Potential impacts of climate change on water quality and ecology in six UK rivers

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ABSTRACT

A modelling study has been undertaken to assess the likely impacts of climate change on water quality across the UK. A range of climate change scenarios have been used to generate future precipitation, evaporation and temperature time series at a range of catchments across the UK. These time series have then been used to drive the Integrated Catchment (INCA) suite of flow, water quality and ecological models to simulate flow, nitrate, ammonia, total and soluble reactive phosphorus, sediments, macrophytes and epiphytes in the Rivers Tamar, Lugg, Tame, Kennet, Tweed and Lambourn. A wide range of responses have been obtained with impacts varying depending on river character, catchment location, flow regime, type of scenario and the time into the future. Essentially upland reaches of river will respond differently to lowland reaches of river, and the responses will vary depending on the water quality parameter of interest.

Key words | climate change, nitrate phosphorus, rivers, sediments, water quality

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INTRODUCTION

The 2007 conference of the parties to the United Nations Framework Convention on climate change in Bali and the latest Intergovernmental Panel on Climate Change (IPCC) report (2007) confirmed the consensus among scientists and policy makers that human-induced global climate change is now occurring. However, there is less certainty about the magnitude of future temperature changes and how these will drive precipitation, evaporation and hydrology at regional scales. Nonetheless, climate model scenarios provide the best available information for assessing future impacts of climate change on the water quality and ecology of surface water bodies (Kundzewicz *et al.* 2007).

The Freshwater chapter in the IPCC Fourth Assessment Report (Kundzewicz *et al.* 2007) was unable to consider the impacts of climate change on water quality in great detail, but this topic is attracting more attention. For example, the EU Eurolimpacs Project (www.eurolimpacs.ucl.ac.uk) is a multi-partner, €20 million research project investigating impacts on rivers, lakes and wetlands across Europe (Battarbee *et al.* 2009). A wide range of laboratory and field experiments, data analysis and process-based modelling is being undertaken to evaluate potential impacts of climate change. This research, plus activities elsewhere (Jones & Page 2001) are addressing many important questions including the following.

- How will climate change impact river flows and hence the flushing of diffuse pollutants or the dilution of point effluents?
- In what ways might more intense rainfall events affect nutrients and sediment loads in urban drainage systems, rivers, lakes and estuaries?
- How might rising temperatures combined with water quality changes affect freshwater ecosystems?
- How might the carbon balance and recovery of acidification be affected in upland catchments?

A modelling study of surface water quality cannot be undertaken without considering changes in hydrological regimes. The UK Climate Impacts Programme (UKCIP) 2002 scenarios (Hulme *et al.* 2002) suggest that winter

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precipitation in the UK could increase by 10–20% for a low emissions scenario and by 15–35% for a high emissions scenario by the 2080s. Low and high emission scenarios refer to the emission of carbon dioxide from man-made sources over a period of time into the future (Hulme *et al.* 2002).

The largest changes are predicted in the south and east of England and the smallest in northwest Scotland. In the summer, the pattern is reversed and almost the whole of the UK could become drier, with precipitation decreases of up to 35% under a low emissions scenario and 50% or more under a high emissions scenario. Marsh & Hannford (2007) have shown that summer precipitation has already fallen to some extent. Furthermore, the frequency of extreme events is also predicted to increase with two-year (return period) winter precipitation event intensities estimated to become between 5% (low emissions) and 20% (high emissions) heavier by the 2080s. These changes in precipitation have been used to simulate changes in flow across the UK (Limbrick *et al.* 2000; Arnell 2003). More recently, Romanowicz *et al.* (2006) modelled changes in river flow for a range of catchments, under different climate model projections. They conclude that by the 2020s flows in winter could increase by between 4% and 9% and that summer flows could decrease on average by 11%. This could range between 1% to 32% depending on the catchment location, land-use, soils, geology and model uncertainty.

Lower minimum flows imply less volume for dilution and hence higher concentrations downstream of point discharges such as Wastewater Treatment Works (WTWs). This could affect efforts to improve water quality or achieve Water Framework Directive (WFD) objectives to restore and protect freshwater ecosystems. Reduced dilution effects will also impact organic pollutant concentrations with increased biological oxygen demand (BOD) and hence lower dissolved oxygen (DO) concentrations in rivers.

Cox & Whitehead (2009) show that DO in the Thames will be affected in the 2080s under a range of UKCIP scenarios by enhanced BOD and by direct effects of temperature which reduces the saturation concentration for DO. A recent study investigated BOD, DO nitrate, ammonia and temperature in rivers but there were insufficient data to adequately calibrate and validate the model (Conlan *et al.* 2006). However, a model sensitivity analysis illustrated the links between climate change and water quality. As expected, under reduced flows in summer, BOD and phosphorous levels would increase whereas ammonia levels would fall due to higher nitrification rates. This gives rise to increased nitrate concentrations as ammonia decays to nitrate. The authors concluded that there could be enhanced growth of algal blooms in rivers and reservoirs that could affect DO levels and water supply. Also with increased storm events, especially in summer, there could be more frequent incidences of combined sewer overflows discharging highly polluted waters into receiving water bodies, although there could be benefits in that storms will also flush away algal blooms.

The most immediate reaction to climate change is expected to be in river and lake water temperatures (Hassan *et al.* 1998; Hammond & Pryce 2007). River water temperatures are in close equilibrium with air temperature and as air temperatures rise, so will river temperatures. There has already been a 1–3°C temperature rise over the past 100 years in large European rivers such as the River Rhine and the River Danube (EEA Technical Report 2007). Small streams have shown an increase in winter temperature maxima in Scotland (Langan *et al.* 2001), and there have been large increases in temperature reported for water courses in Switzerland at all altitudes (Hari *et al.* 2006). There have been two sudden shifts in river temperatures in 1988 and 2002 following changes in air temperature. Abrupt water temperature rises could have important implications for some aquatic organisms, if species are unable to adapt at the same pace.

As most chemical and microbiological reactions are temperature dependent, it is essential to use hydrochemical models to determine the potential impacts of climate change on water quality. Six different river systems are considered in this article. In each case, the INCA (INtegrated CAtchment) water quality models are applied to each river (Whitehead *et al.* 1998*a*,*b*) and climate change scenarios investigated.

THE SIX UK RIVERS

The six catchments analyzed during this study were the Rivers Lugg, Tamar, Tame, Lambourn, Kennet and Tweed, as shown in Figure 1. These rivers represent differing geographical locations, different geologies and represent

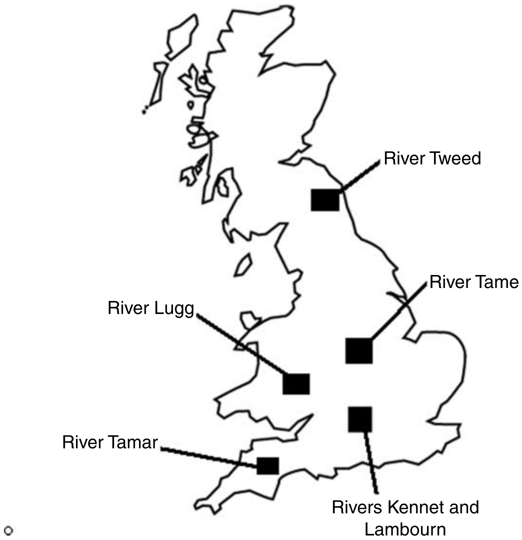

Figure 1 | Map of the UK and the location of the six rivers.

both upland and lowland systems. Full descriptions of the INCA model applications to these catchments are given in Jarvie *et al.* (2002), Wade *et al.* (2002*a*,*b*,*c*,*d*), Wilby *et al.* (2006), Whitehead *et al.* (2002, 2006), Jarritt & Lawrence (2007) and Uncles *et al.* (2002).

All of the INCA model applications for sediments, nitrogen, ammonia, phosphorus and ecology (macrophytes and epiphytes) are based on data obtained from a range of sources including the Environment Agency (flow and quality data), the UK Meteorological Office, the CEH land cover maps, nitrogen deposition maps, agricultural census data, sewage treatment works (STWs) discharges, river mapping, digital terrain maps and river velocity information. The model applications therefore incorporate a significant quantity of historical data and encapsulate the hydrological, chemical and biological dynamics and processes operating in these diverse catchments. The various versions of INCA have been calibrated and validated in each case and provide a sound basis for climate change impact studies. Rather than explain in great detail each model application, all of which are described in the literature, only selected model results are presented here.

CLIMATE CHANGE DOWNSCALING

We have used two approaches to evaluate the impacts of climate change on water quality. These are the delta change method as applied by UKWIR (Romanowicz *et al.* 2006) and the statistical downscaling scheme developed by Wilby *et al.* (2002). The UKWIR methodology was applied for consistency with water quality assessments undertaken by UKWIR. However, the long-term transient effects of climate change were also explored because this might give additional insights into potential water quality impacts arising from changes in the temporal sequencing of daily weather.

UKWIR delta change method

The UKWIR study (Romanowicz *et al.* 2006) developed a methodology for downscaling global circulation models (GCMs) information and translating GCM outputs into key variables. These key variables were local precipitation, temperature, potential evapotranspiration (PET) and, via the water resource model CATCHMOD, into river flows. The procedure was applied to over 70 catchments across the UK and has therefore provided valuable resources for the current study. Information from the UKWIR project covers all the scenarios and time periods required for the water quality modelling tasks. The IPCC Special Report on Emission Scenarios (SRES) and corresponding UKCIP02 emissions scenario nomenclature are listed in Table 1. These scenarios are described in detail by Hulme *et al.* (2002).

The results of the UKWIR project are available in spreadsheets containing delta change factors for each catchment, averaging results from six GCMs (Romanowicz *et al.* 2006). In the case of precipitation and PET, the delta change is expressed as (%) changes whereas for temperature the changes are in degrees Celsius relative to the 1961–1990 baseline. These delta changes were then used by Romanowicz *et al.* (2006) to determine river flows and groundwater recharge for the catchments using the CATCHMOD model (Wilby *et al.* 1994). In the current study, the delta change information from the UKWIR project has been used to modify the input data for the

Table 1 | UKCIP02 Scenario nomenclature and matching SRES emission scenarios

UKCIP02 scenarios	SRES emissions scenarios
Low emissions	B1
Medium-low emissions	B2
Medium-high emissions	A2
High emissions	A1F1

water quality models. Thus each scenario of interest (Table 1) has been run for the three time periods, namely 2010s, 2020s and 2050s for all the selected rivers to give an idea of how the water quality will change over time.

Downscaling methodology

The second approach to the downscaling of GCM outputs to the UK Rivers was undertaken using the statistical downscaling model (SDSM) (Wilby *et al.* 2002, 2006). This involves calibrating observed rainfall and PET series against gridded data from the National Centre for Environmental Prediction (NCEP). The UKSDSM archive holds 29 daily predictors originating from NCEP and four GCMs for nine degree grid squares covering the British Isles for the period 1961–2100. In the present study, only predictors such as mean sea level pressure from grid boxes centred on southeast England (SEE) were employed for the A2 (medium-high emissions) SRES emissions. The A2 emissions were chosen because this scenario has been widely used in previous impact studies.

Statistical downscaling future climate change scenarios for the River Kennet and Lambourn involved two main steps. First, empirical relationships were established between the target variables of interest, namely daily temperature, precipitation amounts and PET across the catchment and large-scale weather patterns obtained from the NCEP re-analysis for the *current* climate. These relationships were then used in the second step to downscale ensembles of the target variables for the *future* climate, using data supplied by the three GCMs (CGCM2, CSIRO, HadCM3) driven by A2 emission scenario for the full period 1961–2100.

The procedures for downscaling GCM output are explained in detail by Wilby *et al.* (2006), alongside an analysis of impacts on evaporation, soil moisture, flow and groundwater in the catchment. Full details of the application of this methodology in the Kennet catchment are given elsewhere (Whitehead *et al.* 2006; Wilby *et al.* 2006). The effects of different GCMs can be very different, as shown in Figure 2, for the simulated flows in the River Kennet for the three GCMs. The HadCM3 model is noticeably drier in that significant reductions in flows are simulated in the second half of the century.

WATER QUALITY MODELLING RESULTS

The INCA model simulations were performed for all four scenarios listed in Table 1, for the 2010s, 2020s and 2050s. Three versions of the INCA model were used in the study, namely INCA-P for simulating phosphorus dynamics, INCA-N for nitrogen dynamics and INCA-SED for sediment dynamics. The combination of four scenarios and three time periods therefore involved generating 12 input data files for the versions of INCA used for the catchments. Given the scope of the study, only well-established applications of the models were utilized. These were INCA-P for the Lambourn, the Lugg and the Tame; INCA-N for the Tamar and the Tweed; and INCA-SED for the Lambourn.

INCA-P does incorporate sediment, however; where possible, sediment is considered. In addition, the water quality and flow regimes change significantly down river systems as land-use changes and inputs from discharges affect water quality. Thus, simulations have been executed for upper

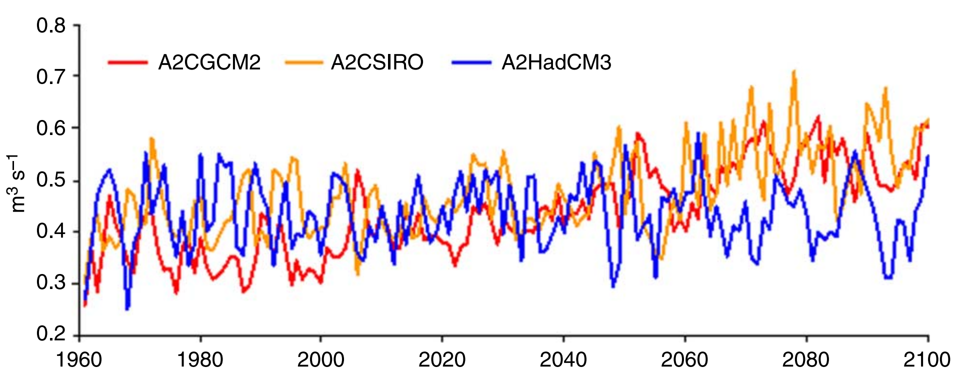

Figure 2 | Annual average river flows simulated in the River Kennet for three different GCM outputs from 1960–2100.

and lower reaches, thereby generating 144 sets of results. Only a subset of these results is presented here. A more complete description is available in Whitehead *et al.* (2008).

River Lambourn phosphorus results

The impacts of climate change on Soluble Reactive Phosphorus for the Lambourn River under the four scenarios and for the 2050s is depicted in Figure 3. The pattern of change through the year is the same for each scenario with declining concentrations of SRP during the high-flow winter months when flows are generally increasing (i.e. wetter winters) and increasing concentrations during summer and autumn months when flows are decreasing. There is therefore less dilution of discharges and agricultural runoff.

River Tame results

The results for the River Tame are very different to the Lambourn due to the fact that the Tame drains the heavily urbanized area of Birmingham and the summer flows are sustained by the effluent discharges. For example, a major sewage treatment works in the upper Tame has a discharge of approximately $4\,m^3\,s^{-1}$ compared with an average summer discharge of approximately $10\,m^3\,s^{-1}$. Also, the geology in the Tame is significantly different with sandstone, mudstones and silt clay soils compared to the chalk bedrock of the Lambourn. The Tame is therefore more affected by direct runoff, whether it is urban in the upper reaches or agricultural in the lower reaches.

The results of the scenarios for the Tame reflect this differing hydrological and diffuse pollution response. Figure 4 depicts the scenario for the 2050s. They all show

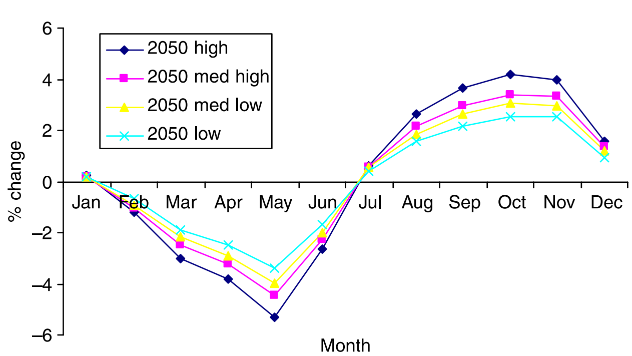

Figure 3 | Monthly (%) changes in phosphorus for the 2050s.

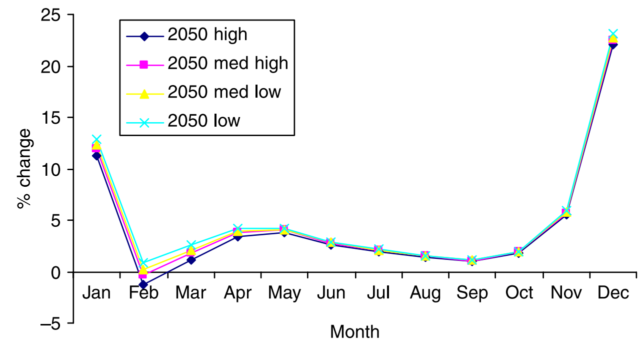

Figure 4 | River Tame monthly (%) changes in phosphorus (SRP) for the 2050s.

the same pattern of increased SRP concentrations in the summer due to the reductions in flows and hence decreased dilution. However, much higher increases are seen in winter. This appears counterintuitive but it reflects the fact that increased winter flows will flush increased nutrients from the urban area (e.g. via storm water drainage) and from the agricultural areas (e.g. via nutrient runoff) in the lower reaches of the Tame.

River Lugg results

The River Lugg phosphorus results for the upper reaches of the river (Figure 5) are very similar to the Lambourn, in that decreased phosphorus concentrations are obtained in the winter and increased concentrations in the summer. This reflects the changed flow conditions, with reduced summer flows producing less dilution.

River Tweed results

The results for nitrate (as N) in the upper Tweed are depicted in Figure 6. Here the nitrate concentrations are

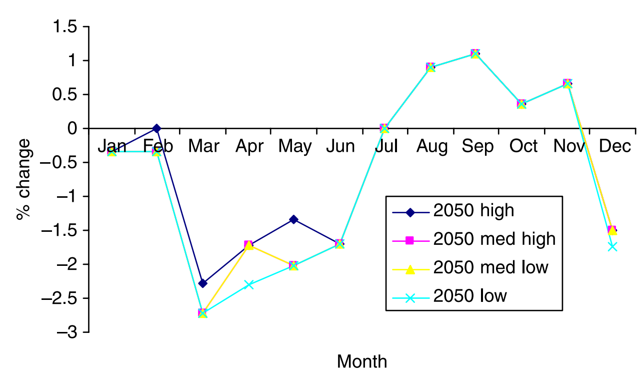

Figure 5 | River Lugg monthly (%) changes in phosphorus (SRP) for the 2050s.

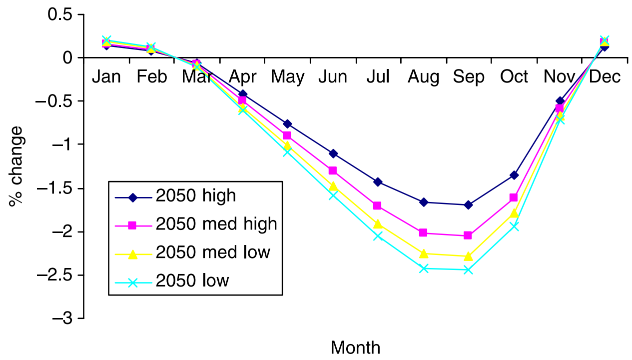

Figure 6 | River Tweed (upper reaches) monthly (%) changes in nitrate (as N) for the 2050s.

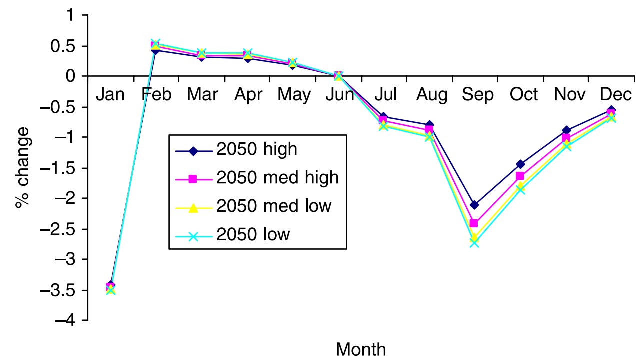

Figure 7 | Upper River Tamar monthly (%) changes in nitrate (as N) for the 2050s.

seen to be slightly higher in the winter months, perhaps reflecting the higher flows and the flushing of nitrogen load from the upland peaty soils. However, in the summer months nitrates fall significantly. This probably reflects the action of increased temperatures, reduced flow velocities and increased residence times which would enhance denitrification processes in the river.

Denitrification is highly dependent on temperature and residence time so that with warmer conditions and slower velocities in the river, there is a bigger rate of nitrate loss via denitrification. This generates lower nitrate concentrations in the river. Of course, the downside of this is that the nitrate loss via denitrification results in the release of nitrous oxide which is a significant greenhouse gas. INCA could be used to calculate the flux of nitrous oxide under these situations, although this would need to be looked at in terms of the (%) change in the total nitrous oxide from denitrification and in the context of other changes affecting nitrate. Interestingly, the nitrate results for lower down the river are quite different, as reported by Whitehead *et al.* (2008). Here, the nitrate concentrations are significantly higher in the summer months. This is most probably due to the fact that there is significant runoff from agriculture in the lower reaches of the Tweed, with upland moorland and grassland being replaced by arable farming, and there are also some significant discharges from sewage treatment works. Lower flows in summer therefore reduce the dilution of point and diffuse sources of nitrate, and hence concentrations rise.

Interestingly, the simulation suggests by the 2050s that denitrification is overcoming this effect and the denitrification rate is having a larger effect than the lack of dilution. It is known that large lowland rivers such as the Thames can lose up to 70% of the nitrate through denitrification processes in summer low-flow conditions and this situation could be happening in the Tweed from the 2050s (Whitehead & Williams 1982). Such large rivers systems are also subject to long-term nitrogen dynamics, as reported by Howden & Burt (2008). These effects can be superimposed on the future climate changes.

River Tamar results

The results for the River Tamar are similar to the River Tweed in that upper reaches of the river behave as a natural stream whereas, lower down the river system, the impacts from sewage treatment works and diffuse sources from agriculture have a large effect. Figure 7 shows a strong seasonal pattern of change, with slightly increased concentrations in the winter months (as in the case of the upper Tweed) but significantly lower concentrations in summer months. This reduction in summer is again most probably linked to the denitrification processes operating in the

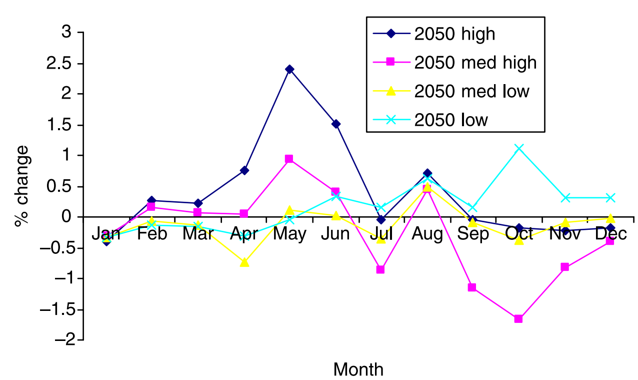

Figure 8 | Percentage changes in monthly sediment concentrations in the upper Lambourn for the 2050s.

upper reaches of the river. Lower down the river system, the pattern is reversed with significant increases in summer reflecting the lack of dilution.

River Lambourn fine sediment simulation

The Lambourn sediment results show two periods of increase in the spring and the autumn for fine sediment delivery (Figure 8). These increases reflect the river flow changes and storm conditions, with increased storm events in early spring and at the end of the summer. Sediment release is also a function of antecedent conditions and the rate of change of flow. Hence, by the end of the summer, there has been sufficient time for the accumulation of sediments on the land surface. With the onset of autumn flows, these

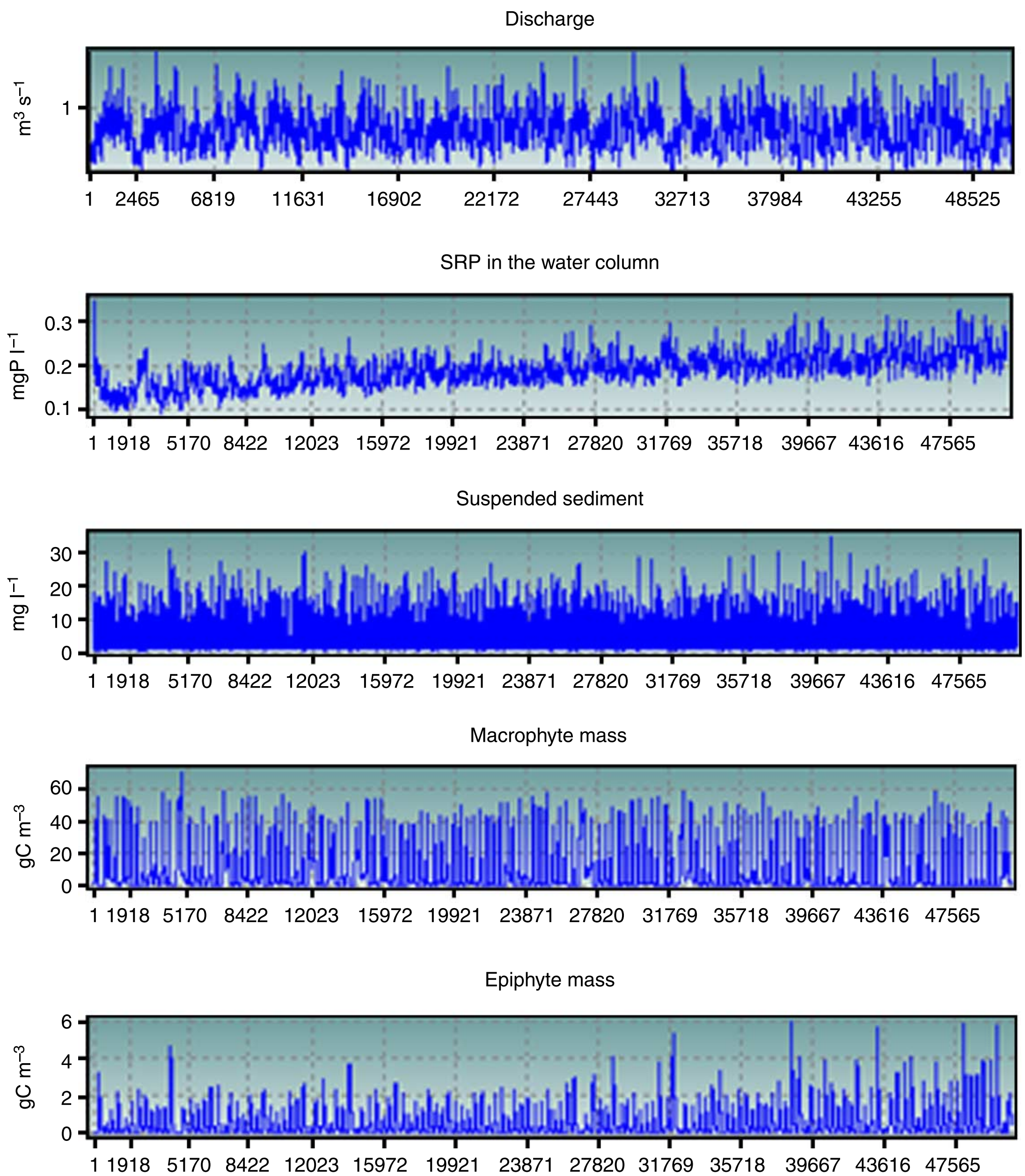

Figure 9 | Simulated flow, phosphorus (SRP), sediment, macrophyte and epiphyte biomass ($g C m^{-2}$) for the Lambourn for the A2 scenario 1961–2100 (*x* axis: days from 1 January 1961).

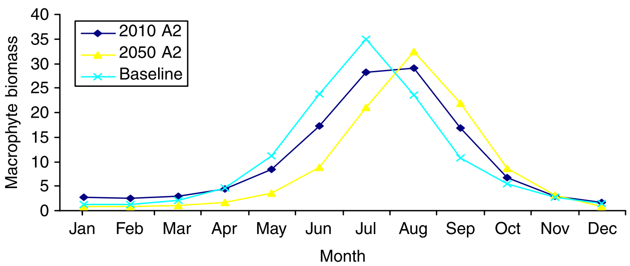

Figure 10 | Lambourn macrophyte monthly biomass ($g\,C\,m^{-2}$) for the A2 long-term scenario.

sediment deposits are flushed into the river. It should be noted that the sediment response is also dependent on the scenario with sediment release increasing with higher emission scenarios reflecting the increased storminess and flows creating higher erosion and resuspension of sediments.

LONG-TERM SCENARIO RESULTS IN THE LAMBOURN AND THE KENNET

The INCA-P model has also been run using the transient downscaled A2 scenario utilized in an earlier study of the River Kennet (Whitehead *et al.* 2006; Wilby *et al.* 2006). The input daily data for the period 1961–2100 indicates a significant increase in soil moisture deficit at certain times, reflecting the enhanced summer drought conditions in the future. This change in soil moisture conditions can be important because it affects soil processes such as phosphorus adsorption or release, nitrogen mineralization, nitrification and denitrification.

Figure 9 shows the daily time series of flow, phosphorus, sediment, macrophyte and epiphytes generated by the model over the period 1961–2100. River flow is seen to decline marginally in response to dryer conditions and the phosphorus concentrations rise due to these declining flows and reduced dilution of effluents in the Lambourn. What is remarkable is the stable nature of macrophyte and epiphyte dynamics simulated for the Lambourn. The biomass levels follow the patterns as seen at present, although at certain times the annual patterns of growth and death change. For example, there appears to be increased epiphytic growth towards the end of the period, perhaps reflecting increased phosphorus concentrations in the stream. The parameters used to set up this aspect of the model are those used by Wade *et al.* (2002*a*). The fact that stable populations are obtained is indicative that the parameters chosen are reasonable for the Lambourn.

There are a wide range of parameter values for macrophyte and epiphyte growth in the literature (Wade *et al.* 2002*b*) and selecting appropriate rates is difficult and subject to considerable uncertainty. However, Figure 10 shows the macrophyte monthly biomass for the baseline period and two future time periods. Although there are no major biomass increases there is a shift in production to later months in the year, which probably reflects changes in flow patterns and phosphorus conditions.

CONCLUSIONS

Downscaling procedures have been utilized to generate local weather patterns which are then used to drive the INCA suite of water quality models. This suite of models has been used to assess the potential impacts of water quality on six rivers systems in the UK. These rivers represent differing geology and geographical locations around the UK and are significantly different in the extent to which they are impacted by agriculture or point sources of pollution. The models have been run to simulate flow, total and soluble phosphorus, nitrate, ammonia, sediments and ecology (macrophytes and epiphytes).

The models were run for four UKCIP02 climate change scenarios and for three periods (the 2010s, the 2020s and the 2050s). In addition, a continuous long-term scenario from the present to 2100 has been simulated to investigate the increase in climate change. The results from the project are complex as might be expected, but consistent patterns are obtained and it is possible to make some statements about the likely outcomes.

In the lowland southern River Lambourn, declining concentrations of Soluble Reactive Phosphorus (SRP) were predicted for winter months and increasing concentrations during summer and autumn months, caused by lower flows and hence reduced dilution. Sediments in the Lambourn are predicted to increase throughout the year but are particularly high in autumn after dry summers. The build up of sediments over dry periods followed by increased autumn flows seems the main mechanism here. Results from the urbanized midlands River Tame show similar increased SRP levels in summer but higher increases in winter due to diffuse urban runoff. In the western and rural River Lugg (a tributary of the River Wye) the SRP is predicted to decrease in winter but increase in summer months. Nitrate levels in the northern River Tweed show increased winter levels in upland headwaters as organic nitrogen is released and decreased levels in summer months due to drought and increased denitrification in the river. However, the lower Tweed shows increased nitrates in winter but the highest increases are in summer. This is due to change in land use to agriculture and point source discharges in the lower reaches of the Tweed. Nitrate levels in the southwest River Tamar have a similar response to the Tweed with higher nitrate in winter and lower summer nitrates in the upper reaches. In the lower reaches of the river, nitrates increase both in summer and in winter. The rate of change increases over time and also with the severity of the emission scenario for all the river systems.

The macrophyte and epiphyte dynamics within rivers, according to the modelling, show significant interaction and suggest that increased drought could create problems by increasing nutrient concentrations and hence stimulating epiphytic growth at the expense of macrophyte growth. Water quality impacts are therefore different depending on geographic location and water body location within a catchment.

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