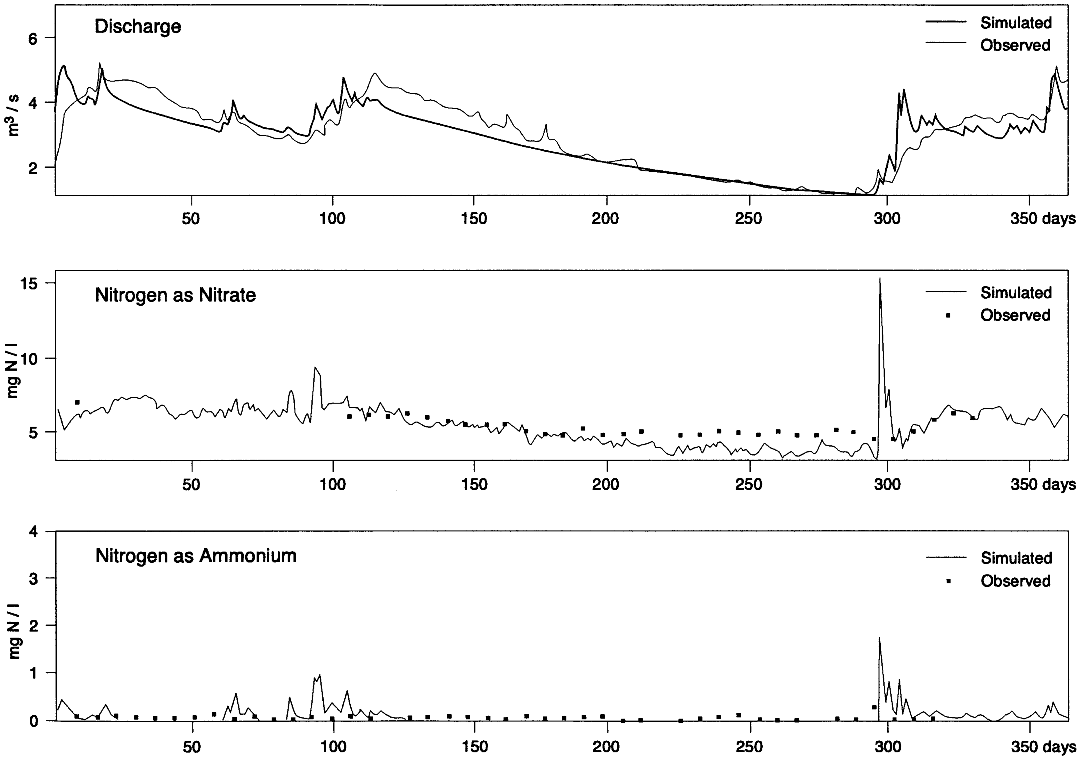


Fig. 8. Simulated and observed flow, nitrate and ammonia in the River Kennet at Knighton during 1998.

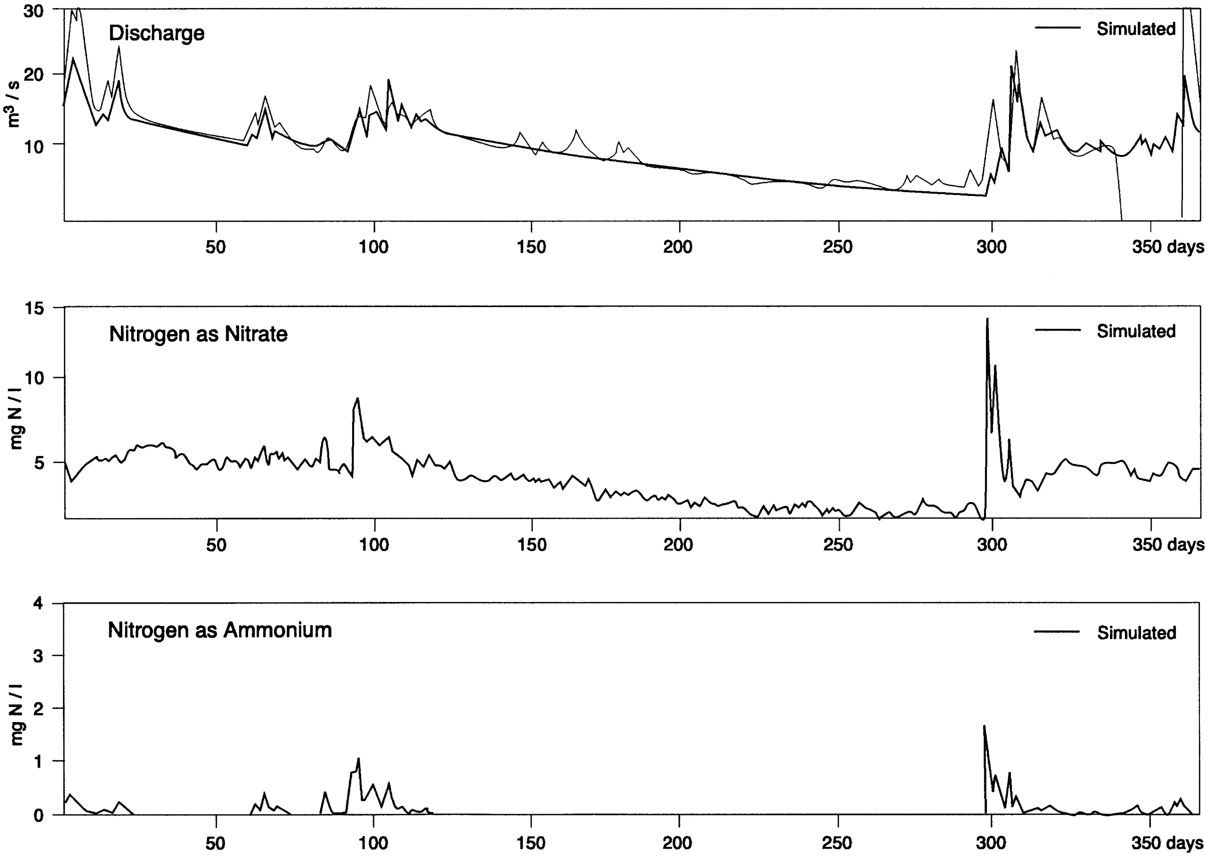


Fig. 9. Simulated and observed hydrology and water quality at Theale on the River Kennet during 1993.

the Kennet catchment using current land use descriptions and the 1998 hydrological time series data shown in Fig. 7. The hydrological effective rainfall, temperature and soil moisture deficit data shown in Fig. 7 have been obtained following application of the MORECS model (Meteorological Office, 1981) to local weather station data from the UK Met. Office. The river system is divided into 25 reaches and details of the reach structure and sub-catchment (land use characteristics are given in Table 2).

Note the current high percentage area for arable land in the River Kennet catchment. The wet and dry deposition of nitrogen is approximately 15 kg ha^{-1} year^{-1} and this is a relatively high input, split evenly between the wet and dry form of nitrogen. The base flow index in the Kennet is high, of the order of 0.95, and this reflects the predominance of the underlying chalk geology. Inevitably, this controls the hydrological response of the stream and Fig. 8 shows the response of the model to the 1998 rainfall time series in the reach at Knighton in the upper reaches of the Kennet. The long recession of the hydrograph after day 109 reflects the slow response of the groundwater, although the hydrograph responds quickly to a sudden storm event. The modelled flow, nitrate and ammonia shown in Fig. 8 matches the observed levels at Knighton, in the upper reaches of the Kennet. This good model performance is continued down all the reaches as far as Theale and Fobney near Read-

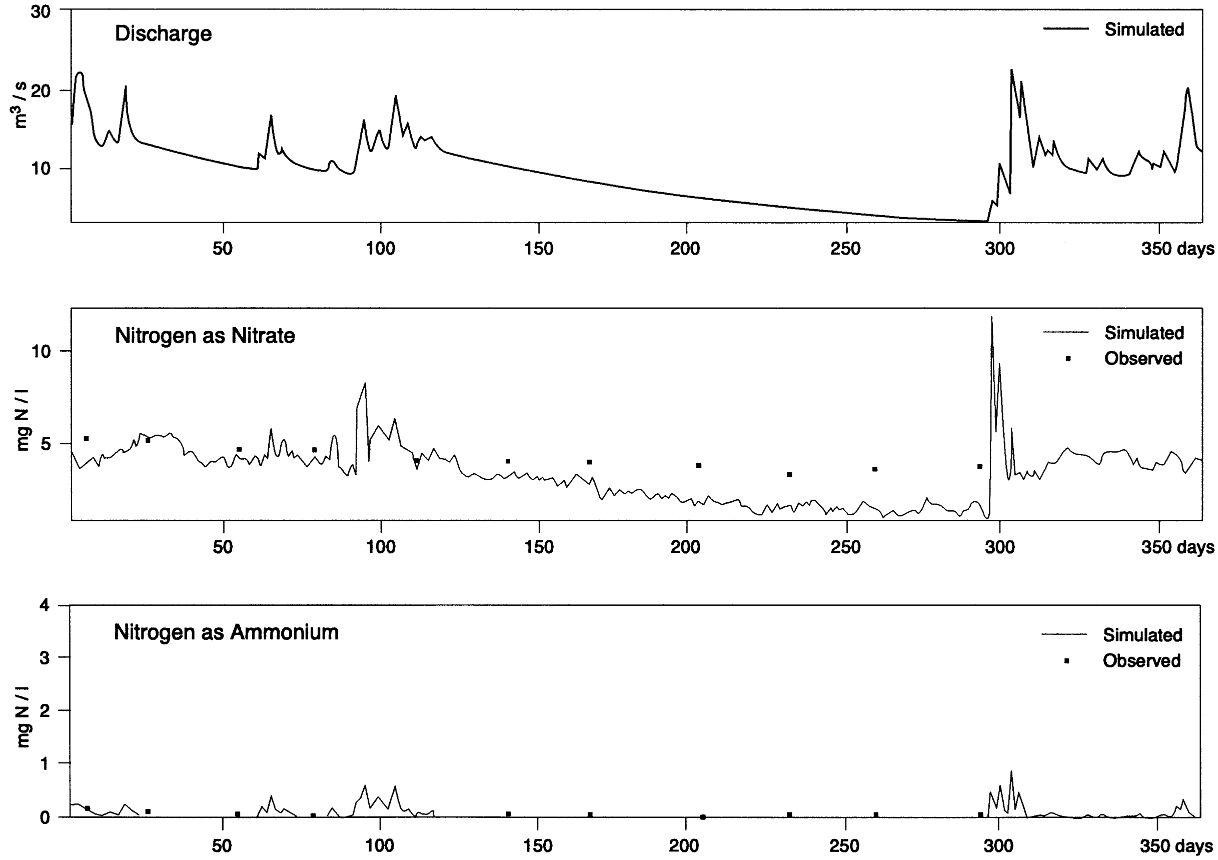


Fig. 10. Simulated and observed flow and water quality at Fobney during 1998.

ing, as shown in Figs. 9 and 10. The modelled flows in the Kennet compare well with observed flows at Knighton and Theale, as shown in Figs. 8 and 9, and the simulated response at Theale is particularly good showing that the underlying structure of the hydrological model is adequate for river systems such as the Kennet. INCA produces data at all reaches down the Kennet and, hence, a profile along the river can be generated for any day throughout the year. As shown in Fig. 11, the flows rise steadily down the river as groundwater inflow occurs and nitrate falls, reflecting the increased in-stream denitrification occurring as the water residence times lengthen in the lower reaches of the river. Increases of ammonia occur at points such as Marlborough and Newbury where major effluent discharges affect the river. Note also that nitrate increases in the lowest reaches, near Reading, due to the influx of urban run-off and high nitrate water from streams such as Foudrey Brook. Another interesting feature is the frequency distribution for nitrate and flow, as shown in Fig. 12. A biomodal distribution for NO_3–N is obtained at all sites on the Kennet, probably due to the biomodal distribution of flow. The table of statistics in Figs. 12 and 13 for the simulated NO_3–N shows that the 95th percentile concentration is higher at Knighton compared to the downstream site at Fobney (Fig. 13). This reduction reflects denitrification processes in the river.

A significant feature of the INCA simulation is

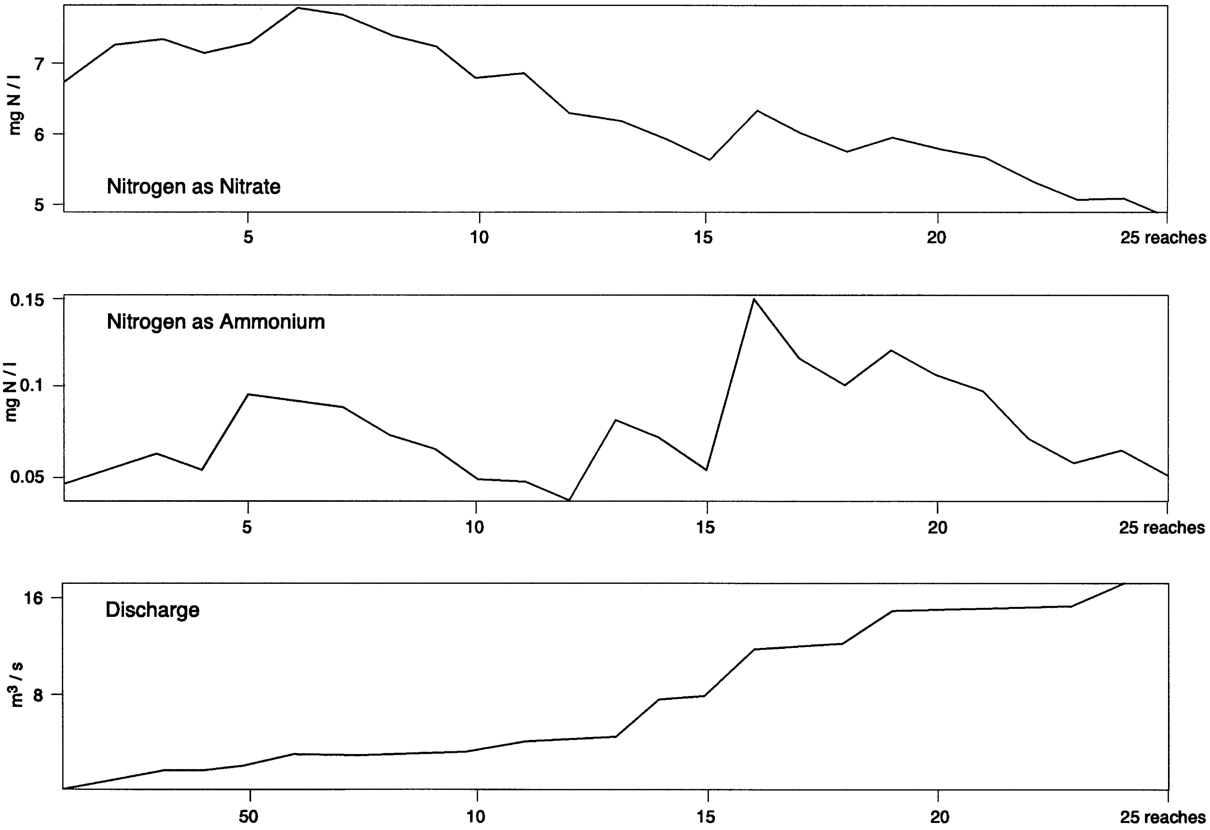


Fig. 11. Profile down the River Kennet on 20 January, 1998.

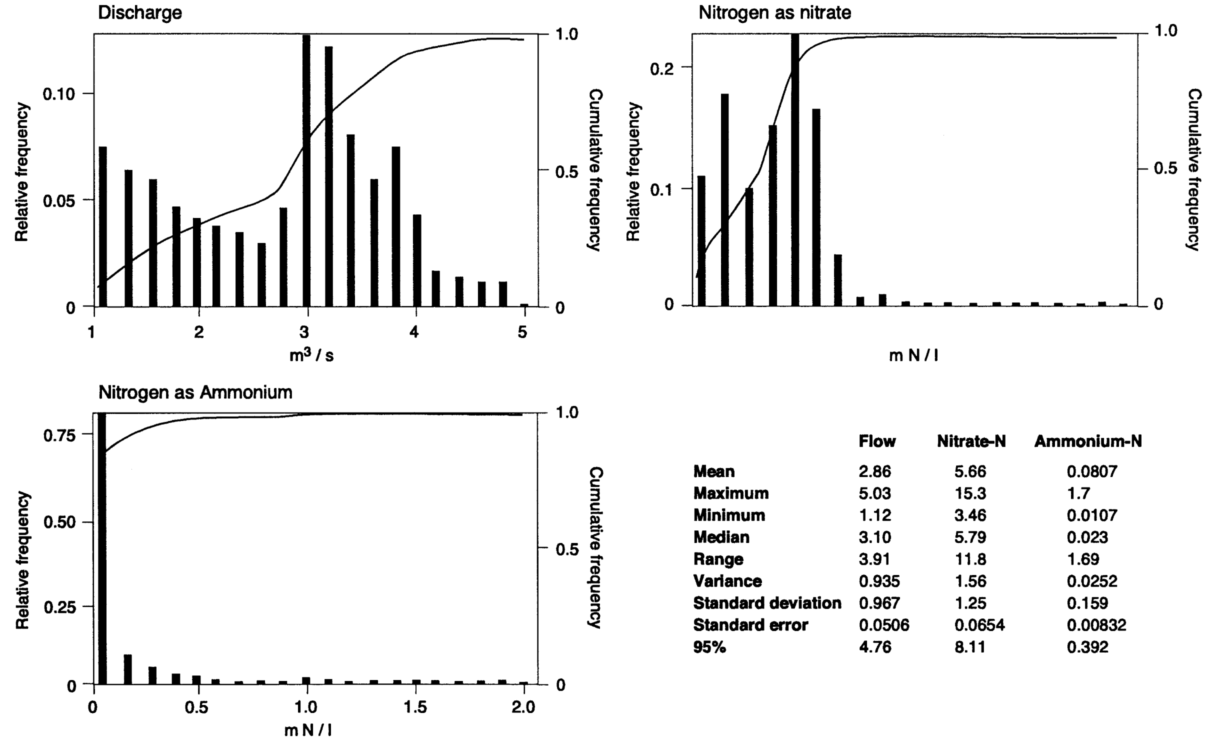
that in order to simulate the damped nitrate response of the river it is necessary to reduce the effective fertiliser impact rates. The extensive research at Rothamstead (Hart et al., 1993; Addiscott and Powlson, 1992) shows that fertiliser enters the organic pool of nitrogen and that only a proportion actually transfers into the water soluble form for immediate run-off into streams. Isotope experiments show that 15% of fertiliser N is still available for uptake in the season following application. However, a higher proportion of fertiliser will enter the groundwater zone and be held in storage prior to being released to the river. Given the Base Flow Index of 0.95 in the Kennet, this certainly appears to be happening in the River Kennet system.

4.3. Impacts of land use change

Table 3 shows the land use change in the Kennet catchment between 1931 and 1991, which shows that there has been a large increase in arable and grazed area, and this has been at the expense of forest land with a 70% reduction and a reduction of 97% in permanent grassland. Within INCA, it is possible to re-run the model with these changes in land use by altering the land use percentages shown in Table 2. These changes have a significant impact on the nitrogen response, as might be expected. As shown in Fig. 14, there is a significant shift in nitrogen, with 95 percentile levels falling from 6.44 in the 1991 simulation to 3.48 mg l^{-1} in the 1931 simulation.

5. Conclusion

The steady state and dynamic modelling studies



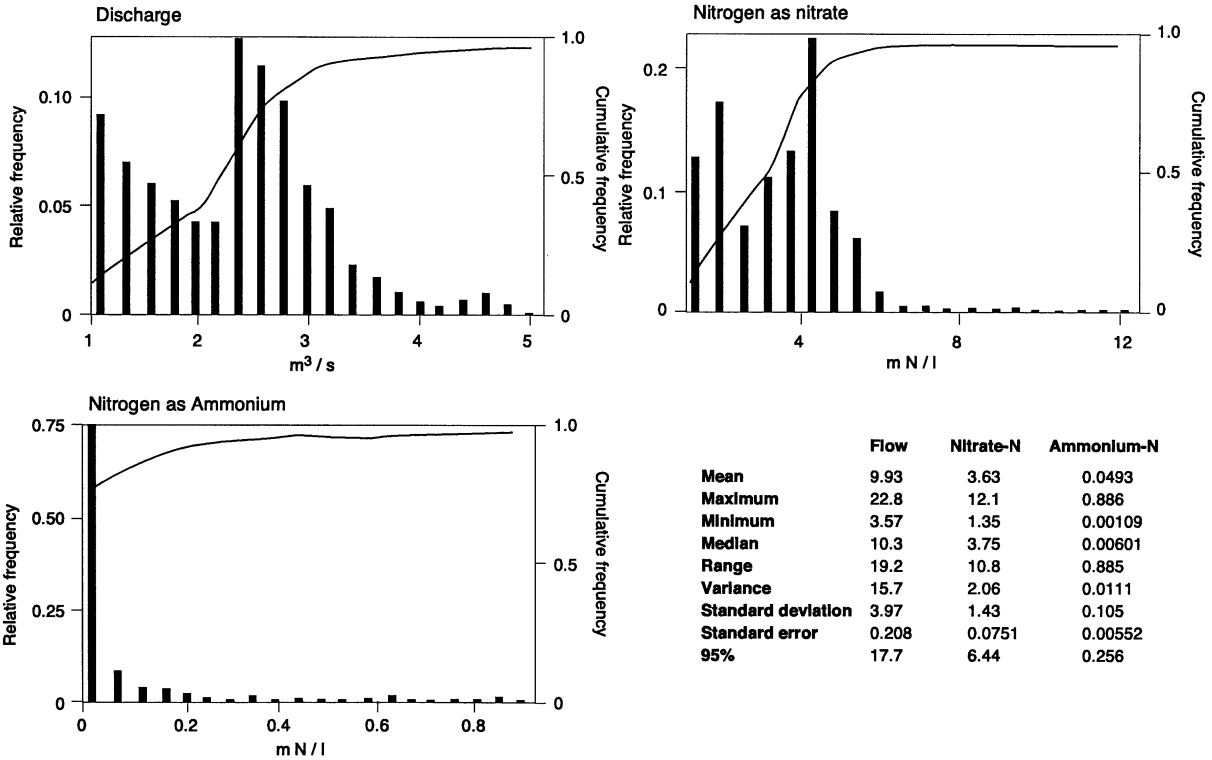
	Flow	**Nitrate-N**	**Ammonium-N**
Mean	2.86	5.66	0.0807
Maximum	5.03	15.3	1.7
Minimum	1.12	3.46	0.0107
Median	3.10	5.79	0.023
Range	3.91	11.8	1.69
Variance	0.935	1.56	0.0252
Standard deviation	0.967	1.25	0.159
Standard error	0.0506	0.0654	0.00832
95%	4.76	8.11	0.392

Fig. 12. Frequency and cumulative distribution of simulated flow, nitrate and ammonium at Knighton for 1998.

illustrate the impact of land use change and population change on stream water quality. There has been a significant shift in the nitrogen balance in the River Kennet system with increases in livestock, population levels and arable areas producing a major shift in nitrogen conditions. These new high nitrogen levels have been exacerbated by increased phosphorus concentrations to produce the ideal nutrient mix for algae, epiphyte and macrophyte growth, and this has led to the concern by conservation and angling interests within the River Kennet community. The River Kennet system is important on a national and international scale as the upper Kennet is designated a site of special scientific interest by English Nature, and also the Kennet contributes nitrogen to the River Thames and, hence, to the North Sea. Thus, EU and international conventions on nutrient controls on the North Sea are likely to have a future effect on nitrogen management in the River Kennet. Indeed, the EU Directive on Habitats will require the local authorities

Table 3
Land use change since 1931 in the Kennet catchment

	1931 Area km^2	1991 Area km^2	% Chance since 1931
Forest	126.9	37.9	−70%
Arable	292.1	697.8	+138%
Sveg fertilised	684.2	359.7	−47%
Sveg ungrazed	58.9	3.9	−93%
Sveg grazed not fertilised	1.7	64.9	+3654



	Flow	Nitrate-N	Ammonium-N
Mean	9.93	3.63	0.0493
Maximum	22.8	12.1	0.886
Minimum	3.57	1.35	0.00109
Median	10.3	3.75	0.00601
Range	19.2	10.8	0.885
Variance	15.7	2.06	0.0111
Standard deviation	3.97	1.43	0.105
Standard error	0.208	0.0751	0.00552
95%	17.7	6.44	0.256

Fig. 13. Frequency and cumulative distributions of simulated flow, nitrate and ammonium at Fobney for 1998.

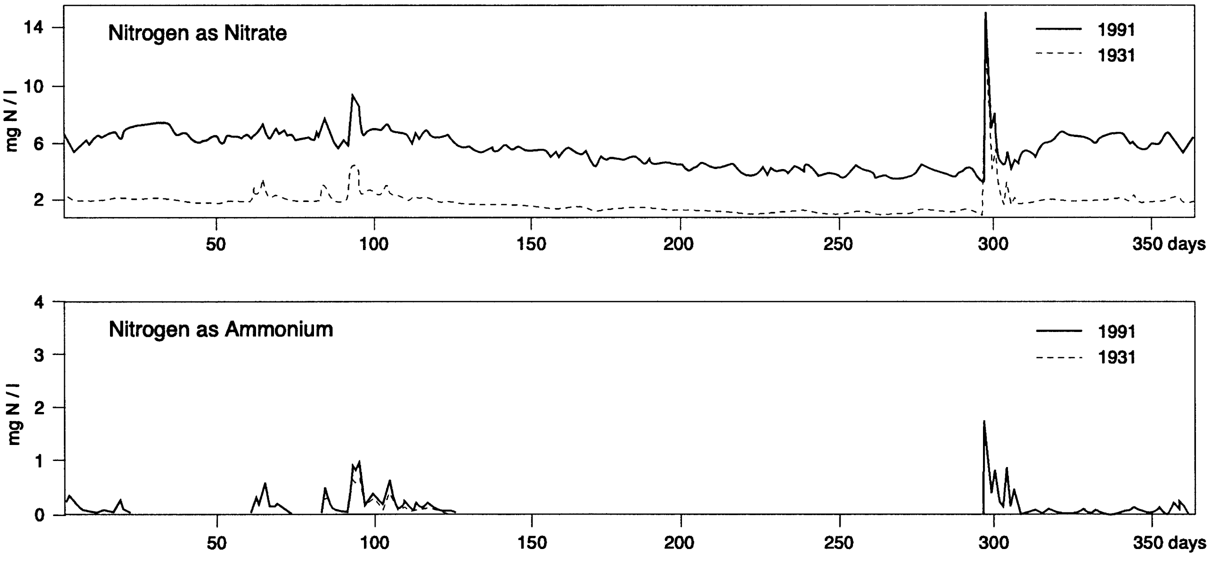


Fig. 14. Simulated nitrate and ammonium for 1931 and 1991 land use.

to control nutrient management so that habitats are restored to their previous status. How to define the natural state of the nutrients and, hence, the habitat of the river is an extremely difficult task, but models such as INCA can provide the necessary management tools to evaluate historical and future water quality conditions in the river.

References

Addiscott TM, Powlson DS. Partitional losses of nitrogen fertilizer between leaching and denitrification. J Agric Sci 1992;118:101–107.

Environment Agency. River Kennet Management Plan, 1994.

Environment Agency. Local environment agency plan for River Kennet, 2000.

Hart PBS, Powlson DS, Poulton PR, Johnston AE, Jenkins DS. The availability of the nitrogen in the crop residues of winter wheat to subsequent crops. J Agric Sci 1993;121:355–362.

Johnes PJ. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. J Hydrol 1996;183:232–349.

Limbrick KJ, Whitehead PG, Butterfield D, Reynard N. Assessing the potential impact of climate change scenarios on the hydrological regime of the River Kennet at Theale, Berkshire, south-central England, UK: an application and evaluation of the new semi-distributed model, INCA. Sci Total Environ 2000;251/252:539–556.

MAFF. Annual agricultural census returns: parish summaries. Kew, London: Public Records Office, 1866 to date, p. 125.

Meteorological Office. The MORECS system, hydrological memorandum No.45, 1981, p. 91.

Wade AJ, Whitehead PG, Hornberger GM, Jarvie HP, Flynn N. On modelling the impacts of P treated effluent in instream phosphorus and macrophyte dynamics: the River Kennet case study, Sci Total Environ 2002a;282–283: 395–415

Wade AJ, Whitehead PG, Hornberger GM. Low flow controls on the phosphorus and macrophyte dynamics of the River Kennet, Sci Total Environ 2002b;282–283:375–393.

Whitehead PG, Howarth SM, Neal C. The science and myth of hydrochemical and ecological change in the River Kennet, England: the Axford Public Enquiry. Hydrology in a changing environment, Volume 1. In: Wheater H, Kirby C, editors. Proc Br Hydrol Soc Int Conf, Exeter, July 1998. Chichester: John Wiley and Sons, 1998a:259–267.

Whitehead PG, Wilson EJ, Butterfield D. A semi-distributed integrated nitrogen model for multiple source assessment in catchments (INCA): part 1 model structure and process equations. Sci Total Environ 1998b;210/211:547–558.

Whitehead PG, Wilson EJ, Butterfield D, Seed K. A semi-distributed integrated nitrogen model for multiple source assessment in catchments (INCA): part 11 application to large river basins in South Wales and eastern England. Sci Total Environ 1998c;210/211:559–583.