Impacts of Climate Change on Nitrogen in a Lowland Chalk Stream: An Appraisal of Adaptation Strategies

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ABSTRACT

The impacts of climate change on nitrogen (N) in a lowland chalk stream are investigated using a dynamic modelling approach. The INCA model is used to simulate transient daily hydrology and water quality in the River Kennet using temperature and precipitation scenarios downscaled from General Circulation Model (GCM) output for the period 1961-2100. The three GCMs (CGCM2, CSIRO and HadCM3) yield very different river flow regimes with the latter projecting significant periods of drought in the second half of the 21st century. Nitrogen concentrations increase over time as higher temperatures enhance N release from the soil and lower river flows reduce the dilution capacity of the river. Particular problems are shown to occur following severe droughts when N mineralization is high and the subsequent breaking of the drought releases high nitrate loads into the river system. Possible strategies for reducing climate-driven N loads are explored using INCA. The measures include land use change or fertiliser reduction, reduction in atmospheric nitrate and ammonium deposition, and the introduction of water meadows or connected wetlands adjacent to the river. The most effective strategy is to change land use or reduce fertiliser use, followed by water meadow creation, and atmospheric pollution controls. Finally, a combined approach involving all three strategies is investigated and shown to reduce nitrate concentrations to pre-1950s levels even under climate change.

KEY WORDS

River Kennet, climatic change, water quality modelling, nitrate, ammonia, River Thames, land use change, atmospheric deposition, adaptation strategies.

Word count
5866

INTRODUCTION

The scientific consensus is that future increases in atmospheric greenhouse gas concentrations will result in elevated global mean temperatures with subsequent effects on regional precipitation, evapotranspiration, soil moisture levels and altered flow regimes in streams and rivers (Arnell *et al*., 2003, 2004, Wilby *et al*., 1994). Recent flood and drought episodes across Europe have highlighted the sensitivity of water resource systems to climate extremes. Superimposed upon any future climate change are other impacts of human activity, for example, the release of atmospheric pollutants such as oxides of nitrogen into the atmosphere (Skeffington, 2002), or the application of nitrogen based fertilisers onto the land surface (Whitehead, 1990). For example, recent estimates suggest that the nitrogen (N) flux to the North Sea has increased ten fold over the last 40 years (Howarth *et al*., 2002). Nitrogen inputs in intensive-agricultural catchments have been identified as the major causal factor driving trends of increased nutrient concentrations in surface, ground and coastal waters (Heathwaite *et al*., 2003, Worrall et al, 2003), although inputs from effluents and atmospheric deposition are also important. The latter particularly so in upland river systems where low background stream water N concentrations indicate a potential sensitivity to small changes in N inputs. Moreover nutrient over-enrichment of fresh and coastal waters is of concern because it can alter the competitive balance of aquatic species, sometimes leading to potentially toxic and unsightly algal blooms.

Integrating climate change, land use change and atmospheric deposition is particularly challenging because of numerous process interactions and differing effects of all the driving variables. However, all these processes and interactions are being considered by Eurolimpacs (www.eurolimpacs.ucl.ac.uk). The project is highly ambitious because, besides there being 38 partners across Europe and North America, the objective of the project is to not just to investigate stand alone impacts of climate change but to consider impacts simultaneously (e.g., changing land use and air pollution). As part of Eurolimpacs, impacts of climate change on hydrology and nitrogen are being investigated. During a previous EU project, INCA (Integrated Nitrogen Model for European Catchments) a sophisticated process-based flow and N model was shown to be applicable to all major European ecosystem types from the drier Mediterranean environments through temperate Atlantic and Continental systems to Arctic northern conditions. The major project findings reported to date are presented in a special volume of Hydrology and Earth System Sciences (Neal,2002, Wade et al., 2002a).

The first applications of INCA were assessments of the inputs of land use change and atmospheric deposition on N fluxes in catchments (Whitehead et al., 1998a;b; Wade et al, 2002b). The impacts of climate change on the hydrology of catchments were investigated by Limbrick et al. (2000), who found significant changes in lowland, southern UK catchments because of increased doughtiness. More recent analysis by Wilby et al (2005) suggests that water resource and nutrient yields could be significantly affected although there is considerable uncertainty in General Circulation Model (GCM) projections of regional climate (Jakeman et al,1993) and this uncertainty is translated into uncertainty in flow-dependent processes.

In this paper, we consider the nitrate-N and ammonium–N output from the INCA model driven by output from three GCMs under two greenhouse gas emission scenarios. This analysis is performed for the River Kennet under a range of conditions such as increased drought, enhanced microbiological activity, and changes in effluent discharge. Given the unavoidable impacts of climatic change, it is not too early to consider adaptation strategies to minimise impacts on river systems. To some extent this is already happening with water companies planning long term water resources to counter reduced summer flows through enhanced reservoir storage or water transfer schemes. From a water quality perspective there are several actions that could be taken to minimise N concentrations in streams and rivers and some of these are explored using INCA. The objective is to find a mix of strategies that could counter the impacts of climate change and achieve stable or reduced nitrogen concentrations in the River Kennet system in the UK.

THE RIVER KENNET SYSTEM

The Kennet is a major tributary of the River Thames, the principal river in the south east of England. The Kennet flows broadly west to east, with a catchment area of about 1200 km^2 and a main river length of about 40km. Altitude varies across the catchment from 215 m.a.s.l. (the source of the Kennet near Avebury) to 40 m.a.s.l. (the confluence of the Kennet with the Thames at Reading). The catchment is approximately 80 km from the south coast at the English Channel and about 100 km from London and the Thames estuary and the southern North Sea. Land-use within the Kennet catchment is largely rural and agricultural, with an underlying geology predominantly of Cretaceous Chalk.

This study focuses on the upper reaches of the Kennet, around the market town of Marlborough (Figure 1). The upper Kennet catchment is defined as the area draining into the Environment Agency gauging station at Knighton and receives runoff from two tributaries, the Rivers Og and Aldbourne. At Knighton (105 m.a.s.l.), the catchment area is 295 km^2, equating to ~25% of the total catchment area of the Kennet. The annual average rainfall for the upper Kennet is relatively low for the UK at 787 mm and, with high evaporation at around 520 mm, only about 34 % of the rainfall is converted to river flow (Institute of Hydrology, 1998). Owing to the highly permeable nature of the bedrock, the Kennet is primarily groundwater fed. Thus, the hydrograph response to rainfall is highly damped with a baseflow index of 0.95 for the upper Kennet (Institute of Hydrology, 1998; Johnes and Burt, 1993).

The upper River Kennet is designated a Site of Special Scientific Interest (SSSI) in recognition of its outstanding chalk river plant and animal communities.

Hence, there is keen interest in protecting the high conservation value of the river. In the last decade, there have been concerns about perceived ecological deterioration of the river, particularly poor growth of *Ranunculus* downstream of Marlborough, accompanied by unsightly growth of epiphytes. Attention has focused on the effects of protracted droughts in 1991/2 and 1996/7, water abstraction pressures, and declines in water quality associated with reduced dilution of effluent from Marlborough water treatment works (WTW). The Kennet, thus, provides a good case study because it has been the focus of previous investigations on climate change and land-use change (Limbrick et al., 2000; Wade et al., 2002a; Whitehead et al., 2002a), and is data-rich due to the legacy of an extensive water quality monitoring network (Figure 1).

THE INCA MODEL

The INCA model is designed to investigate the fate and distribution of N in aquatic and terrestrial environments (Whitehead, et al., 1998a; b). The model simulates flow, nitrate-N and ammonium-N and tracks the flow paths operating in both the land phase and riverine phase. The model is dynamic in that day-to-day variations in flow and N can be investigated following a change in input conditions such as atmospheric deposition, sewage discharges or fertilizer addition. INCA can also be used to investigate changes 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 N uptake by vegetation.

The hydrological component of the INCA model provides information on the flow moving through 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-N and ammonium-N in both the soil and groundwater zones. The key processes that require modelling in the soil zone 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 vary by land use type so generalised equations are employed, supported by different parameter sets for each land use. The land phase model also accounts 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). In addition, 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.

INCA is 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 vary input N deposition loads. The following outputs are provided:

- Daily time series of flows, nitrate-N and ammonium-N concentrations at selected sites along the river;
- Profiles of river flow and N concentrations at selected times;
- Cumulative frequency distributions of river flow and N at selected sites;
- Tables of statistics for all sites;
- Daily and annual N loads for all land uses and all processes.

Detailed descriptions of the models and their applications, including calibration and testing are reported in Whitehead et al. (1998a; b) and Wade et al. (2002a;b).

GCMS AND DOWNSCALING METHODOLOGY

Three GCMs were used to construct climate change scenarios: the Hadley Centre's coupled ocean/atmosphere climate model (HadCM3), the Canadian Centre for Climate Modelling and Analysis model (CGCM2), and the Australian Commonwealth Scientific and Industrial Research Organization model (CSIRO Mk2). Downscaling of the GCM output to the River Kennet was accomplished using the Statistical DownScaling Model (SDSM) (Wilby et al., 2002). Data for calibrating SDSM were obtained from the National Center for Environmental Prediction (NCEP). The archive of NCEP and GCM output contains 29 daily predictors for nine regions covering the British Isles, for the period 1961–2100. In the present study, only predictors from grid-boxes centred on southeast England (SEE) were employed for the A2 (Medium-High Emissions) and B2 (Medium-Low Emissions) scenarios of the IPCC Special Report on Emission Scenarios (SRES).

Statistical downscaling future climate change scenarios for the River Kennet involved two main steps. First, empirical relationships were established between the target variables of interest (i.e., daily temperature, precipitation amounts and potential evaporation across the catchment) and large-scale indices of regional weather over SEE obtained from the NCEP re-analysis for the *current* climate. These relationships were then used in the second step to downscale ensembles of the same local variables for the *future* climate, using data supplied by the three GCMs driven by the two emission scenarios for the full period 1961-2100. The procedures for downscaling GCM output are explained in detail by Wilby et al. (2005), alongside an anlysis of impacts on evaporation, soil moisture, flow and groundwater in the Kennet catchment.

Wilby et al. (2005) found that, overall, CGCM2 yields the largest increases in river flow for both emission scenarios (Table 1). The scenarios downscaled from CSIRO produced less dramatic changes than CGCM2 but still signify river flows close to, or greater than baseline conditions from the 2050s onwards. In contrast, the HadCM3 scenarios suggest relatively small changes in mean annual flows (Table 1) but large reductions to summer flows of ~20%, and autumn flows by ~50% in the

2080s, as show in Figure 2. These flow reductions imply increased droughts in the 2080s that could have significant impacts on water quality. All GCMs yield larger changes in river flow in the upper than lower Kennet.

APPLICATION OF INCA TO THE RIVER KENNET

The INCA model has been applied to the River Kennet in previous studies to evaluate current and historic N behaviour (Whitehead et al., 2002a) as well as the impacts of climate change on hydrology (Limbrick et al, 2000). In this paper we apply the INCA model version set up for the Kennet to simulate the transient behaviour of daily river flow, N and ammonium for the three GCMs under A2 and B2 emission scenarios. As in the investigation of water resources (Wilby et al, 2005), GCM outputs were downscaled to the River Kennet and model runs performed for the whole 140 year period from 1961-2100 on a daily basis.

Daily dynamics are important when considering water quality because of the many processes such as mineralisation and nitrification that affect N which are dependent on variables such as daily temperature, soil moisture conditions, rainfall and flow. INCA was set up to simulate a ‘natural’ reach in the upper Kennet and a second lower reach receiving effluent from Marlborough sewage works. This is of interest because of the concern in the Kennet about the water quality and ecology of this section of the river. An additional model run was performed in each case to allow for the likely increased bacterial populations that may occur with climatic change. As temperature increases, bacterial populations controlling N mineralisation and nitrification processes in soils will increase and this will raise the process rate coefficients resulting in increased nitrate and ammonia. There is some historical evidence of this already as Wright et al (1998a,b) have shown for catchments in Wales and Norway, and Whitehead et al. (2002b) have shown for the Tillingborne, another tributary of the Thames.

Figure 3 shows typical output from INCA with the simulated flow, nitrate (as N) and ammonium (as N) in the upper ‘natural’ reach of the river with the control run in blue and the enhanced bacterial population run in green. The blue curves show the nitrate and ammonia response to the CGCM2 scenario under A2 emissions. Concentrations rise over the 140-year period due to the dual effects of increased temperature and decreased summer flows, although the nitrate concentrations stabilise in the 2060s and even decline in the 2080s as river flows increase under this scenario. The green lines in the nitrate and ammonia plots indicate the effects of increasing the bacterial populations and, hence, the nitrification rate coefficient. In this case the ammonia is converted more rapidly to nitrate and thus ammonia levels fall but nitrate increases. Figure 4 shows the same simulations but for the lower reach, affected by an effluent discharge. The effluent discharge generally raises nitrate and ammonia concentrations in the river, as might be expected. The effects of climate change appear to be similar to Figure 3 with increasing nitrate and ammonia over the duration of climate change but with the enhanced bacterial populations having a more significant effect, raising nitrate concentrations and reducing ammonia concentrations.

Tables 2 and 3 present changes in mean annual nitrate and ammonia concentrations for the three GCMs under the A2 and B2 scenarios. All changes were estimated with respect to the concentrations produced by each GCM for the 1961-1990 baseline. Overall, there are significant increases in nitrate and ammonia during the 21st century despite increases in average flow (Table 1). Higher temperatures and the enhanced microbial activity drive much of the increase. This is particularly evident for the effluent affected reach, where nitrate levels approach the EU limit of 11.3 mg/l for all three GCMs. In the case of HadCM3 the 95th percentile (C95) nitrate concentration exceeds this limit, indicating potential problems for water supply.

Figures 5 and 6 show time series of the C95 outputs for the upper reach with the CSIRO and CGCM2 scenarios yielding rising concentrations of nitrate and ammonia until the 2050s, and a decline in nitrate thereafter. However, HadCM3 generates rising nitrate with large extremes occurring towards the end of the century. The final peak in nitrate-N is of the order of 11 mg/l and even higher when the effects of enhanced nitrification are taken into account (dotted blue line in Figure 5). This increased nitrate is caused by a sustained drought period projected by HadCM3 in the last decade of the simulation. A sequence of dry summers generates a build up of nitrogen in the soil that is flushed out of the catchments into the streams when the drought breaks. High concentrations of nitrate have occurred previously as indicated by Figure 7 which shows the observed nitrate values recorded at Teddington Weir on the Thames (i.e., downstream of the Kennet) since 1930. Concentrations at the end of the drought year of 1976 reached similar levels to the drought extremes predicted by INCA. Whilst 1976 was an extreme year, HadCM3 suggests that we may experience more such drought sequences in the future and hence INCA generates nitrate levels that are plausible. Extended periods of high nitrates could create problems for the water industry because of the need to maintain public water supplies with nitrate-N below the EU legal limits of 11.3 mg/l. Also, there are implications for export of nitrate to coastal ecosystems and downstream impacts such as enhanced eutrophication.

APPRAISAL OF ADAPTATION STRATEGIES

Although the impacts of climate change are significant with respect to N (certainly if HadCM3 is correct about future lower flows) it is possible to consider a range of strategies for ameliorating the effects. The INCA model provides a means of testing alternative adaptation strategies and these can be assessed alongside policy outcomes such as land use change due to EU CAP reform, or lower atmospheric deposition of nutrients as a by-product of the EU Emissions Trading Scheme. The model was run using representations of three interventions: 1) reduced fertiliser application rates/land use change; 2) reduced atmospheric deposition rates for nitrate and ammonia; and 3) river water quality management via the creation of water meadows or connected wetland areas. All these changes can be simulated by altering parameters within the model (e.g., fertiliser application rates, N deposition rates and, in the case of the water meadows, by changing the instream denitrification rate). In each case, climate change scenarios downscaled from the A2 emissions run of HadCM3 were utilised as this represents the worst case from the range of GCMs considered (see Figures 5 and 6).

Water meadows behave like natural shallow reservoirs. They increase the residence time of water, have higher water temperatures, and increase the surface area of water exposed to sediments. These are ideal conditions for denitrifying bacteria to convert nitrate-N in the water column, to nitrogen gas and nitrous oxide, a greenhouse gas, in the anaerobic zone of the sediments. This mechanism is built into the INCA river reach component as a first order process dependant on temperature, residence time and area of bed in contact with the water. This process-based model has been widely confirmed as a suitable method of simulating N loss in lakes, reservoirs and streams (Whitehead, 1993; Chapra, 1997). Thus, by increasing the denitrification rate in the model it is possible to effectively simulate the enhanced denitrification effects associated with water meadow creation.

Reduced fertiliser application or land use change

In order to investigate the effects of adaptation strategies a set of simulation runs were produced assuming a 50% reduction in fertiliser use or the equivalent of converting 50% of the land to set aside or some other non-fertilised use (e.g., forest plantation- see Whitehead et al, 2004). The nitrate and ammonia effects are shown in Figures 8 and 9 for the upper ‘natural’ reach of the Kennet and the lower effluent affected reach respectively. The effects in the upper reach are dramatic with significantly reduced nitrate-N levels over time compared to the control run, declining to an annual mean concentration of ~3 mg/l as nitrate-N. This is similar to the levels in the River Thames in the 1940s (see Figure 7 above). In the effluent affected reach the decay of nitrate is also significant but the concentrations stabilise at ~4 mg/l, the levels being artificially raised by the direct effluent discharge. The ammonia levels also fall reflecting the lower nitrate concentrations and, hence, the reduced nitrification conversion occurring.

Reduced atmospheric deposition

The second set of simulations involved reducing the wet and dry nitrate and ammonia in the atmospheric deposition source. The results shown in Figures 8 and 9 for the two reaches are obtained by assuming that the deposition is reduced by 50% (i.e., a change form 14.9 kg/ha/year of N to a level of 7.45 kg/ha/year). In this simulation, enhanced bacterial activity yields relatively small reductions in nitrate-N and ammonium-N in the natural and effluent affected reaches. However, the levels do reduce by about 0.5 mg/l for nitrate-N and about 0.05 mg/l for ammonium-N, even for this drought prone scenario.

Creation of water meadows

The third simulation assumes that the river system is altered by the development of upland water meadows. This involved changing the effective surface area of the River Kennet fourfold so that the denitrification rate is a factor of four times higher. The effect of this is an average reduction of ~2 mg/l nitrate-N (Figure 8). Note that water meadow creation does not affect ammonium concentrations, as the water meadows tend to enhance denitrification, which converts the nitrate directly to nitrogen gas and nitrous oxide. Whilst the meadows did not fully counter the effects of climatic change or N from fertilisers, the effect is significant. The wetland strategy has to be considered carefully, however, as during drought years it might not be possible to divert river flows across wetlands due to lower in stream volumes, and increased stress on river ecology. On the other hand, wetlands could act as a sink for first flush of nitrates from terrestrial systems when droughts break.

Multiple interventions

Finally, a simulation that considers all three effects simultaneously is shown in Figures 8 and 9. Here, fertiliser applications have been reduced by 25%, the N deposition from the atmosphere has been reduced by 25% and the water meadows have been set to double the effective surface area of the Kennet. The results for both the upper reach and the effluent affected reach indicate a reduction of nitrate-N to about 4 mg/l (Figures 8 and 9), a significant improvement over the longer term. Perhaps more importantly peak values during drought conditions were significantly reduced implying that nitrate in public water supplies could be maintained below the existing EU and WHO limit of 11.3 mg/l of nitrate-N (Figure 8b). Ammonia levels also fall slightly in the combined strategy.

Tables 4 and 5 summarise the water quality changes arising from each adaptation measure by the 2020s, 2050s and 2080s. In all cases, adaptation yields water quality improvements relative to the non-intervention (control) situation. Furthermore, the benefits may be realised as early as the 2020s. Larger changes for ammonium in the upper Kennet reflect low initial concentrations for the baseline period; actual incremental changes were comparable to the effluent affected reach.

CONCLUSIONS

Simulation models such as INCA are useful tools for investigating the impacts of climate change and potential adaptation strategies. Such models offer the only effective way of accounting for all the non-linear behaviour in river systems. Interactions between hydrology, residence times, reaction kinetics, as well as natural and human influences, ensure that prediction is particularly difficult. INCA provides a tool for incorporating all these effects and shows climate to be a significant driver of changes in surface flow, groundwater and water quality in the upper River Kennet (Wilby et al, 2005). This paper examines the effects of climate change on ‘natural’ and ‘effluent affected’ reaches, for a range of hypothetical adaptation measures.

The likely effects on peak nitrate following drought periods are especially of interest because of the effects of N on the biological diversity of streams, and the requirement for public water supplies to meet EU water quality standards. Nitrogen in rivers originates from a variety of sources and is removed or converted to other forms of N via a range of processes. These mechanisms were manipulated in order to explore ways of countering the effects of climatic change. Options included reducing nitrogen fertilisers (either by reducing application rates or by taking land out of production), reducing N deposition from the atmosphere, and recreating water meadows along the Kennet to enhance natural denitrification processes. Despite significant, climate-driven changes to the flow regime, this set of measures could reduce nitrate–N in the river system to below 4 mg/l, a level not seen in the Kennet since the 1950s.

One major problem with any long-range projection such as that those presented here is that of uncertainty. Uncertainty about the future emission pathway had a modest effect on water quality even for the 2080s. However, even from a relatively small sample of GCMs it is evident that different climate models yield very different water quality projections and, by implication, different levels or timing of adaptation. There are also inherent uncertainties in the process parameters incorporated in impact models and this uncertainty needs to be reflected in projections (Wilby, 2005). As part of Eurolimpacs there will be an assessment of these uncertainties so that confidence bounds on future predictions can be better estimated. It is also recognised that the range of potential adaptation measures considered was far from exhaustive. Other options include the introduction of buffer strips, or deliberate degradation of land-drainage systems to reduce hydrologic connectivity between the land and river. Differences in the responsiveness to adaptation measures of the upper and lower reaches also merit further investigation.

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Table 1 Percentage changes in mean daily flow in the Upper and the Lower River Kennet projected by three GCMs under A2 and B2 emission scenarios. All changes are calculated with respect to the 1961-1990 baseline of each model.

	A2			**B2**		
	CGCM2	**CSIRO**	**HadCM3**	**CGCM2**	**CSIRO**	**HadCM3**
Upper						
2020s	15	6	0	29	12	5
2050s	36	15	2	29	19	6
2080s	54	33	-3	47	28	4
Lower						
2020s	13	5	0	26	11	5
2050s	33	14	2	26	18	5
2080s	48	30	-3	42	26	4

Table 2 As Table 1 but for nitrate-N concentrations.

	A2			**B2**		
	CGCM2	**CSIRO**	**HadCM3**	**CGCM2**	**CSIRO**	**HadCM3**
Upper						
2020s	24	18	19	22	18	19
2050s	30	25	27	29	26	25
2080s	32	26	33	34	28	29
Lower						
2020s	16	14	15	13	13	15
2050s	20	19	21	19	19	19
2080s	20	18	27	22	20	23

Table 3 As Table 1 but for ammonium-N concentrations.

	A2			**B2**		
	CGCM2	**CSIRO**	**HadCM3**	**CGCM2**	**CSIRO**	**HadCM3**
Upper						
2020s	61	69	67	64	69	68
2050s	92	100	98	86	102	98
2080s	113	120	122	107	121	120
Lower						
2020s	3	13	16	-1	10	15
2050s	1	17	23	4	15	22
2080s	1	15	31	2	16	28

Table 4 Percent changes in mean nitrate-N concentrations for different adaptation strategies compared with the no intervention (control). All changes were derived from the HadCM3 A2 emissions scenario and calculated with respect to the 1961-1990 baseline.

	Control	Fertiliser	Deposition	Meadows	Combined
Upper					
2020s	19	-27	10	14	-11
2050s	27	-37	15	19	-15
2080s	33	-44	19	23	-14
Lower					
2020s	15	-21	9	10	-9
2050s	21	-29	12	14	-11
2080s	27	-33	16	17	-13

Table 5 As Table 4 but for ammonium-N concentrations.

	Control	Fertiliser	Deposition	Meadows	Combined
Upper					
2020s	56	46	39	56	45
2050s	84	70	58	84	66
2080s	107	89	70	107	102
Lower					
2020s	12	9	8	12	8
2050s	17	14	11	17	14
2080s	24	19	13	24	17

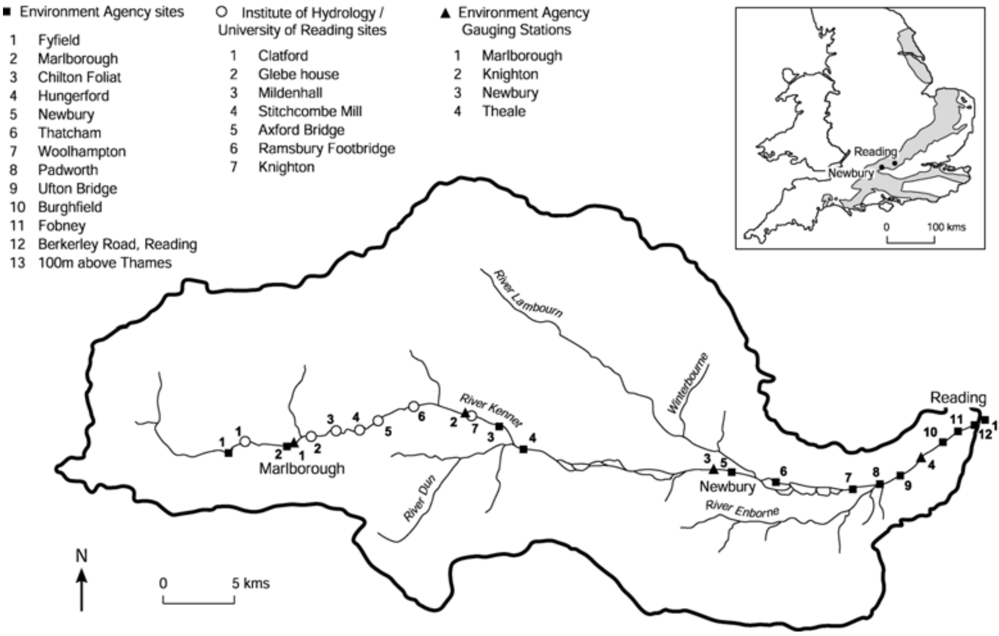

Figure 1 River Kennet catchment with the inset map shows the location of Cretaceous Chalk in England. Earlier studies established weekly monitoring programmes throughout the catchment with samples taken by the University of Reading, CEH Wallingford and the Environment Agency.

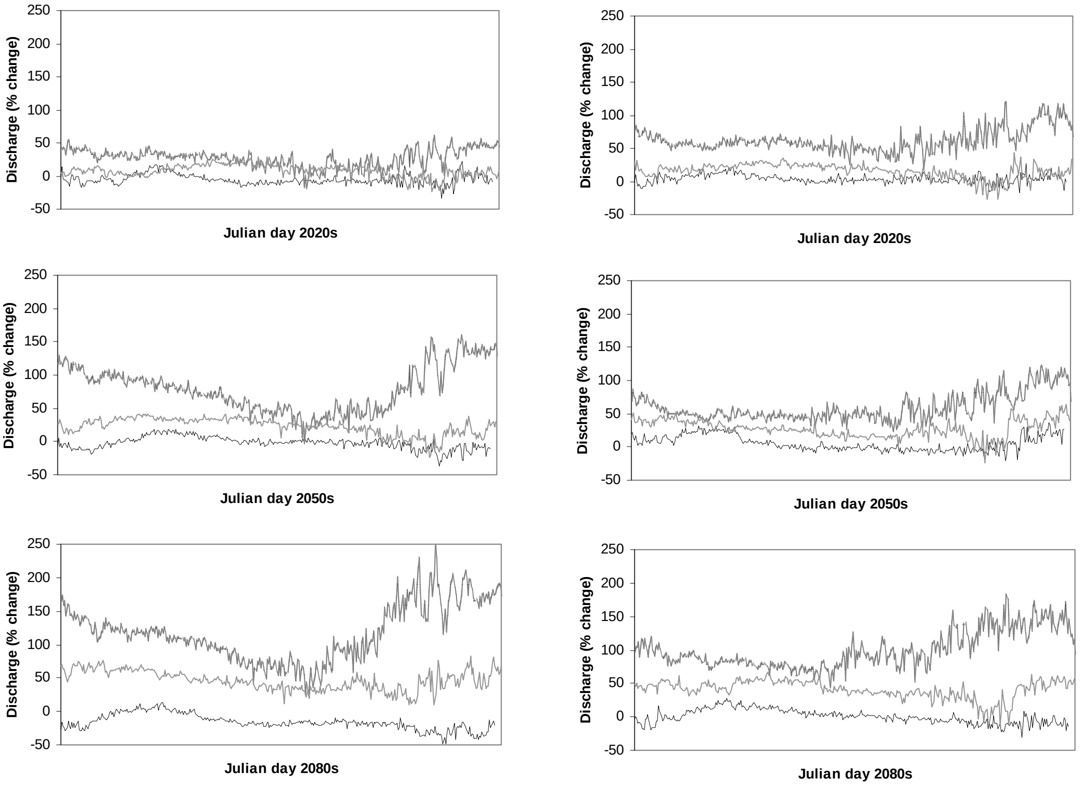

Figure 2 Percent changes in the daily discharge of the River Kennet by Julian day under A2 (left column) and B2 (right column) emissions downscaled from three GCMs (HadCM3 [black line], CGCM2 [dark grey line], and CSIRO [light grey line]) in the 2020s, 2050s and 2080s. Source: Wilby et al. (2005).

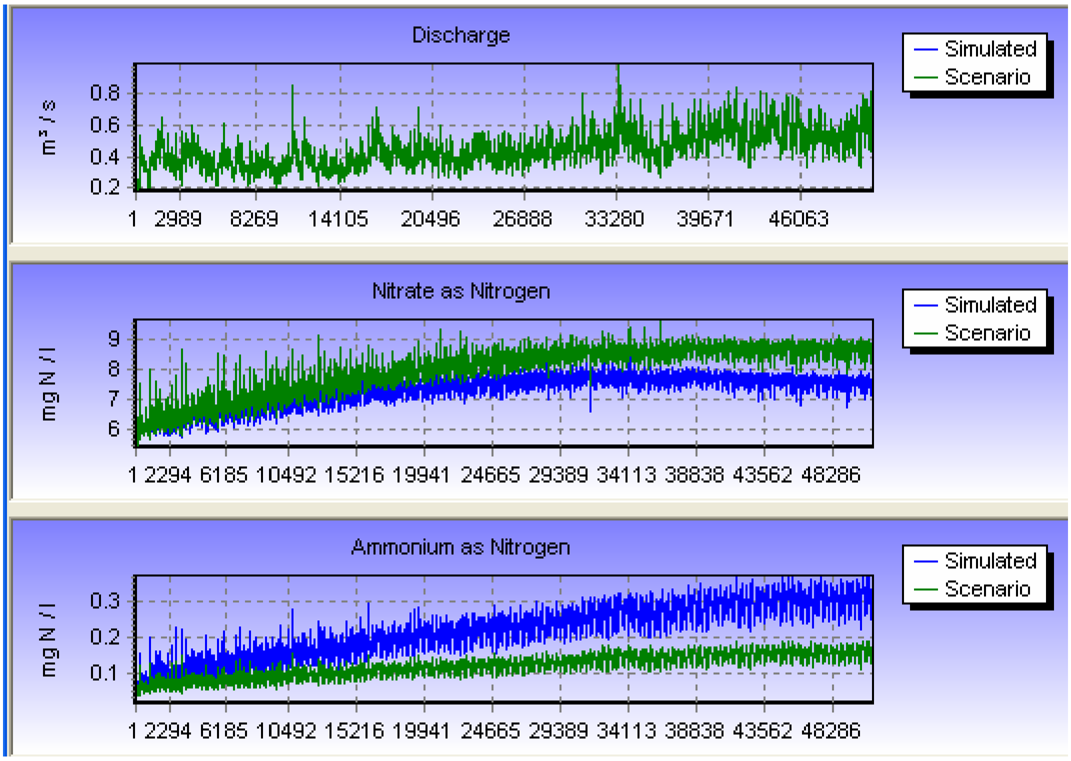

Figure 3 Daily flow, nitrate and ammonium concentrations simulated for the upper Kennet over the years 1961-2100 using CGCM2 under the A2 emissions scenario.

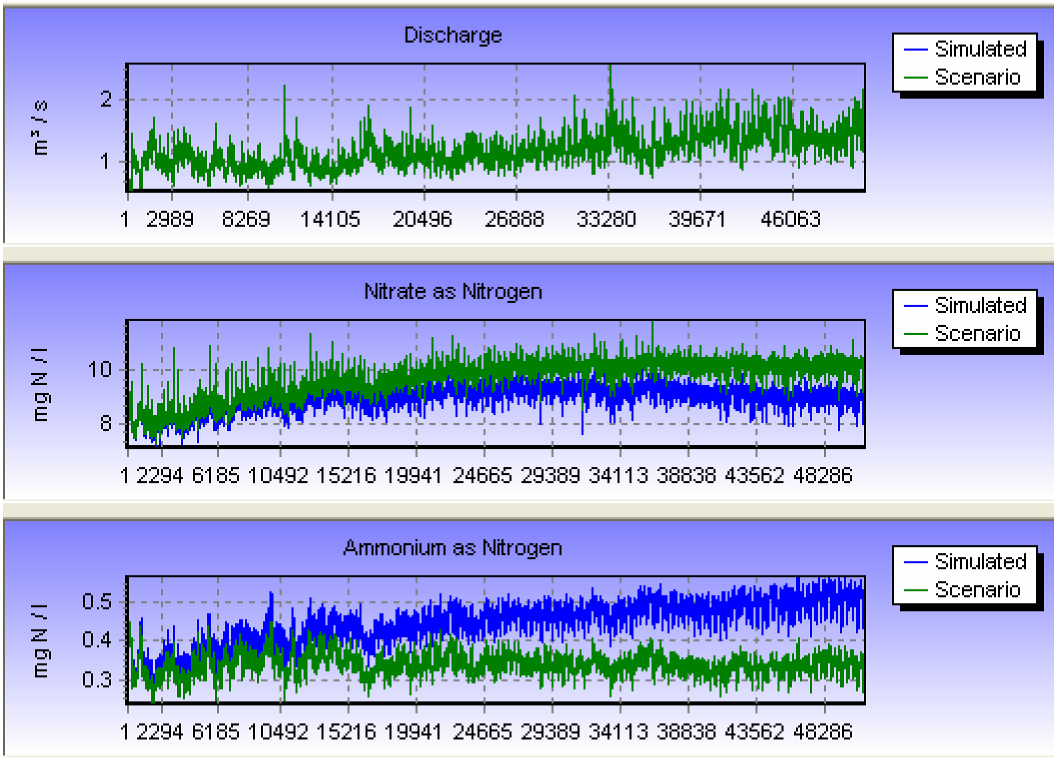

Figure 4 As Fig.3 but for the lower Kennet.

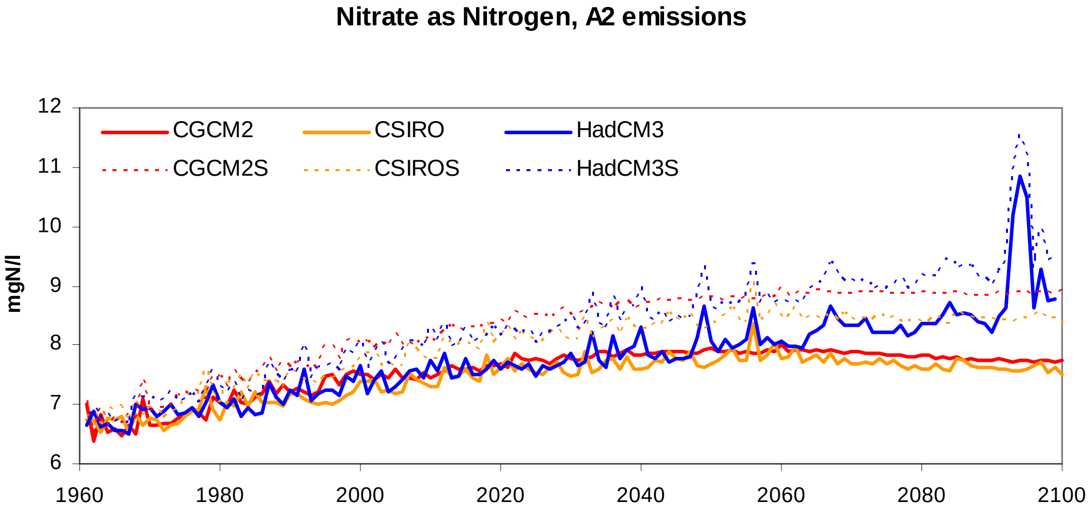

Figure 5 Effect of climate change on 95th percentile (C95) nitrate- N concentrations with (dotted line) and without (solid line) enhanced nitrification.

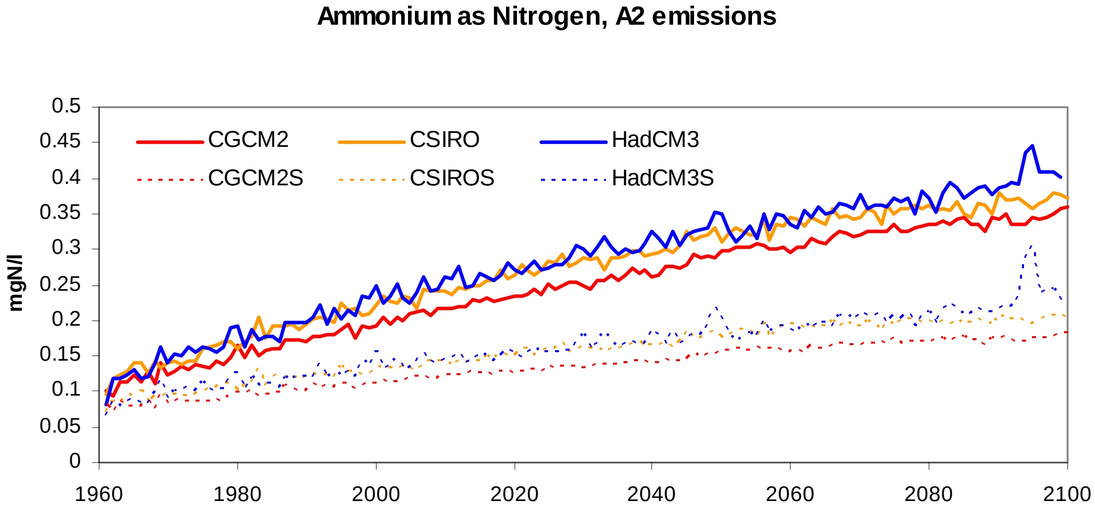

Figure 6 As Fig.5 but for ammonium-N concentrations.

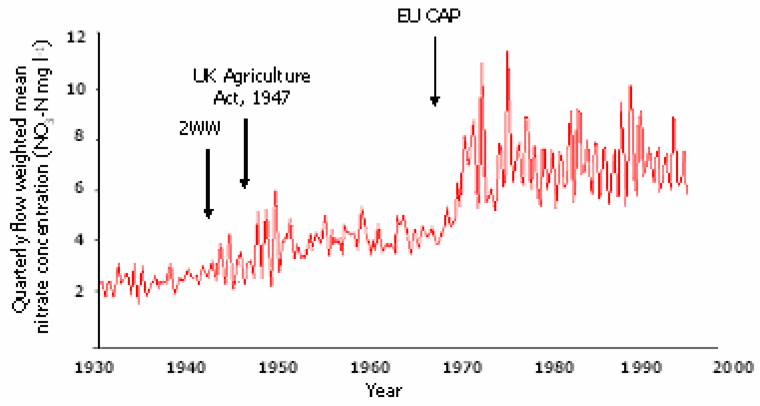

Figure 7 Long-term trends in nitrate enrichment in the River Thames, 1930-2000. Source: Data from Thames Conservancy, Thames Water Authority and Environment Agency).

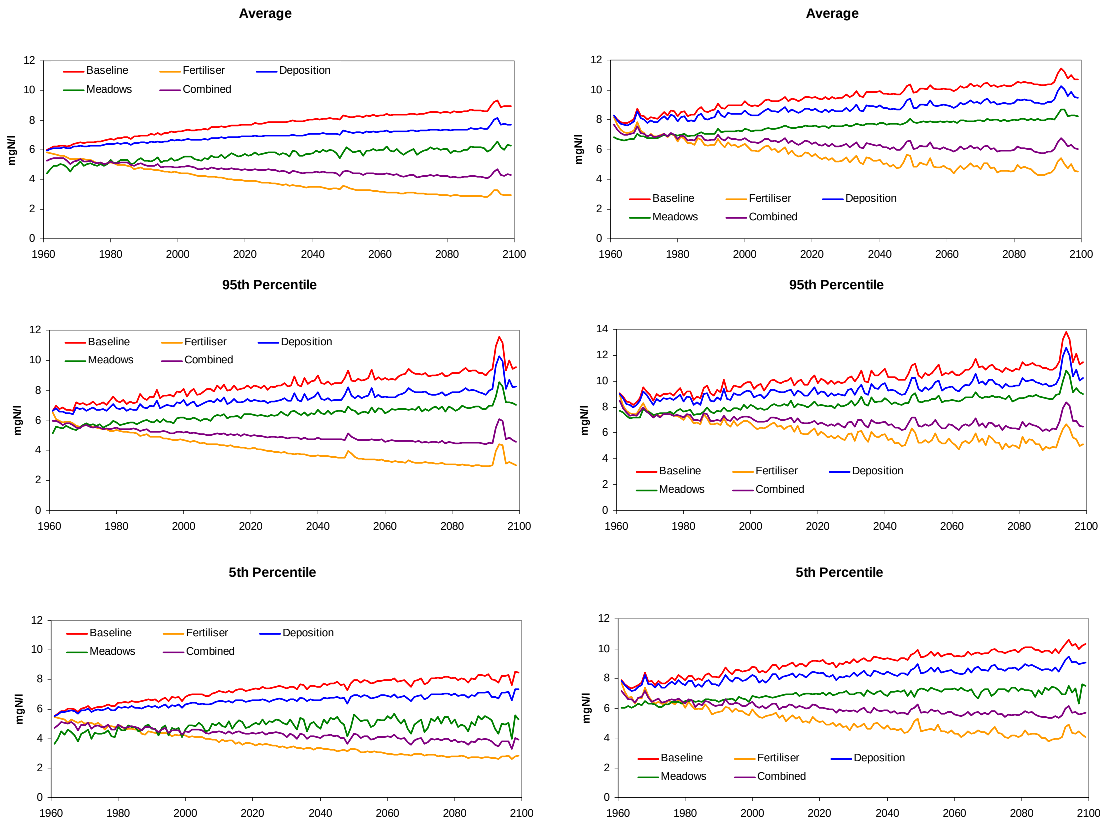

Figure 8a Adaptation runs using HadCM3 and A2 emissions showing nitrate impacts in the upper 'natural' reach (left column) and in the lower 'effluent affected reach' (right column) for 1961-2100. The runs represent baseline conditions, fertiliser reduction, N deposition reduction, water meadow creation, and a combined strategy.

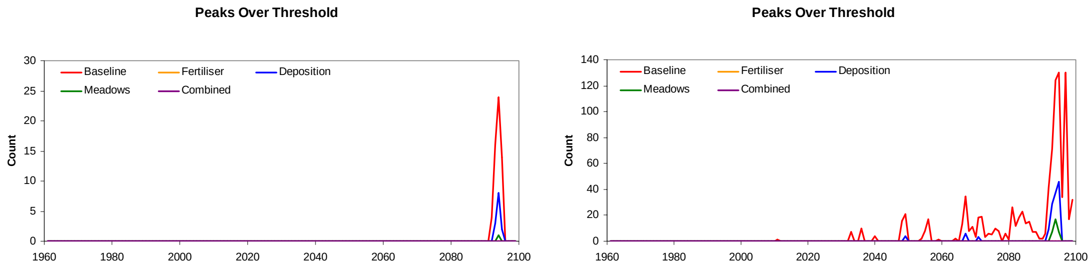

Figure 8b As Fig. 8a but for annual peaks over threshold (11.3 mg/l).

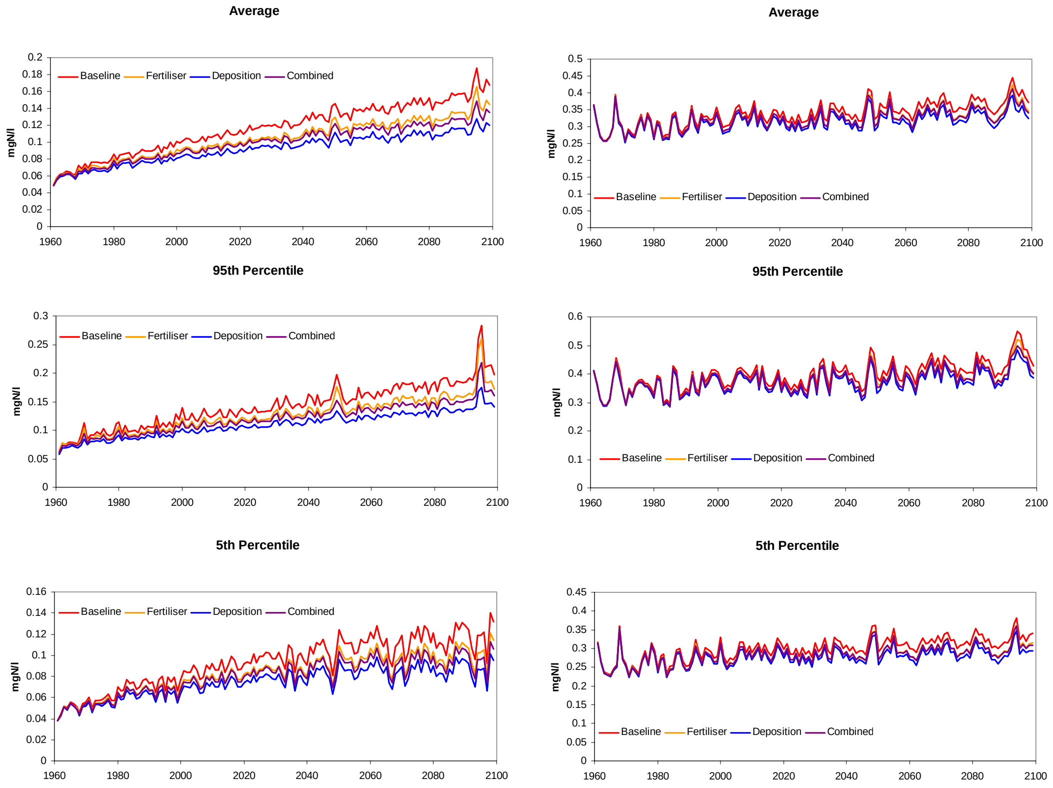

Figure 9 Adaptation runs using HadCM3 and A2 emissions showing ammonia impacts in the upper ‘natural’ reach (left column) and in the lower ‘effluent affected reach’ (right column) for 1961-2100. The runs represent baseline conditions, fertiliser reduction, N deposition reduction, water meadow creation, and a combined strategy.