Modelling the impacts of climate change on flow and nitrate in the River Thames: assessing potential adaptation strategies

Li Jin, Paul G. Whitehead, Martyn N. Futter and Zunli Lu

ABSTRACT

The catchment of the River Thames, a principal river system in southern England, is densely populated and highly vulnerable to changes in climate, land use and population. In order to predict its vulnerability to climate change, the Integrated Catchments Model for Nitrogen (INCA-N) has been applied to the whole of the River Thames. The model was calibrated from 1999 to 2006, to simulate streamflow and nitrate (NO_3-N) concentrations. Despite the highly variable land use and river flows within the catchment, INCA-N reproduced both the hydrological regime and NO_3-N dynamics in the river. A sensitivity analysis was performed on measured flow and in-stream nitrogen transformation rates. It showed that simulated NO_3-N concentrations were sensitive to denitrification rates and flow velocity. Measured parameter values were generally within the range of behavioural model simulations. Temperature and precipitation scenarios from the UK Climate Projections 2009 climate model outputs were used to project possible future flow and NO_3-N concentration changes. Results showed generally drier hydrological conditions, increased river NO_3-N concentration in winter and decreases in summer. An assessment of the planned new reservoir at Abingdon showed that, if managed appropriately, it may help offset the impact of climate change on riverine NO_3-N concentrations and London's water supply.

Key words | catchment hydrology, climate change, nitrate, river flow

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INTRODUCTION

The 2007 IPCC Fourth Assessment Report confirmed the consensus amongst scientists and policy makers that human induced climate change is occurring and that regardless of future greenhouse gas emission reductions, substantial climate change is unavoidable. One of the most significant effects of climate change is on the hydrological cycle (Gleick 1987; Wilby *et al.* 1994). Extreme hydrological events in the UK during the past decades have reflected the vulnerability of our water resource systems to climatic fluctuations (Marsh & Sanderson 1997; Marsh 2007).

The UK Climate Projections 2009 (UKCP09) is the latest climate model output and is the fifth generation of climate information for the UK. It provides climate change projections with greater spatial and temporal detail and is the first dataset which gives probabilistic projections of future climate change (Murphy *et al.* 2009). UKCP09 reports that by the 2080s under the medium emission scenario, all areas of the UK will become warmer relative to 1961–1990 baseline conditions. Summer mean temperature in parts of southern England could increase by 4.2 °C at the 50% probability level. Precipitation patterns are projected to change significantly with more precipitation in winter (up to +33% change at the 50% probability level) and less precipitation in summer (down by −40% in the south of England at the 50% probability level). These probabilistic data are available for 23 river regions in the UK. Changes are given for seven future 30-year time period with 10 years overlapping, covering the 2020s (2010–2039) and the 2080s (2070–2099), each with low, medium and high emission levels.

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According to UKCP09, southern England could suffer the most from the effects of increased annual mean temperature and less summer precipitation. The River Thames is the major river system flowing through southern England, and supplies about two thirds of London's water from the main abstraction at Datchet on the lower Thames. The Thames catchment is highly vulnerable to future changes in climate, land use and population. Public water supplies may become more vulnerable to drought and more people may be at risk from flooding. Aquatic ecosystems in the Thames and tributaries such as the Kennet will be placed under greater stress in warmer summers with high rates of water abstraction. In addition, sea-level rise may threaten the lower part of the Thames basin (WWF 2008).

Low flows and elevated nitrogen (N) loading from point and non-point source pollution in the Thames have been a significant problem in the past (Whitehead 1990; Neal *et al.* 2006). In the future, drier conditions could occur more frequently in lowland southern UK catchments and these will not only affect water supply but will also cause significant changes in water quality (Jin & Whitehead 2010).

There is a considerable literature on projected climate change effects in the Thames River basin. There are several studies of possible changes in water quantity (Arnell & Reynard 1996; Wilby 2005; Cloke *et al.* 2010), flood risk management (Lavery & Donovan 2005) and potential policy responses (Lonsdale *et al*, 2008). However, with the exception of Whitehead *et al.* (2006, 2009b), there have been relatively few studies of the possible effects of climate change on water quality in the Thames River basin.

The Integrated Catchments model (INCA) was first developed for the assessment of multiple sources of N in catchments (Whitehead *et al.* 1998a, b). The model is process based and uses reaction kinetic equations to simulate the main processes operating. INCA is a dynamic, mass-balance model, and as such can track the temporal variations in the hydrological flowpaths, transformations and stores, in both the land and in-stream components of a river system. The model can be applied to any catchment as a semi-distributed simulation and has an inbuilt multi-reach structure for river systems. INCA has been applied to assess nutrient and solute cycle and storage (Limbrick *et al.* 2000; Langusch & Matzner 2002; Futter *et al.* 2007; Whitehead *et al.* 2009a). It has also been used to investigate the effects of different climate scenarios and adaption strategies (Limbrick *et al.* 2000; Whitehead *et al.* 2006; Hadjikakou *et al.* 2011). The short-term time steps (daily mass balance) and capability of using output from climate model scenarios make INCA suitable for assessing climate impacts on water flow and water quality.

In this paper, INCA-N was applied to the whole River Thames basin to assess temporal variation in flow and N dynamics, model sensitivity to in-stream processes; and to examine the possible impacts of climate change on river flow, water availability and nitrate (NO_3-N) concentration. Near future (2020s time period) and far future (2080s time period) temperature and precipitation scenarios at the medium emission level from the UKCP09 climate model outputs were used. The potential for a proposed reservoir at Abingdon on the River Thames to minimize the impact of climate change induced low flows and provide the sufficient and good quality water supply downstream to London was also assessed.

STUDY SITE AND METHODS

The River Thames system

The River Thames is a principal river in southeast England and drains approximately 10,000 km^2 (Figure 1). The river starts in the Cotswold Hills of Gloucestershire and runs through major cities including Oxford, Reading and London before eventually discharging into the North Sea. The geology in the region is mainly of permeable chalk and low permeability clays. The water quality is characterized by high pH and high base cation concentrations where chalk aquifers are present. The mean annual flow (1999–2008) ranges from about 1.5 m^3 s^{-1} at Cricklade, to 33.5 m^3 s^{-1} at Days Weir and 65.5 m^3 s^{-1} at Teddington (Figure 1). Seasonally, high flows normally occur in the winter and early spring (January to April) and low flow occurs in the summer and late autumn (July–November). On average, the base flow index (BFI) ranges between 0.65 and 0.70, indicating a significant groundwater component. Average rainfall for the catchment is 700 mm year^{-1} (1961–1990 record) at Teddington. The catchment is predominantly rural in the upper reaches and becomes more

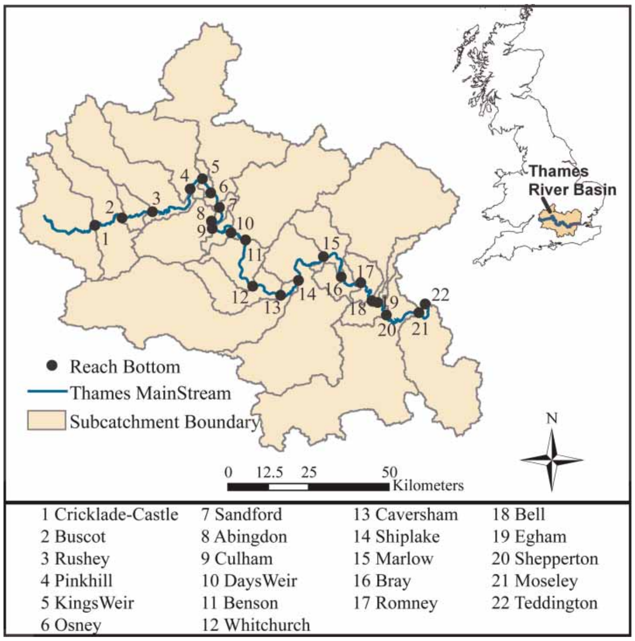

Figure 1 | Map of the Thames catchment showing the reach and sub-catchment boundaries.

urban further downstream (Table 1). There are many flow and water quality monitoring stations along the river system (Table 1). Flow and water quality data collected by Environment Agency over the past decades have been used in this study.

The INCA-N model

INCA-N is a process-based model which simulates flow and the NO_3-N and ammonium (NH_4-N) concentrations in soil, groundwater and in-stream (Whitehead *et al.* 1998a, b; Wade *et al.* 2002). It has both a land component and a river component, allowing it to track N inputs which flow into the river from throughout the catchment (Flynn *et al.* 2002). INCA-N is semi-distributed and takes some account of spatial variations in land use, vegetation and hydrology by dividing the catchment into sub-catchments (Wade *et al.* 2002). Each sub-catchment area is described as six different land use percentages. Hydrology in each corresponding reach is characterized by specifying the a and b parameters of the velocity–flow relationship, $V = aQ^b$, which is used to calculate residence times within each reach. The model then sequentially integrates N inputs to each reach and can also consider point effluents such as sewage discharges (Whitehead *et al.* 2002). The model is dynamic as it calculates variations in flow, N fluxes and N concentrations on a daily time scale (Whitehead *et al.* 1998a). The model includes all key biochemical processes taking place in the soil zone (Wade *et al.* 2002). Process rate estimates and other parameters may be measured, derived from the literature, or fitted during model calibration.

Fluxes and concentrations of N are simulated by solving mass balance equations for terrestrial processes whilst simultaneously solving flow equations which determine the amount of runoff and leaching into the channel and the dilution potential of the river (Wade *et al.* 2002). INCA requires daily time series of soil moisture deficit (SMD), hydrologically effective rainfall (HER), air temperature and precipitation as well as spatial data describing the major land use types, estimates of growing season for different crops and vegetation types, timing and quantity of fertiliser application and locations of point sources and effluent concentrations as inputs. INCA-N then provides daily time series of flow, nitrate and ammonia at each reach boundary, as well as profiles along with descriptive statistics of these variables at selected sites. A more detailed explanation of model components and equations is available in Wade *et al.* (2002) and Whitehead *et al.* (1998a, b).

Integrated model setup

In order to model the Thames, the river system was divided into 22 reaches and sub-catchments from the source at Cricklade to the lowest weir on the freshwater downstream boundary at Teddington (Figure 1 and Table 1). Reach boundaries were selected at confluences, gauging stations and water quality monitoring stations. The sub-catchment boundaries were derived using a Digital Terrain Model (DTM). Reach and sub-catchment information including the reach length, sub-catchment area and six land use percentages are shown in Table 1. Land use types used in INCA are forest, short vegetation-ungrazed (SVegUG), short vegetation-grazed but not fertilized (SVegGNF), short vegetation-fertilized (SVegF), arable and urban.

The daily time series of HER and SMD have been derived using the Meteorological Office Rainfall and Evapotranspiration System (MORECS) (Thompson *et al.*

Table 1 | INCA reach and sub-catchment land use information

			% of land use							
Reach number	Reach length (m)	Sub-catchment area (km^2)	Forest	SVegUG	SVegGNF	SVegF	Arable	Urban	Flow station	Water quality station
1	8,000	368	5	1	0	30	54	10		
2	12,800	588	2	1	0	11	77	8		Y
3	12,600	579	3	0	0	12	83	2		Y
4	20,700	951	3	0	0	17	74	6	Y	Y
5	6,750	310	4	0	0	13	74	8		Y
6	5,670	261	6	0	0	20	44	31	Y	
7	13,000	597	2	0	0	19	72	8		
8	1,820	84	6	0	0	5	66	24		Y
9	4,140	190	2	0	0	9	79	9	Y	Y
10	9,320	428	3	0	0	0	79	18	Y	Y
11	6,380	293	4	0	0	21	67	7		Y
12	18,010	828	6	0	0	10	77	8		Y
13	10,760	494	14	0	0	5	70	11	Y	Y
14	8,910	409	8	0	0	10	72	9		Y
15	18,990	873	18	1	1	12	45	23		Y
16	13,660	628	16	0	0	13	46	25		Y
17	8,850	407	10	0	0	10	49	32		Y
18	9,540	438	17	3	0	18	23	37		
19	2,000	92	10	0	0	14	50	26		
20	8,460	389	18	0	0	8	18	52	Y	Y
21	9,540	438	24	0	3	13	37	22	Y	Y
22	7,740	356	18	0	0	15	31	36	Y	Y

1981) (Figure 2) and a simple Excel spreadsheet model (Limbrick 2002) for the INCA calibration and climate scenario applications, respectively. Climate scenario SMD and HER were calculated from the meteorological data and a root constant of 200 mm, which has been suggested as optimal for use across the chalk outcrop of southern England (Limbrick 2002). The root constant method was also applied to the INCA calibration time period (1999–2006) and compared with the MORECS derived values. The estimated SMD and HER from two methods agreed well ($r^2 > 0.80$). The other two inputs for the INCA model are average daily temperature and actual daily precipitation.

The effects of land surface and topography on flow are simulated through a semi-distributed approach incorporating the dynamics and characteristics of each

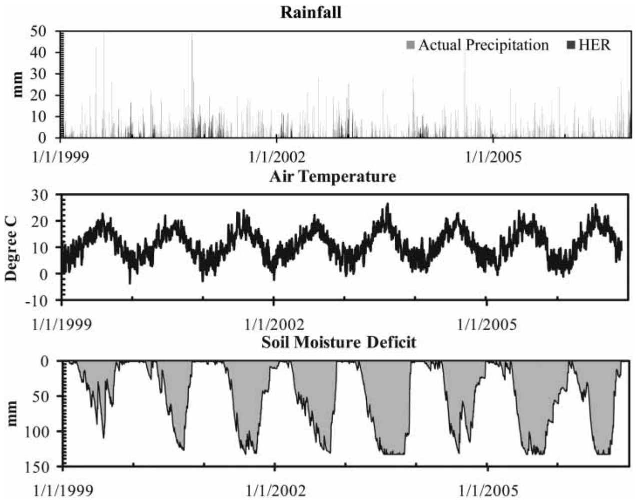

Figure 2 | INCA-N input parameters including actual precipitation, effective rainfall (HER), air temperature and soil moisture deficit (SMD).

sub-catchment (Whitehead *et al.* 1998a). The residence times and flow rates in the soil and groundwater zones in the model are also essential to the simulation of flows through these zones. These can be adjusted manually during the calibration process.

Model calibration

INCA-N generated daily simulated stream flows, NO_3-N and NH_4-N concentrations from 1/1/1999 to 31/12/2006 at each of the 22 reaches in the Thames system. The general flow regime of the River Thames is simulated efficiently with good matches between modelled and observed flow data with r^2 of 0.79 for the most downstream flow gauge at Teddington. The model fits to flow at eight flow gauges have r^2 between 0.71 and 0.80 (Table 2). Two examples in the upper/middle reach at Days Weir and the lowest reach at Teddington are shown in Figure 3, indicating that the complete hydrograph is simulated well, including the timing and magnitude of the high flow conditions. However, summer low flows are sometimes under-estimated, such as during 2005 and 2006 at Days Weir. This might be because MORECS data often over-estimate daily SMD, therefore leading to an under-estimation of daily HER and river flow (Limbrick *et al.* 2000).

Table 2 | The squared correlation coefficients (r^2) between observed and measured flow and NO_3-N data at 22 reaches in the River Thames

Reach number	Flow calibration	NO_3-N Calibration
1	n.a.	n.a.
2	n.a.	0.69
3	n.a.	0.66
4	0.71	0.70
5	n.a.	0.70
6	0.71	n.a.
7	n.a.	n.a.
8	n.a.	0.83
9	0.72	0.87
10	0.72	0.82
11	n.a.	0.83
12	n.a.	0.81
13	0.74	0.74
14	n.a.	0.78
15	n.a.	0.79
16	n.a.	0.79
17	n.a.	0.88
18	n.a.	n.a.
19	n.a.	n.a.
20	0.80	0.82
21	0.79	0.90
22	0.79	0.88

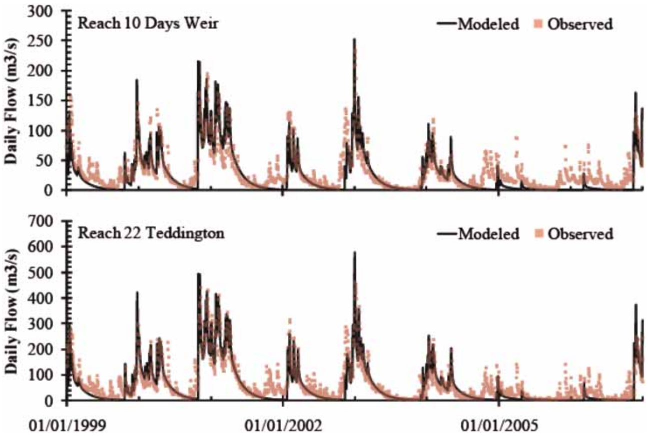

Figure 3 | INCA calibration results for hydrology: observed and simulated river flows at Days Weir (reach 10) and Teddington (reach 22) from 1999 to 2006. Observed flows are shown in solid squares and modelled flows are shown in black solid line.

The INCA-N simulated NO_3-N concentrations agree well with the observed values such as at reach 21 (Molesey) with r^2 of 0.90. Table 2 lists the r^2 values for all 17 reaches where NO_3-N measurements were available during 1999–2006.

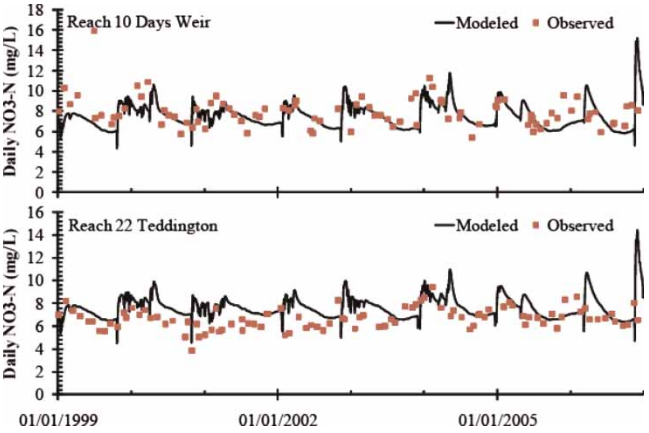

Figure 4 | INCA calibration results for water quality parameter: observed and simulated nitrate concentrations at Days Weir (reach 10) and Teddington (reach 22) from 1999 to 2006. Observed nitrate concentrations are shown in solid squares and modelled values are shown in black solid line.

Figure 4 shows the observed and modelled NO_3-N concentrations at Days Weir and Teddington. Annually, NO_3-N concentrations in the river are lowest in the summer and autumn and then increase over the winter period as water with high NO_3-N concentrations drains from surrounding soils. The lower concentrations in the summer may reflect high rates of in-stream denitrification. Denitrification is enhanced in summer months due to the higher temperatures and the longer residence times which allow more time for microbiological processes to occur.

Sensitivity analysis

There have been several full sensitivity analysis studies undertaken for the INCA model (Raat *et al.* 2004; McIntyre *et al.* 2005; Futter *et al.* 2009a, b) and these have assessed, in a comprehensive manner, the various sources of uncertainty in the model, including parametric, observational and model structural uncertainty. However, the sensitivity analysis in this study was performed solely to assess the effects of variability of in-stream process rates on model simulations as well as to evaluate a hypothesis that better model results could be obtained if simulated denitrification rates were higher in the lower reaches of the catchment compared to the upper reaches. The differences in denitrification rates were hypothesized to be a result of changing water residence times along the river system, caused largely by the effects of the weirs that create pools of slower moving water in the lower reaches of the river system. As the mass of NO_3-N denitrified in INCA-N is a function of flow velocity and denitrification rate, it was hypothesized that better correspondence between modelled and observed data could be obtained if flow velocities and nitrification/denitrification rates were allowed to vary throughout the river. Nitrification and denitrification rates are both modelled as temperature-dependent first order processes. The measured and maximum and minimum parameter values used in the sensitivity analysis are listed in Table 3.

Table 3 | Measured in-stream parameter values and ranges used in sensitivity analysis

Parameter	Units	Measured value	Minimum	Maximum
Flow velocity ‘a’	null	0.005	0.0025	0.025
Flow velocity ‘b’	null	0.95	0.8	0.99
Denitrification rate	d^{-1}	0.01	0	0.05
Nitrification rate	d^{-1}	4	0.2	5

The sensitivity analysis was performed in the manner outlined in Futter *et al.* (2007). A Latin Hypercube design was used to sample the parameter space. The parameter space was defined as a uniform distribution bounded by maximum and minimum values (Table 3). 5000 model runs were performed. Parameter ranges were obtained from previous studies on the River Thames (Whitehead & Hornberger 1984; Whitehead 1990; Whitehead & Toms 1993). Behavioural parameter distributions were generated from the 100 best-performing model simulations for each reach. Performance was assessed in terms of correlation between modelled and observed NO_3-N concentrations and flow simulations. Parameter sets were only included in the behavioural set if the flow simulations were at least as good as those derived from measured flow velocities. Parameter sensitivity was assessed using a Kolmogorov-Smirnov test comparing the behavioural and non-behavioural model runs. A threshold probability of 0.0001 was used as a cutoff. This conservative threshold was employed as tabulated significance estimates do not account for the change in probabilities associated with repeated testing (Futter *et al.* 2009a, b)

In each reach, model performance can be sensitive to one or more parameters in the current or upstream reaches. For the 18 reaches where sensitivity was assessed, there were 123 instances where the distribution of behavioural values was not uniform: 60 denitrification rates, 61 flow ‘a’ and two flow ‘b’ parameters. Model performance was not sensitive to simulated nitrification rates. Model performance was only sensitive to parameter values in the current and upstream reaches; there were no cases where model performance in a given reach appeared to be sensitive to parameter values in downstream reaches. Median values for sensitive parameters are shown in Tables 4 and 5. It can be seen that reaches in upper part of the catchment generally have fewer sensitive parameters than those lower down in the catchment. Measured denitrification rates are generally within the range of behavioural parameter values for model simulations. Simulations of NO_3-N are generally better lower in the river when higher than estimated flow ‘a’ velocities are assumed. The fit of modelled to observed NO_3-N is better at slightly higher denitrification rates than those measured, especially lower down in the river.

Table 4 | Median values of sensitive flow 'a' parameters during INCA-N simulations. Reaches where sensitivity was assessed are listed in the rows and reaches where non-uniform behavioural distributions were observed are shown in the columns (i.e. model performance in Kings Weir was sensitive to flow 'a' rates in Pinkhill and Kings Weir). Bold values in a cell indicate that the measured flow 'a' was within the range of behavioural simulations. An italicized value in a cell means that the measured rate was not within the behavioural range

	Crickdale Castle	**Buscot**	**Rushey**	**Pinkhill**	**Kingsweir**	**Sandford**	**Abingdon**	**Culham**	**Days Weir**	**Benson**	**Whitchurch**	**Caversham**	**Shiplake**	**Marlow**	**Bray**	**Bell**	**Romney**	**Shepperton**	**Mosley**
Crickdale Castle	*0.0025*																		
Buscot																			
Rushey																			
Pinkhill				**0.019**															
Kings Weir				**0.017**	**0.018**														
Abingdon		**0.011**	**0.007**	**0.003**		**0.017**													
Culham			**0.005**	**0.006**		*0.019*	**0.016**	***0.019***											
Days Weir		**0.007**	**0.008**	**0.006**		**0.018**		**0.017**	*0.02*										
Benson		**0.006**	**0.009**	**0.006**				**0.017**	*0.018*	**0.016**									
Whitchurch		**0.007**	**0.009**	**0.007**					**0.018**	**0.019**	*0.02*								
Caversham		**0.008**	**0.009**	**0.009**					**0.016**		**0.018**	**0.017**							
Shiplake									**0.016**		**0.019**	**0.017**	**0.018**						
Marlow									**0.017**		**0.019**	**0.018**	**0.017**	**0.018**					
Bray									**0.016**		**0.018**			*0.019*	**0.018**				
Romney																	**0.017**		
Shepperton	**0.007**	**0.01**													*0.016*		**0.016**		
Mosley	**0.008**	**0.008**													*0.017*	**0.017**			
Teddington																		**0.017**	**0.018**

Table 5 | Median values of sensitive denitrification rates during INCA-N simulations. Reaches where sensitivity was assessed are listed in the rows and reaches where non-uniform behavioural distributions were observed are shown in the columns (i.e. model performance in Kings Weir was sensitive to denitrification rates in Rushey, Pinkhill and Kings Weir). Bold values in a cell indicate that the measured denitrification was within the range of behavioural simulations. An italicized value in a cell means that the measured rate was not within the behavioural range

	Crickdale Castle	Buscot	Rushey	Pinkhill	Kings Weir	Days Weir	Benson	Whitchurch	Caversham	Shiplake	Marlow	Bray	Romney	Bell	Shepperton	Mosley	Teddington
Crickdale Castle	*0.04*																
Buscot	**0.011**	*0.001*															
Rushey		**0.004**	*0.002*														
Pinkhill			**0.009**	*0.001*													
Kings Weir			**0.012**	*0.002*	**0.005**												
Abingdon				**0.03**													
Culham				**0.037**													
Days Weir						**0.01**											
Benson				**0.032**		**0.011**	**0.012**										
Whitchurch						**0.009**	**0.012**	**0.006**									
Caversham						**0.012**		**0.008**	**0.014**								
Shiplake						**0.013**	**0.012**	**0.006**	**0.013**	**0.015**							
Marlow						**0.012**		**0.008**	**0.013**		**0.007**						
Bray							**0.013**	**0.01**	**0.012**		**0.005**	**0.006**					
Romney						**0.013**	**0.012**	**0.009**	**0.012**	**0.013**	**0.006**	**0.008**	**0.011**				
Shepperton											**0.012**		**0.016**	**0.011**	**0.012**		
Mosley											**0.012**		**0.014**	**0.014**	**0.014**	**0.014**	
Teddington								**0.012**			**0.011**	**0.01**	**0.012**	**0.009**		**0.01**	**0.011**

The fact that the measured parameter values fell within the range of behavioural simulations in 108/121 (89.3%) of sensitive reach/parameter combinations is encouraging. It suggests that measured values are a credible estimate of process rates throughout the whole Thames River.

General model uncertainty

A catchment hydrochemical modelling study unavoidably involves uncertainty (Jakeman *et al.* 1993; Wilby 2005). One of the issues is structural uncertainty as models only represent simplifications of reality (Wade *et al.* 2002). As the catchment hydrochemical dynamics are complex and the optimum model structure to represent them is unknown, the structure of the INCA-N model is also unavoidably different to that of the catchment (Wade *et al.* 2008). Additional uncertainty about chemical processes in catchments may arise from a lack of understanding of the relevant processes and a lack of soil and groundwater solute concentration data. Most research efforts use available measured or observed data as parameter inputs for model calibration and validation. Unfortunately, an accurate simulation of flow does not guarantee a correct estimation of internal processes, such as evaporation, infiltration and snowmelt. Multiple processes might compensate each other and give equally good matches between modeled and observed data (Beven 2009). In most cases, additional observations of snowmelt or evaporation are not available to constrain this problem. All these, together with the limitations of the available data and model parameter uncertainty, suggest that the flow and water quality dynamics could never be reproduced exactly (Wade *et al.* 2008). Despite these problems, there are studies which have shown that it is possible to build models that reproduce the long-term trends and seasonal dynamics of catchment hydrochemistry (Cosby *et al.* 1985a, b; Wade *et al.* 2005).

To date, research on climate change impacts on water quality is still in its early stage and a majority of modelling studies have addressed only hydrological effects (Whitehead *et al.* 2009c). Studies which place greater emphasis on water quality and ecosystems are needed. If models provide the only way to evaluate and understand the impact of environmental changes in the future, the aforementioned limitations need not undermine the use of the modelling, despite the uncertainty issue. Previous studies using INCA-N models have been tested worldwide, especially in Europe (Jarvie *et al.* 2002; Wade *et al.* 2002; Barlund *et al.* 2009; Futter *et al.* 2009a). Given the reasonably well calibrated INCA-N model in the River Thames (Table 2), which incorporated a significant quantity of observed data, it can be stated that the model application has encapsulated the main hydrological, chemical and biological processes operating in this large river basin. Therefore, it can be suggested that the calibrated model provides a sound basis to conduct a climate change impact study, although a full sensitivity analysis of INCA models in the Thames River will certainly be of interest in future research in order to best investigate the model uncertainty.

Climate change scenarios

Sampling UKCP09 data

The UKCP09 climate data can be accessed via the UKCP user interface to produce maps and graphs for any time period and any selection of variables (http://ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php). The sampled data are produced by a statistical model (Murphy *et al.* 2007). The full sample of UKCP09 data for any time period and emission scenario consists of 10,000 rows/projections, which capture all the possible combinations or all the variables. According to UKCP guidance, for practical applications to assess the climate change impact, at least 100 samples for each emission scenario and time period are recommended. These samples can be selected randomly from the full sample of 10,000 projections. Figure 5 shows the central projections (50% probability) and the ranges of temperature and precipitation projections with medium emission level in 2020s and 2080s, each from randomly-selected 100 samples for the River Thames region. Temperature shows consistent increases each month throughout the year with the maximum increase by 1.6 °C and 4.1 °C in 2020s and 2080s, respectively (central projection). However, the precipitation pattern is quite variable. The central projection shows the decrease in summer precipitation (June–September) and increase in winter precipitation (November–March). The pattern of precipitation change is much more profound at 2080s time period than 2020s.

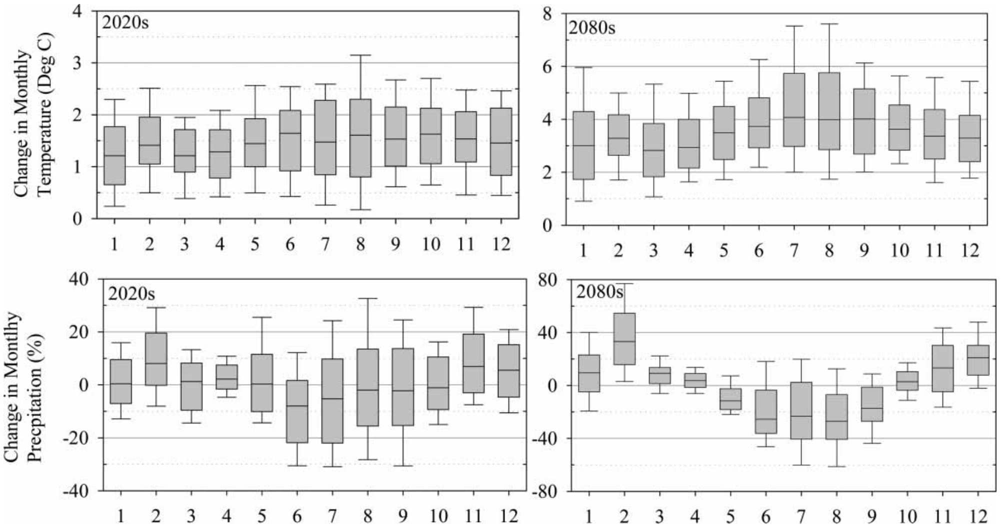

Figure 5 | The monthly temperature change (°C) and precipitation change (%) in the River Thames region at 2020s (2010–2039) and 2080s (2070–2099) with medium emission level, relative to the baseline condition (1961–1990) based on UKCP09 projections. Each time period scenario projection is shown in 10th, 25th, 50th (central), 75th and 90th percentile ($N = 100$).

Scenario application

The INCA model requires an input of daily time series data. For the climate change scenarios (100 samples), each offers monthly perturbations. Therefore, monthly scenario changes were applied to the existing baseline climate data (1961–1990) to perturb each day of the month by the same monthly scenario value (working as a monthly change factor).

Scenario simulation results

For each time period scenario, 100 INCA-N model outputs were generated from 100 future climate change scenario samples to provide a range of estimates for the climate change impact on the flow and water quality. The changes in flow and water quality relative to 1961–1990 baseline conditions were calculated. Figure 6 shows monthly flow change relative to the baseline with 10th, 25th, 50th (central), 75th and 90th percentile estimates at 2020s and 2080s. The central estimates (50% probability) indicate flow reductions for 2020s and general drier hydrological condition from less precipitation, warmer temperature and stronger evaporation. During the low flow time (July–November), the percentage reduction is higher. It is then followed by less reduction during the winter (December–February). Compared to the projected flow change during the 2020s, flow reductions during the 2080s are much greater, especially during periods of low flow. While the central estimates provide a reasonable summary of possible future changes in flow, the range of changes

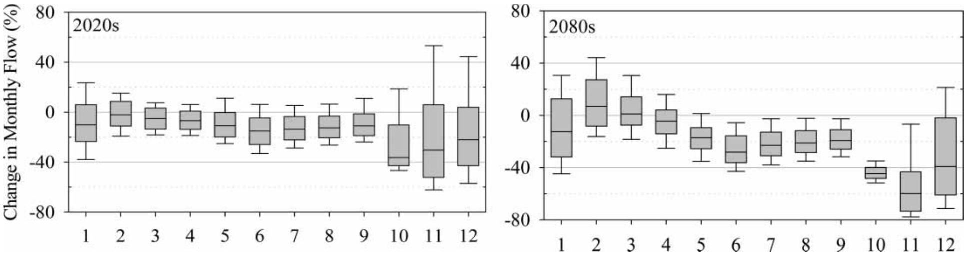

Figure 6 | At 2020s and 2080s with medium emission, the monthly River Thames flow change (%) relative to the baseline condition (1961–1990). For each time period scenario, the monthly estimates are shown in 10th, 25th, 50th (central), 75th and 90th percentile ($N = 100$).

reflects the wide spread of UKCP09 climate changes for precipitation, temperature and potential evaporation. This also suggests that choosing a small number of climate change scenario samples may provide misleading results.

The change in projected NO_3-N concentration is relatively minor compared to the change in flow. At 2020s, the central estimates (50% probability) of the monthly change in NO_3-N concentrations are less than 5% except in February with a 6.2% change (Figure 7). The increase in NO_3-N concentration occurs in the winter (January–March) and then decreases in the summer and fall. The general pattern of NO_3-N concentration change at 2080s is similar to 2020s with greater increases in the winter and more decreases during summer (Figure 7). Higher NO_3-N concentrations in the winter months might reflect greater flushing from the soil. The lower summer NO_3-N appears to be due to greater amounts of denitrification in the river. With warmer water temperature and slower water movement in the summer, there is a greater amount of NO_3-N lost from denitrification. Even though there is less flow in the summer, which could lead to an increased NO_3-N concentration, denitrification has a larger effect on water quality. This is consistent with Whitehead & Williams (1982) who reported that large lowland rivers such as the Thames can lose up to 70% of the NO_3-N through denitrification processes in summer low flow condition.

A study in the River Tweed using UKCIP02 climate scenario showed similar results to the Thames, which have suggested future changes in NO_3-N concentrations as a result of climate change (Whitehead *et al.* 2009b). In the upper Tweed, the NO_3-N concentrations are projected to be slightly higher in the winter months and significantly lower in the summer months (Whitehead *et al.* 2009b). Lower NO_3-N concentrations in summer may reflect the effects of increased temperature, reduced flow velocity and longer residence time on denitrification.

Suggestions for water management and future work

As future climate change appears to be unavoidable, scientists in a large number of fields are working together to assess the impacts from climate change in terms of water resources and water quality, and to develop management and adaptation strategies for coping with climate change. With the latest UKCP09 probability projection data, it becomes possible to take into account of different uncertainty level when assessing the climate change impact.

This study using UKCP09 and INCA model indicates that the range of estimates of future monthly flow change is rather wide. Water companies may need to consider the robustness of their plans (both short-term and long-term) to adapt to this wide range of climatic and hydrological conditions. Also, low flows in summer mean that there is less dilution of effluent discharges and this will raise water quality concentrations (Whitehead *et al.* 2009b). The model simulations project a fairly wide range of increases in NO_3-N concentration from January to March, indicating higher N flushing in winter months. Previous studies indicate that increased flushing of NO_3-N can occur following precipitation events after drought, as happened in 1976 (Whitehead 1990). Thus extreme precipitation events could cause significant water quality problems which could threaten public water supplies.

One interesting potential new development in the Thames catchment is the construction of a new reservoir at Abingdon which would provide extra capacity to sustain

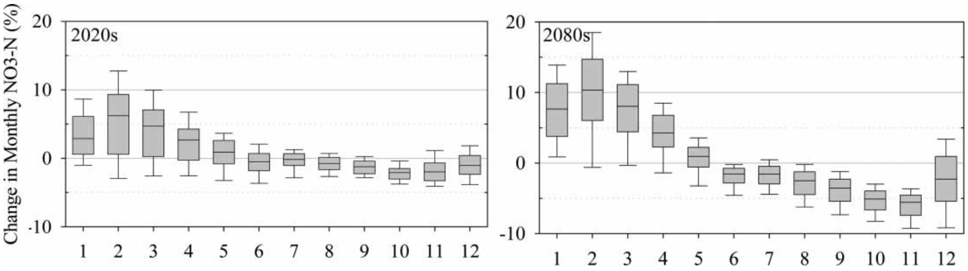

Figure 7 | At 2020s and 2080s with medium emission, the monthly River Thames nitrate concentration change (%) relative to the baseline condition (1961–1990). For each time period scenario, the monthly estimates are shown in 10th, 25th, 50th (central), 75th and 90th percentile ($N = 100$).

flow in low flow summers. It is important to consider the operation of the reservoir to minimize the impact of climate change induced low flows and provide the sufficient water supply downstream to London. The plans for the reservoir operation are to fill the reservoir in winter months (e.g. December–April) and then release water at approximately a rate of $10\,m^3\,s^{-1}$ during the summer low flow period (e.g. June–September). This water would then be abstracted from the lower Thames for filling the London reservoirs. Such a scheme would have several consequences. Although the extra flows will be of considerable benefit to London's water supply and decrease the vulnerability of London to drought, there could be unintended impacts. For example, in summer months the nutrient-rich reservoir will be ideal for phytoplankton growth (Elliott *et al.* 2006) and these could seed the river system as the warmer reservoir water is released back into the river. Toxic algae such as cyanobacteria (Guven & Howard 2006) could grow in the reservoir and the Thames and thus threaten water supplies. Moreover, filling the reservoir with high NO_3-N water from the Thames in winter time could create problems later in the year when the water is released. Significant denitrification has been observed in reservoirs over summer months when microbial populations in sediment are high and warm summer conditions maximize the N losses (Whitehead & Toms 1993). However, in this case, the reservoir water would be released before there was any opportunity for significant denitrification, so the NO_3-N concentrations from the reservoir may increase the river concentration, which would be detrimental to river quality. This effect can be seen in Figure 8 where the NO_3-N concentrations rise in summer when reservoir water stored over the winter is hypothetically released at $10\,m^3\,s^{-1}$ from June to September without significant denitrification occurring (scenario 1). However, if NO_3-N loss from denitrification is enhanced by the long reservoir retention time, high primary production, and high surface area of mud to water volume ratio, the reservoir concentrations will fall (scenario 2) and the overall reduction in NO_3-N loads to the river is quite significant. Potentially, the reservoir can be used to adapt climate change providing water supply with good quality. Future research is needed to obtain accurate field denitrification rates and reservoir changing residence time as well as to assess the impact of extreme hydrological events (drought and floods).

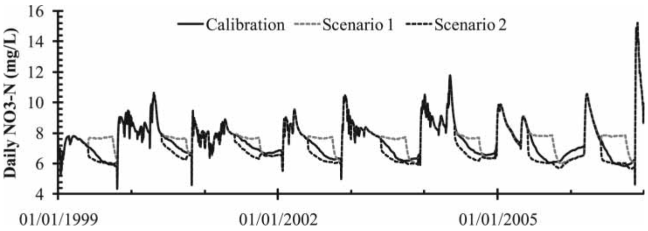

Figure 8 | INCA results on the reservoir behaviour. Scenario 1 shows significant nitrate rise from the winter storage which have higher nitrate concentration assuming no significant denitrification; Scenario 2 shows the reduced nitrate concentration due to the loss at the assumed rate of 2 mg-N l^{-1} from reservoir denitrification.

Flow and water quality differ for each catchment depending on many factors, such as geographic locations, water body locations, local geology and nutrient/solute sources within the catchment. Moreover, climate change especially rising temperatures will lead to increased chemical reaction and biological process rates. With reduced summer flow, the dilution potential becomes less, which could greatly increase solute concentrations. However, the relative importance of these different processes will vary among different catchments or different locations in a same catchment. Therefore, applications and assessment of climate change impact to a wide set of catchments will become important. Since climate change studies in relationship to river water quality are still at an early stage, research on understanding the flow processes, water-sediment reactions and various sources controlling water quality in the context of climate change are essential for better future water management.

CONCLUSIONS

There have been many climate change and climate model scenario studies in the past decade, which provide information for assessments of the potential effects of climate change on water availability and water quality. The INCA model is a useful tool for investigating such impacts. The model offers an effective way to assess the river flow and water quality variations by incorporating hydrology, chemical reaction, flow residence time and human influences into simulation of solute concentrations. The application of INCA to the whole River Thames with the range of probabilistic climate scenarios (UKCP09) is one of the first climate impact assessments using both a central estimate and range. During the 2020s, the central estimate indicates general drier hydrological condition in the region. The degree of dryness is much more profound at 2080s. Warmer temperatures and reduced flow are projected to become prevalent in the summer and late fall, which could lead to severe water stress in the future. The wide range of simulated future monthly flow change reflects wide spread of UKCP09 climate changes for precipitation, temperature and evaporation. How to find the best adaption strategies for water supply is critical and it needs an integrated consideration of hydrology, water quality, and ecology. Finally, uncertainty is unavoidable in modeling applications. This study considered some of the possible uncertainty, which should be taken into account when looking at the results and conclusions presented.

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