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Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK

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Summary An integrated approach to climate change impact assessment is explored by linking established models of regional climate (SDSM), water resources (CATCHMOD) and water quality (INCA) within a single framework. A case study of the River Kennet illustrates how the system can be used to investigate aspects of climate change uncertainty, deployable water resources, and water quality dynamics in upper and lower reaches of the drainage network. The results confirm the large uncertainty in climate change scenarios and freshwater impacts due to the choice of general circulation model (GCM). This uncertainty is shown to be greatest during summer months as evidenced by large variations between GCM-derived projections of future low river flows, deployable yield from groundwater, severity of nutrient flushing episodes, and long-term trends in surface water quality. Other impacts arising from agricultural land-use reform or delivery of EU Water Framework Directive objectives under climate change could be evaluated using the same framework.

Introduction

Climate change could have far reaching consequences for water resources (Arnell, 2003a; Arnell, 2004; Leavesley, 1994; Pilling and Jones, 1999; Wilby et al., 1994), the physiochemistry (Hejzlar et al., 2003; Webb et al., 2003; Wilby et al., 1997) and ecology of freshwater environments

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(Beaugrand and Reid, 2003; EA, 2005; Hiscock et al., 2004; Moss et al., 2003; Sommer et al., 2004). Interpretations of past and future climatic impacts are confounded by other environmental drivers such as changes in agriculture or land management (Dils and Heathwaite, 2000; Whitehead et al., 2002a). Consequently, an integrated approach to impact assessment is required in which high resolution climate change scenarios drive process-based models of freshwater systems to quantify the likely hydrological, water quality and ecological impacts (Worrall et al., 2003).

Climate change impact assessment involves recognising three key aspects of uncertainty. First, there are uncertainties linked to general circulation models (GCMs), in particular: (i) future emissions of greenhouse gases, (ii) their conversion into atmospheric concentrations and (iii) subsequent radiative forcing (Allen et al., 2001; Jenkins and Lowe, 2003; New and Hulme, 2000; Webster et al., 2003). Second, there are uncertainties in the representation of climatology at regional scales, including differences between dynamical and statistical downscaling methods (Leung et al., 2003; Prudhomme et al., 2002). Third, there are parameter and structural uncertainties in the hydrochemical and ecological models used for impact assessment (Bathurst et al., 2004; Jakeman et al., 1993; Wilby, 2005).

This paper focuses on the first source of uncertainty (i.e., future climate impacts projected by different emissions scenarios/GCMs) and has two main aims. First, to develop an integrated approach to climate change impact assessment at the river catchment scale. Second, to explore the range of uncertainty in future river flow and quality indicators arising from the choice of GCM driven by a limited range of emission scenarios. The first aim will be addressed by linking water resource (CATCHMOD) and water quality (INCA) models to GCM output using statistical downscaling techniques. The second aim will be achieved by driving the CATCHMOD and INCA models with downscaled daily precipitation and evaporation series arising from three GCMs. The River Kennet provides an ideal case study because the water resources of south-east England are expected to face growing pressure from urbanisation and projected reductions in summer rainfall (Limbrick et al., 2000).

Study area and data resource

The River Kennet (1200 km^2) is typical of Cretaceous Chalk catchments in southern England (Fig. 1). Rising from a source at 190 m, the Kennet flows broadly eastwards for about 40 km before entering the River Thames at Reading. Chalk underlies approximately 80% of the total area. Gently sloping valleys dominate the relief: the altitudinal range spans ~260 m, from 32 m at the confluence with the Thames, to 294 m at the highest point on the Marlborough Downs. The long-term average annual precipitation over the catchment is ~800 mm, with approximately 38% apportioned to river flow and 62% to evapotranspiration. Much of the effective precipitation percolates into the chalk aquifer, and consequently the flow response of the Kennet is highly damped. The long-term mean annual flow at Theale, the lowest gauging station on the Kennet is 9.6 $m^3\,s^{-1}$ (or ~300 mm of runoff). The catchment is mainly rural, with arable agriculture being the predominant land-use. There are several large towns along the main channel which discharge treated sewage directly into the Kennet. The catchment provides water for public and industrial supply by means of direct surface and groundwater abstractions.

The upper River Kennet is designated a site of special scientific interest (SSSI) in recognition of its outstanding

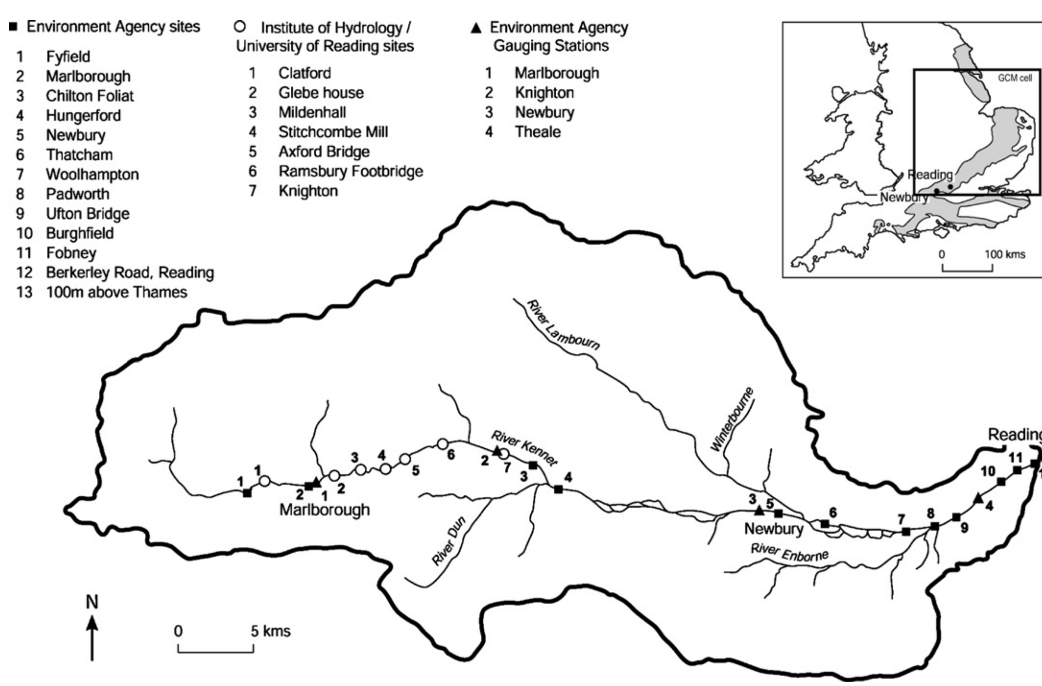

Figure 1 River Kennet catchment. The inset map shows the location of Cretaceous Chalk in England, and a typical GCM grid cell for scale.

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 growing concerns about perceived ecological deterioration of the river, particularly poor growth of *Ranunculus* (Water Crowfoot) downstream of Marlborough, accompanied by unsightly growth of epiphytes. Attention has focused on the effects of protracted droughts in 1991–1992 and 1996–1997, water abstraction pressures, and declines in water quality associated with reduced dilution of effluent from Marlborough water treatment works (WTW).

The Kennet was also chosen because it has been the focus of previous investigations of climate change and land-use effects and is one of several catchments underpinning the Euro-Limpacs Framework VI Project (Limbrick et al., 2000; Wade et al., 2002a; Whitehead et al., 2002a). Furthermore, the NERC LOCAR project and earlier studies established weekly monitoring programmes throughout the catchment with samples taken by the University of Reading, CEH Wallingford and the Environment Agency (EA) (Fig. 1).

Daily area average precipitation amounts were obtained for the Berkshire Downs (Davis, 2000). Monthly Penman potential evaporation (PE) amounts were obtained from nearby climatological stations for the Berkshire Downs, and converted to average daily rates for the period 1960–1989 (Davis, 2001). Daily mean temperatures were extracted from the British Atmospheric Data Centre (BADC) for the station at Malborough. Gauged daily flows at Theale and Knighton (an upstream station draining an area of 295 km^2) were obtained for 1961–2004. However, flows corrected for artificial influences were available only for 1991–1999. Water quality data exist for a broad range of determinands including soluble reactive phosphorous (SRP) and total phosphorus (TP). TP concentrations for the WTW discharge at Marlborough were also provided by Thames Water. In addition, ecological data on macrophyte and epiphyte biomass have been collected over several years (Flynn et al., 2002). Other data collated for the water quality modelling includes: land cover data for 1 km^2 cells; parish statistics describing crop areas and livestock numbers; fertiliser application rates; hydrologically effective rainfall; soil moisture deficit and air temperature data from the MORECS model; and an estimation of dry and wet, nitrate and ammonium deposition within the catchment derived from MATADOR-N (see Whitehead et al., 2004).

Methodology

Climate model products

Atmospheric predictor variables used to calibrate the scenario tool were obtained from the National Center for Environmental Prediction (NCEP) re-analysis. Future climate change scenarios originate from three GCMs: the Hadley Centre's coupled ocean/atmosphere climate model (HadCM3), the Canadian Centre for Climate Modelling and Analysis model (CGCM2), and the Commonwealth Scientific and Industrial Research Organisation model (CSIRO Mk2). The archive of NCEP and GCM output contains 29 daily predictors (describing atmospheric circulation, thickness, and moisture content at the surface, 850 and 500 hPa levels), for nine regions covering the British Isles, for the period 1961–2100 (Wilby et al., 2002). In the present study, only predictors from a grid-box overlying 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). These scenarios cover a range of future socioeconomic, demographic and technological storylines.

Table 1a Definition of CATCHMOD parameters used for daily flow simulation in the River Kennet at Theale

Parameter and description	Zone 1 (baseflow from aquifers mainly chalk)	Zone 2 (runoff from clay areas)	Zone 3 (runoff from urban areas)	Zone 4 (runoff from riparian areas)
Area of contributing zone (km^2)	800	80	30	10
Direct percolation (*DP*) (%). A fixed fraction of precipitation that bypasses the soil horizon even during periods of soil moisture deficit	15	0	0	0
Potential drying constant (*PDC*) (mm). Value of deficit above which evaporation occurs at a reduced rate	50	50	1	0
Gradient of the drying curve (*GDC*). A reduced rate at which soil moisture is evaporated once the potential drying constant has been exceeded	0.3	0.3	0.3	0.3
Linear storage constant (*LSC*) (days). Represents temporary storage in the unsaturated zone	10	1	0.1	0.1
Non linear storage constant (*NSC*) (days/km^2). Represents storage in the saturated zone/aquifer	400	1	0.001	0.001

Parameters were manually calibrated against naturalised flow series for the period 1961–1987.

Note that the GCMs and emission scenarios were selected for several scientific and pragmatic reasons: (1) availability of output for more than one SRES emission scenario; (2) availability of primary downscaling variables archived daily; (3) availability of unbroken daily series for the entire period 1961–2100; and (4) realism of the GCM behaviour with respect to NCEP reference data.

Catchmod

CATCHMOD is a conceptual water balance model in widespread use by the Environment Agency for rainfall runoff modelling (for detailed descriptions see Greenfield, 1984; Wilby et al., 1994). Daily river flows at Theale were simulated using a four-zone model comprising baseflow from the chalk aquifer, runoff from clay and riparian areas, and quickflow from urban areas. Manually calibrated values and parameter definitions for this conceptual water balance model are provided in Table 1a. As with previous applications of CATCHMOD for climate change impact assessment, it is assumed that land cover remains constant; that the relationship between PE and actual evaporation remains the same under climate change; and that soil properties and their hydrological behaviour remain unchanged. With these caveats in mind, CATCHMOD was used to investigate potential changes in river flows arising from downscaled daily precipitation and PE series (the only inputs required by the model).

In CATCHMOD a direct percolation mechanism allows fixed proportions (*DP*) of incoming precipitation, that exceeds the potential evaporation rate, to bypass the soil store even during periods of soil moisture deficit. This process represents the observed behavior of fractured soils and macropores during summer rainfall and is only relevant to soils overlying permeable strata. The soil moisture sub-model is based on a drying curve such that when the supply of moisture is limited, evaporation occurs at a constant proportion (*GDC*) of the potential rate. The value of the soil moisture deficit above which evaporation occurs at the reduced rate is termed the potential drying constant (*PDC*). The ''upper'' soil horizon, therefore, has a finite capacity equal to this constant. The ''lower'' horizon is depleted by the reduced evaporation rate only when the upper horizon is empty, and can accumulate large deficits during droughts. During recharge, wetting by precipitation fills the upper soil horizon before replenishing the lower horizon. When a contributing zone becomes saturated, excess moisture from the soil store (along with *DP*) contributes to total percolation. This flow is held temporarily in a linear store (*LSC*) representing the unsaturated zone. Where a soil is underlain by permeable geological formations, excess water from the overlying soil zone percolates through *LSC* to the aquifer below and is released at

Table 1b Measures of CATCHMOD calibration fit to gauged river flows at Knighton and Theale on the Kennet, 1961–1990

Measure	Knighton		Theale	
	CATCHMOD	INCA	CATCHMOD	INCA
RMSE (m^3/s)	0.64	1.01	2.47	3.92
MAE (m^3/s)	0.44	0.71	1.57	2.79
Nash-Sutcliffe	0.86	0.66	0.78	0.45
Rsq (%)	87	76	81	68
Mean bias (%)	19	34	17	28

For comparative purposes, equivalent statistics are also provided for the hydrological component of INCA. All measures were computed using HydroTest (see: http://www.hydrotest.org.uk).

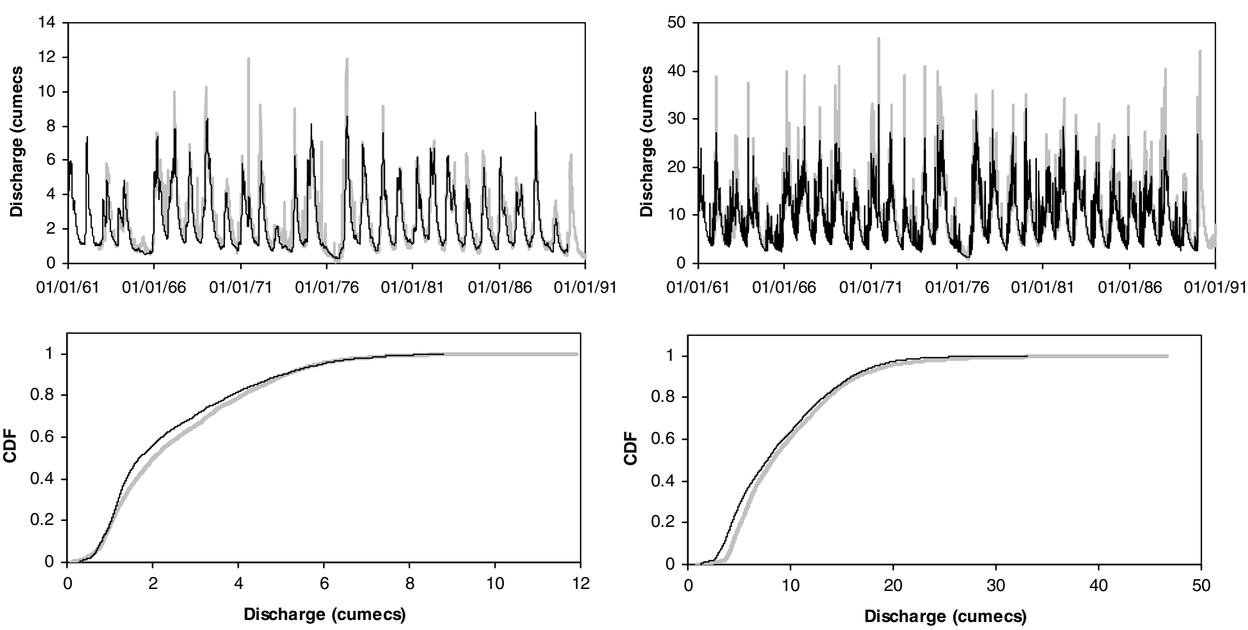

Figure 2 Observed [grey line] and CATCHMOD simulated [dark line] daily flows in the River Kennet at Knighton [left panels] and Theale [right panels] for the period 1961–1990. Note that CATCHMOD was calibrated using data for water years 1961/2–1986/7, and that the west Berkshire groundwater scheme was operational in the autumns of 1975 and 1976.

a non-linear rate (*NSC*) from the groundwater store. Different parameters are used to represent the conditions in each contributing zone (Table 1a) and river flow generated from multiple zones was summed to give the total daily discharge in the upper and lower Kennet, at Knighton and Theale, respectively.

CATCHMOD has already been extensively tested for a range of catchment types in SEE (see: Davis, 2001; Diaz-Nieto and Wilby, 2005; EA, 2004; Wilby et al., 1994). Fig. 2 shows model simulations of river flow at Knighton and Theale for the period 1961–1990. Cumulative distributions of daily river flows indicate that CATCHMOD performs well for low-flows in both the upper and lower reaches of the Kennet, but consistently underestimates peak flows (Fig. 2, lower panels). CATCHMOD performance is superior to that of the hydrological component of INCA for a range of diagnostics (Table 1b) and, according to the Nash statistic, better in the upper than the lower catchment. These results support the choice of CATCHMOD for the detailed assessment of climate change impacts on river flows at Knighton (described below).

Daily discharges for the River Kennet at Knighton were simulated for each climate change scenario to assess the potential impact on reliability of groundwater abstractions at an exemplar source (Axford Pumping Station, Wiltshire). The close interaction between the aquifer and the river means that abstraction from this location has a rapid effect on river flows. To protect downstream flows in this environmentally sensitive area, the abstraction licence limits the maximum volume that can be taken whenever the daily flow at Knighton is less than 90 Ml/d. A simple analysis was performed to investigate the subtle interplay between climate-driven changes in the daily river flow regime and potential water resource deployable *under current abstraction rules*.

INCA modelling framework

The Integrated Nitrogen Model for CAtchments (INCA-N) model is a mass-balance, dynamic model that simulates key factors and processes affecting NO_3 and NH_4 stored in soil and ground water systems (Whitehead et al., 1998a,b). Specifically, INCA-N accounts for input fluxes of atmospheric deposition of ammonium and nitrate (wet and dry), ammonium and nitrate fertiliser applications, mineralisation of organic matter (to form NH_4) and nitrification (to form NO_3), and nitrogen fixation. Output fluxes of plant uptake, immobilisation and denitrification are subtracted from the inputs in order to calculate the amount available for stream output. These inputs and outputs are differentiated by landscape type and varied according to environmental conditions: soil moisture and temperature. The model accounts for stocks of NO_3 and NH_4 in the soil and ground water pools, and in the stream reaches. The model also simulates the flow of water through the plant/soil system from

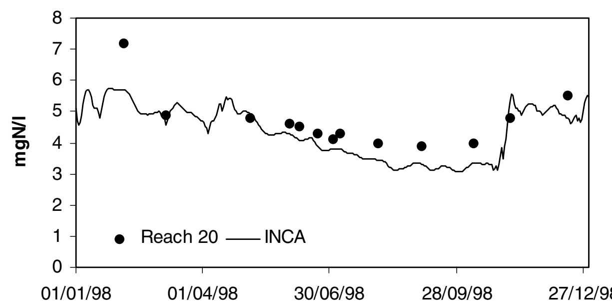

Figure 3 Observed [black circles] and INCA simulated daily nitrogen concentrations at Theale during 1998.

Table 2 Large-scale atmospheric predictor variables for SEE used to downscale daily temperature, precipitation and PE for the River Kennet

Predictand	Predictors (NCEP re-analysis)	Partial *r*
Temperature	Mean sea level pressure	−0.27
	Mean regional temperature at 2 m	0.45
	Vorticity of the atmosphere at 500 hPa level	0.17
	850 hPa geopotential height	0.29
	Near surface westerly wind component	0.19
	Near surface divergence of the atmosphere	−0.14
Precipitation	Mean sea level pressure	0.19
	Near surface specific humidity	0.23
	Near surface southerly wind component	0.29
	Near surface vorticity	0.07
	850 hPa geopotential height	−0.22
PE	Mean sea level pressure	0.15
	Near surface specific humidity	−0.40
	Mean regional temperature at 2 m	0.72
	Near surface westerly wind component	−0.21
	Near surface wind strength	−0.12
	500 hPa geopotential height	−0.26

The partial correlation coefficient (*r*) shows the explanatory power that is specific to each predictor. All are significant at the $p = 0.01$ level.

different land use types to deliver the N load to the river system. The N is then routed downstream after accounting for direct effluent discharges, and in-stream nitrification and denitrification (Whitehead et al., 1998a; Wade et al., 2002b). In-stream plant uptake of N is not modelled explicitly in the current version of INCA-N; it is assumed that the simulated removal of N reflects both in-stream denitrification and plant uptake.

The philosophy of the INCA-N model is to provide a process-based representation of the factors and processes controlling N dynamics in both the land and in-stream components of river catchments, whilst minimising data requirements and model structural complexity (Whitehead et al., 1998a). As such, INCA-N produces daily estimates of soil moisture deficit, as well as discharge, stream water NO_3 and NH_4 concentrations and fluxes, at discrete points along a river's main channel. Also, the model is semi-distributed so spatial variations in land use and management can be taken into account, though the hydrological connectivity of different land use patches is not modelled in the same manner as a fully-distributed approach, such as SHETRAN (Birkenshaw and Ewen, 2000). Rather, the hydrological and nutrient fluxes from different land use classes and sub-catchment boundaries are modelled simultaneously and information fed sequentially into a multi-reach river model.

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). INCA has been applied to the River Kennet in previous studies to evaluate current and historical nitrogen behaviour (Whitehead et al., 2002a) as well as the impacts of climate change on catchment hydrology (Limbrick et al., 2000). Fig. 3 illustrates the ability of INCA to simulate in-stream nitrate concentrations at a reach immediately upstream of Theale. Overall, the model captures the observed decline in nitrogen concentrations from winter to summer, as well as the abrupt increase in autumn.

In this paper, we applied INCA-N to simulate nitrogen response in the Kennet under each emission and GCM scenario described above. As with CATCHMOD, GCM outputs were downscaled to the River Kennet and transient runs performed for the period 1961–2100. A new version of INCA-N was developed to enable continuous daily simulations for the full 140-year period. Daily dynamics are important when considering water quality because many processes that affect nitrogen are dependent on variables such as daily temperature, soil moisture deficit, rainfall and river flow. INCA-N was set up for a 'natural' reach at the top of the Kennet and for a second reach receiving effluent from Marlborough WTW. In addition, an 'enhanced nitrification' scenario was performed in each case to allow for increased bacterial populations expected under climate change. Evidence from long-term studies in the Tillingborne catchment suggest that as temperature increases, bacterial populations that control nitrogen mineralisation and nitrification processes in the soils also increase (Whitehead et al., 2002b). Although INCA-N process rates are first-order and temperature dependent, nitrification rates could increase at an even higher rate in the future, and so sensitivity to this effect was explored. Changes in the C/N ratio of plant residues were not included directly.

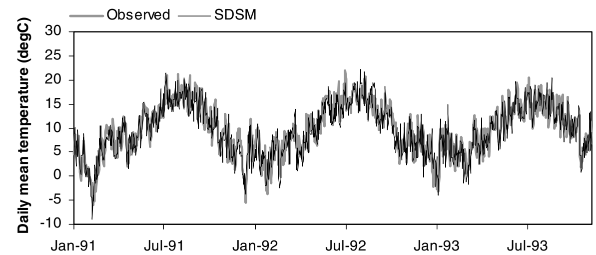

Figure 4a Comparison of observed and downscaled daily mean temperatures at Malborough using data that were not used for model calibration.

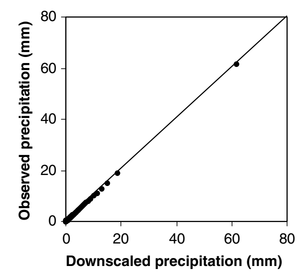

Figure 4b Comparison of observed and downscaled quantiles of daily precipitation amounts for the River Kennet 1961–1990. Note that SDSM slightly underestimated the frequency of days with precipitation (60% days) compared with observations (63% days).

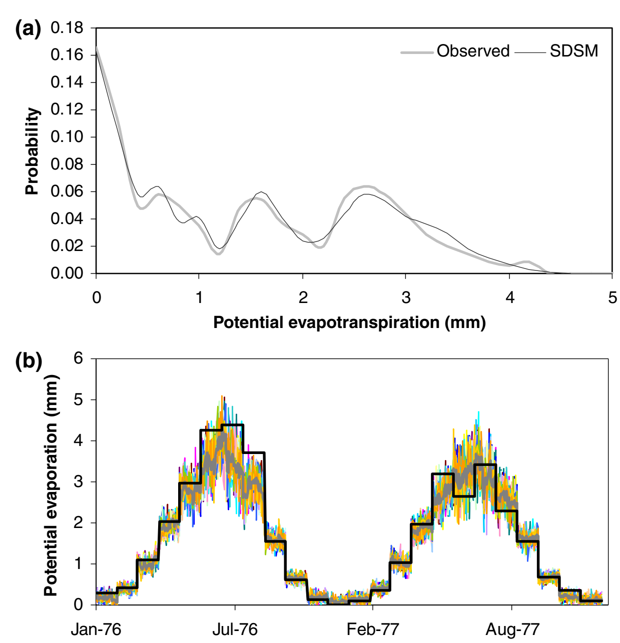

Figure 5 Comparison of observed and downscaled daily PE for the River Kennet (a) probability distribution for 1961–90, and (b) during 1976–77. The lower panel shows all 20 ensemble members and the ensemble mean [thick grey line] compared with the monthly observations [thick black line].

Statistical downscaling model (SDSM)

Climate change scenarios were generated for the Kennet via the statistical downscaling model (SDSM) version 3.1 (Wilby et al., 2002). Full technical details and split-sample tests of SDSM are provided elsewhere (e.g., Diaz-Nieto and Wilby, 2005). SDSM is best described as a hybrid of regression-based and stochastic weather generator downscaling methods, because daily atmospheric circulation patterns and moisture variables are used to condition local-scale weather generator parameters at target sites. The stochastic component of SDSM enables the generation of multiple simulations with slightly different time series attributes, but the same overall statistical properties. This has several advantages over conventional 'change factor' methods not least that new temporal sequences of (extreme) events can be generated for future climate scenario assessment (Diaz-Nieto and Wilby, 2005).

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 PE across the catchment) and large-scale indices of regional weather over SEE obtained from the NCEP re-analysis for the *current* climate. Table 2 shows the partial correlation coefficients for each predictor–predictand relationship. Not surprisingly, models of local temperature and PE are most heavily weighted towards regional temperatures, whereas precipitation is most strongly correlated with the strength of southerly airflows and humidity. 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 (HadCM3, CGCM2 and CSIRO) driven by the two emission scenarios (A2 and B2) for the full period 1961–2100.

Climate change scenarios

Current climate

The efficacy of SDSM for downscaling daily meteorological variables for the current climate has been discussed at length elsewhere (see Diaz-Nieto and Wilby, 2005; Goodess et al., 2003; Harpham and Wilby, 2005; Wilby et al., 2002),

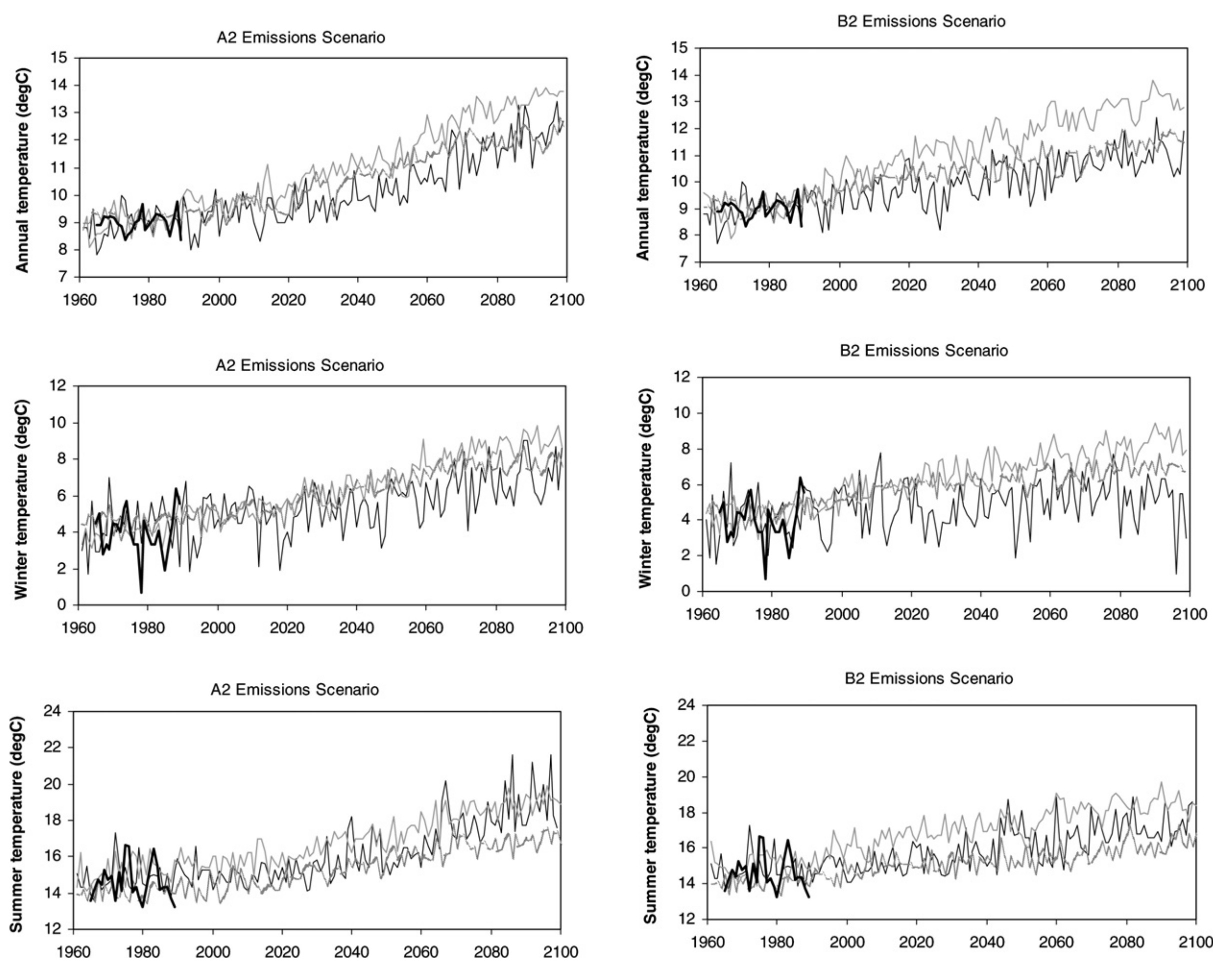

Figure 6 Annual and seasonal temperature scenarios downscaled to the River Kennet (Malborough station) using output from three GCMs (HadCM3 [thin black line], CGCM2 [dark grey line] and CSIRO Mk2 [light grey line]) and two emission scenarios (A2 [left column] and B2 [right column]). Observed temperatures (thick black line) for the period 1961–1990 are shown for comparison.

so only selected examples of model capability are provided in this paper. In line with other weather generator methods, SDSM adequately captures time-series of temperature (Fig. 4a) and the distributions of daily quantities such as precipitation (Fig. 4b) and PE (Fig. 5a), respectively. However, SDSM is susceptible to 'over-dispersion' – a well-documented limitation of daily weather generators in which the variance of lower frequency quantities, such as monthly PE totals (Fig. 5b), is underestimated (Katz and Parlange, 1998). In the present case, over-dispersion occurs because the lag-1 autocorrelation of downscaled PE series ($r = 0.96$) is slightly weaker than observations ($r = 0.98$). This is partly due to the use in SDSM calibration of daily average PE derived from monthly totals. As a consequence, downscaled scenarios tend to underestimate the persistence of extreme events such as the 1976 drought (Fig. 5b). This should be kept in mind when interpreting future climate impacts.

Future climate scenarios

Transient daily mean temperature, precipitation amounts and PE totals were produced for the Kennet basin using HadCM3, CGCM2 and CSIRO model outputs from the A2 and B2 emission scenarios for the full period 1961–2100. The following describes the main changes in these three input variables for the CATCHMOD and INCA-N simulations.

Temperature

Large differences emerge in the rates of winter and summer warming downscaled from the three GCMs (Tables 3a and 3b, respectively). Rates of winter warming for the 2080s range from +1.1 °C by HadCM3 under B2, to +4.5 °C by CSIRO under A2 emissions. The span of summer temperature changes is narrower, ranging from +2.1 °C by CGCM2 under B2, to +3.7 °C by HadCM3 under A2 emissions. Differences

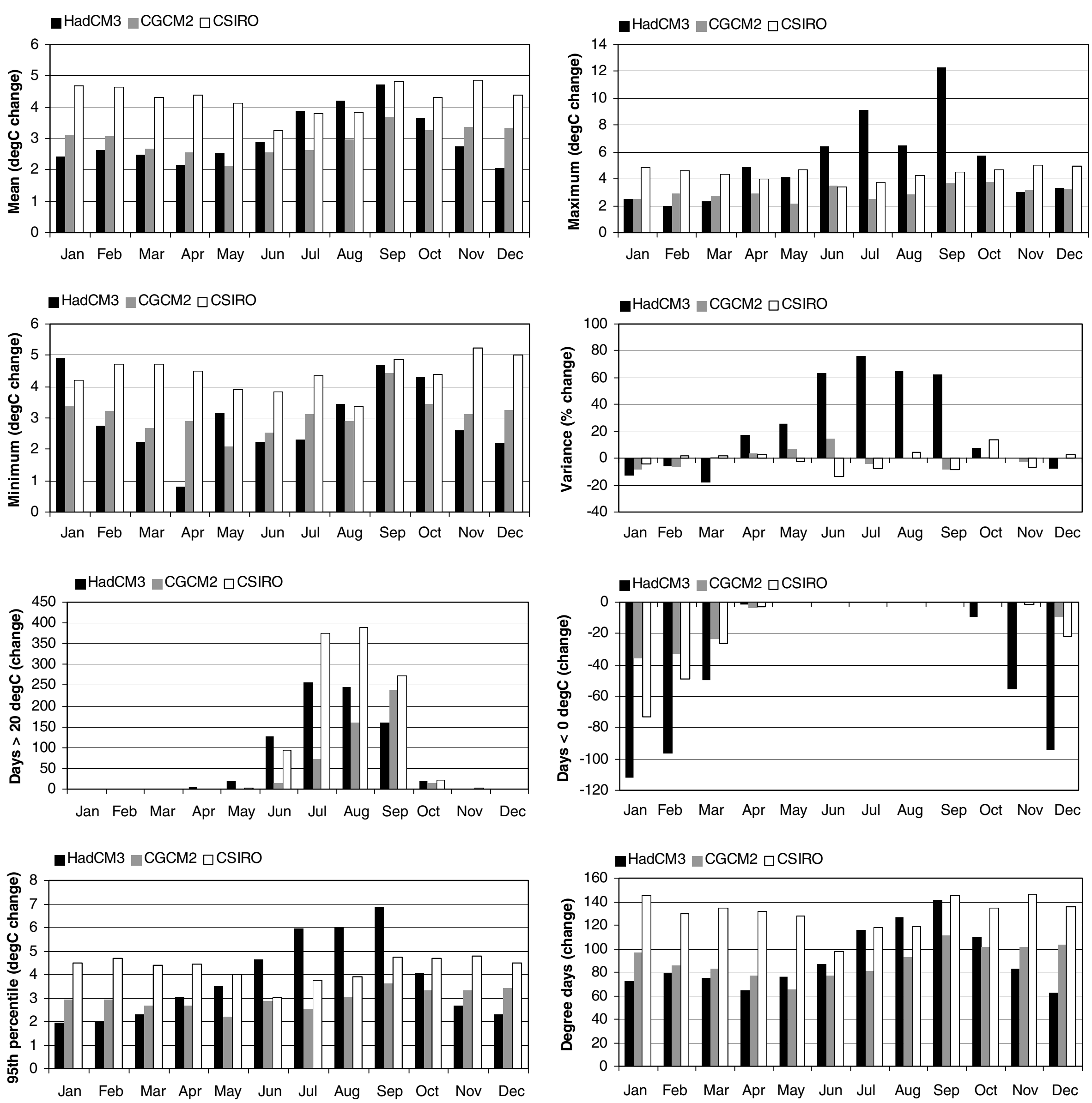

Figure 7 Changes in River Kennet (Malborough station) daily mean temperature indices between 1961 and 1990 and the 2080s under A2 emissions for three different GCMs.

also emerge between the GCMs for the pattern and rates of warming by the 2020s and 2050s (Fig. 6).

Although biases in downscaled long-term seasonal mean temperatures vary between ± 0.6 °C, most downscaled temperatures for the control period 1961—1990 were warm relative to observations. Far more notable, however, is the consistent underestimation of the inter-annual variability in seasonal temperatures relative to observed climatology that is most pronounced in CGCM2 (Fig. 6). This is an artefact of unrealistic representations of inter-annual variability in GCM predictors used to drive SDSM. For example, inter-annual variability in summer temperatures over SEE is 38% lower when downscaled using CGCM2 predictors compared with observations. Overall, HadCM3 appears to reproduce the most realistic inter-annual behaviour in winter and summer temperatures when compared with observations (Fig. 6).

Differences amongst the downscaled temperature scenarios become even more apparent at sub-annual timescales (Fig. 7). The CSIRO model yields the largest changes by the 2080s in monthly mean temperatures in winter and in the frequency of hot days in summer (defined as days >20 °C). However, HadCM3 yields the largest increase in maximum temperatures in summer (absolute and 95th percentile) and hence large increases in the variance of summer temperatures too. Temperature changes projected by CGCM2 generally lie within the bounds set by the other two models.

Precipitation

All three GCMs project increases in winter precipitation ranging between +15% (HadCM3, B2) and +62% (CSIRO, A2) by the 2080s (Table 3b). However, there is large divergence about changes in summer precipitation which ranges from −36% (HadCM3, A2) to +54% (CGCM2, A2) by the 2080s (Table 4b). Such extreme uncertainty in precipitation has been noted previously (Jenkins and Lowe, 2003). However, interpretations should be tempered by the large biases in the mean and standard deviation of seasonal totals returned by CGCM2. As with temperature, the seasonal precipitation series downscaled from HadCM3 most realistically captures the extent of inter-annual variability (due to smaller biases in the predictor variables compared to observations).

The transient precipitation changes highlight the relative aridity of HadCM3 in summer, and wetness of CGCM2 and CSIRO in winter (Fig. 8). This is further emphasised by the projected changes in monthly totals and wet-day frequencies (Fig. 9). The largest increases in precipitation extremes (as indicated by the maximum one-day and 5-day totals and 95th quantiles) are returned by CGCM2 for late summer through to end of winter.

Potential evaporation

All three GCMs project modest increases in winter PE totals ranging from +3% (HadCM3, B2) to +9% (CSIRO, A2) by the 2080s (Table 3c). Changes in summer PE are slightly larger, spanning +5% (HadCM3, B2) to +16% (CSIRO, A2) by the 2080s

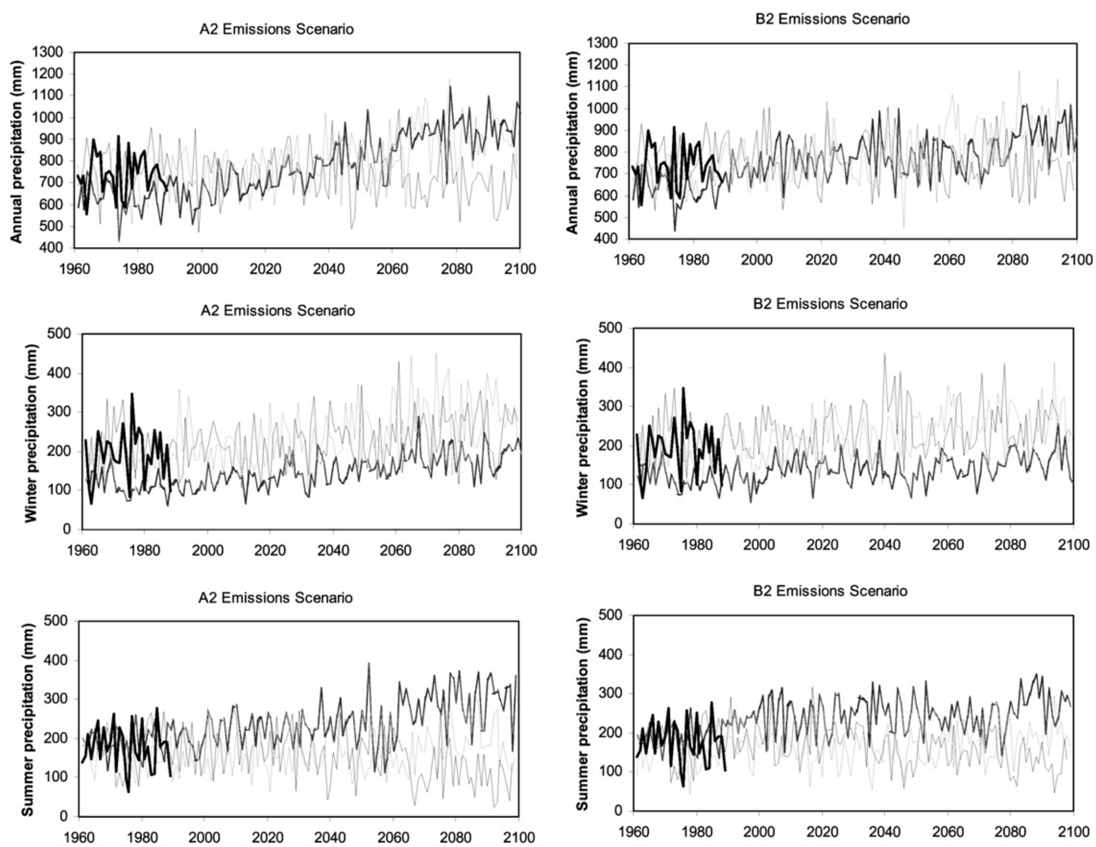

Figure 8 As Fig. 6 but for seasonal precipitation totals.

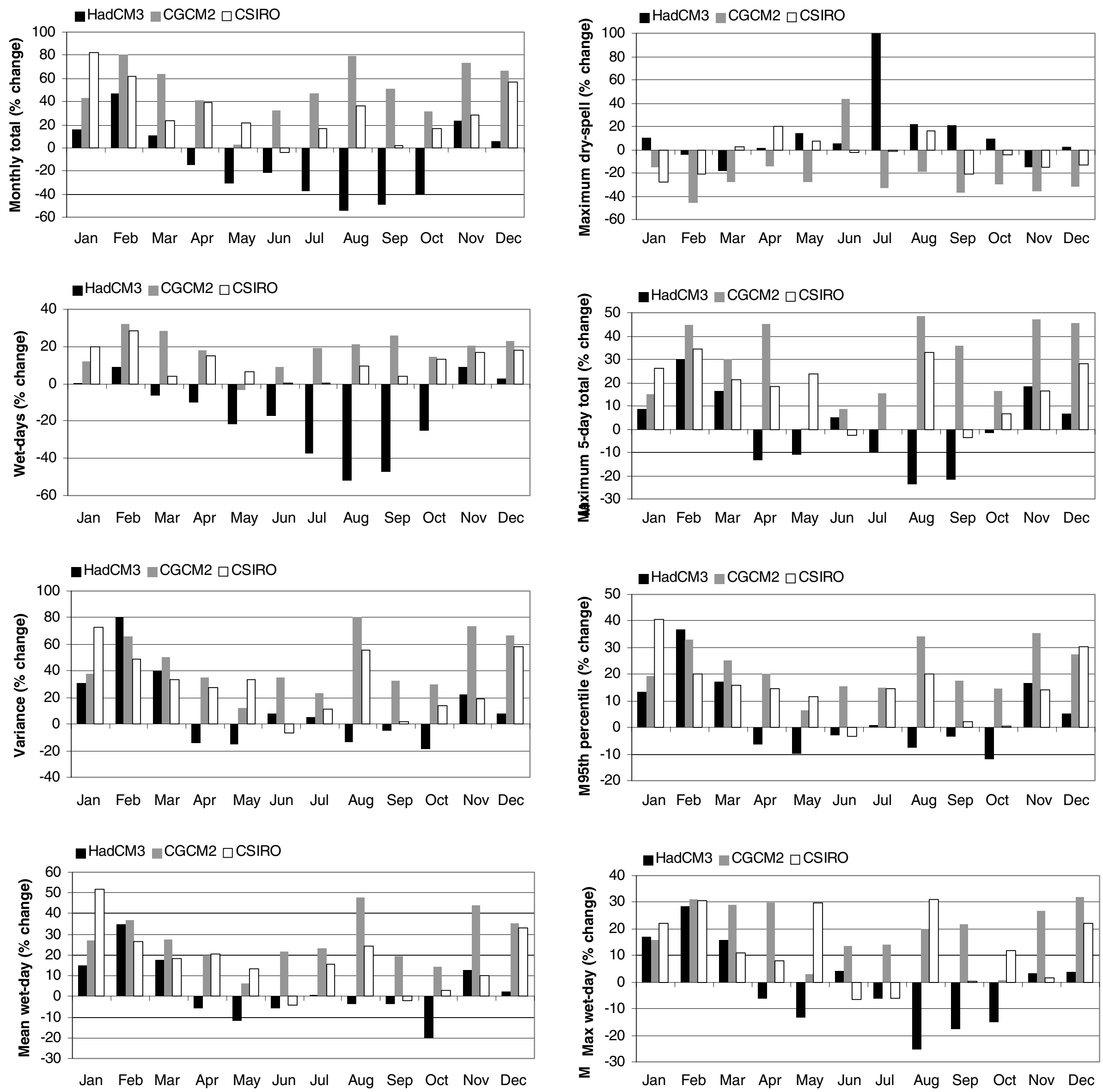

Figure 9 Changes in area-average precipitation diagnostics for the River Kennet between 1961 and 1990 and the 2080s under A2 emissions for three different GCMs.

(Table 4c). These increases are more conservative than those previously reported for SEE using the change factor method (Arnell, 2003b; Diaz-Nieto and Wilby, 2005).

Although biases in the seasonal mean PE are small (~5%), all downscaled scenarios significantly underestimate inter-annual variability (by as much as 90% in winter and 78% in summer in the case of CGCM2). This was attributed to the unrealistic inter-annual behaviour of key predictor variables and the over-dispersion problem. Plots of the transient behaviour of seasonal PE further emphasise the under-estimation of inter-annual totals for the period of observations (Fig. 10). Not surprisingly, the PE series closely mirror projected changes in temperature (Fig. 6), so projected changes in monthly mean PE tend to exhibit maximum increases in mid/late summer (Fig. 11). Inter-model differences in PE are also relatively small compared with changes in precipitation.

Results

The impact of the projected climate changes was first assessed from the point of view of changing river flows, then implications for the reliability of groundwater abstractions at the case study site, and changes in key water quality parameters.

River flows

Overall, CGCM2 yields the most optimistic water resource outlook for all scenarios and time-slices, notwithstanding minor reductions in mid-summer flows in the 2020s (Fig. 12). However, large increases in winter flows projected for the 2050s and 2080s represent a potential increase in flood risk. As implied by the previous analysis of precipitation and PE, the scenarios downscaled from CSIRO yield less

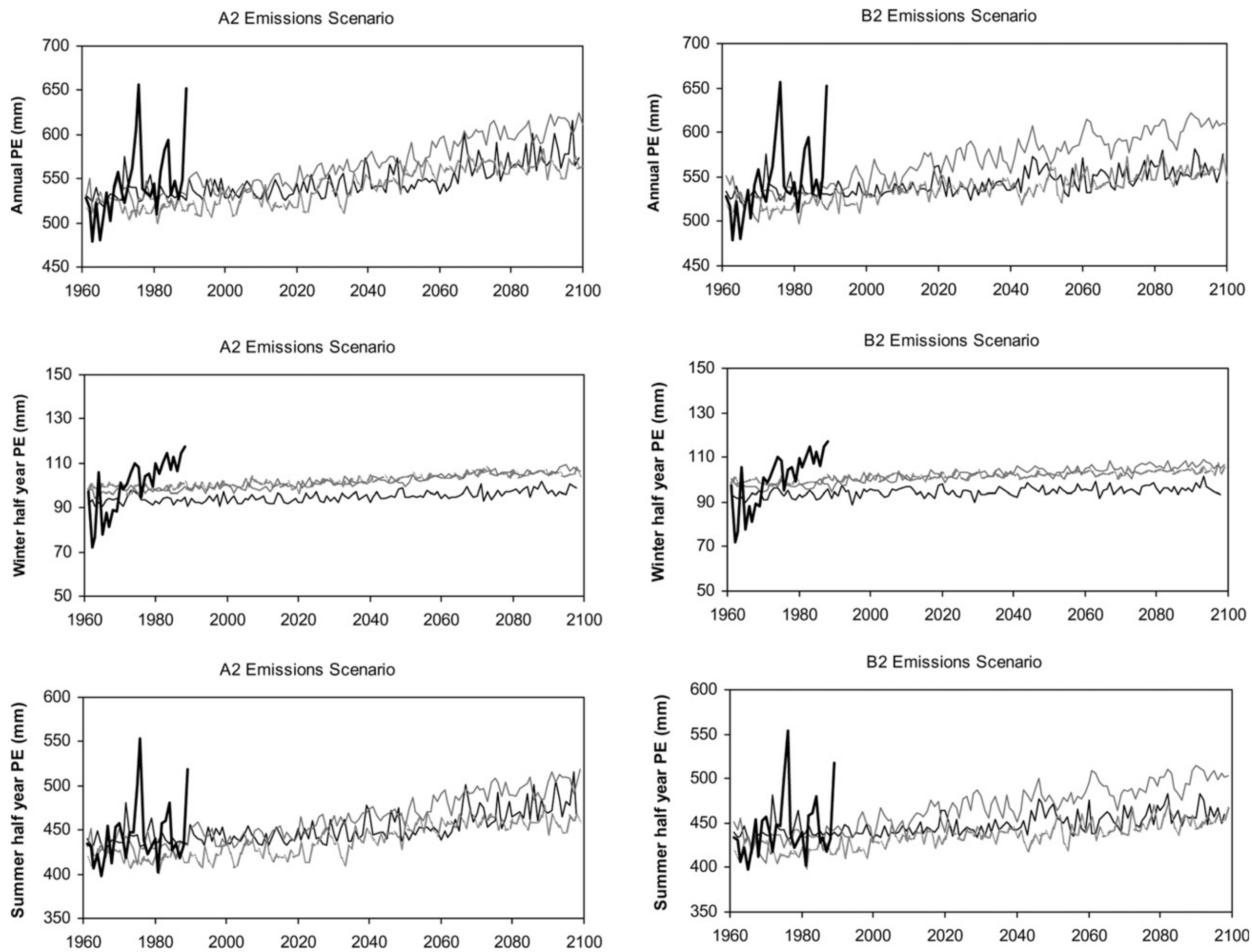

Figure 10 As Fig. 6 but for seasonal potential evaporation (PE) totals.

dramatic changes in daily river flows than CGCM2 but still signify resources close to, or greater than baseline conditions from the 2020s onwards. In contrast, the HadCM3 A2 scenario suggests reductions to summer flows by ~20%, and autumn flows by ~50% in the 2080s. This is countered by slight increases to late winter/early spring flows of ~10% that is suggestive of a delayed and shortened groundwater recharge season. However, it should be recalled that the mean bias of CATCHMOD is of the same order (see Table 1b).

Changes in the annual flow regime are reflected in changes to daily discharge quantiles (Fig. 13). Under B2 emissions all downscaled scenarios suggest greater sensitivity of low (Q95) than high (Q5) river flows – a pattern of change that is amplified through time. Changes in flow quantiles are even greater under the A2 emissions downscaled from CGCM2 and CSIRO as large precipitation increases outstrip relatively modest rises in PE (Tables 3 and 4). All such changes are far greater than the CATCHMOD bias. In comparison, the HadCM3 A2 scenario heralds slight reductions in Q5 and intermediate (Q50) river flows in the 2020s that shift to reductions in Q50 and Q95 by the 2080s reflecting the large decrease in summer precipitation. At this time, large summer soil moisture deficits carry over into autumn and winter, limiting the increased flood risk relative to CGCM2 and CSIRO.

Groundwater abstractions

Although changes in river flow affect potential resources, the reliability and output of a source will reflect a host of other considerations including the terms of abstraction licences. An analysis of groundwater abstractions at Axford illustrates the sensitivity of resource availability to projected changes in the River Kennet's flow regime. The current licence conditions restrict abstraction volumes below a flow constraint to protect low flows. Under the terms of the existing licence and observed river flows, abstractions at a higher rate were permissible above the flow constraint on 80% of days. For the same period, CATCHMOD driven by observed rainfall and PE suggests that the source could be used on 86% of days. This indicates that the combined effect of imperfect climatology inputs and CATCHMOD biases gives too many days, where the source can be used relative to observations. CATCHMOD simulations of river flow at Knighton using climatology downscaled from GCMs suggest that the operator could abstract groundwater at the higher rate on 47–88% days (Table 5a). This translates into 83–96% of the maximum licensed resource depending on choice of GCM for the control period (Table 5b). Hence, the range of uncertainty due to GCMs is far greater than that due to CATCHMOD bias.

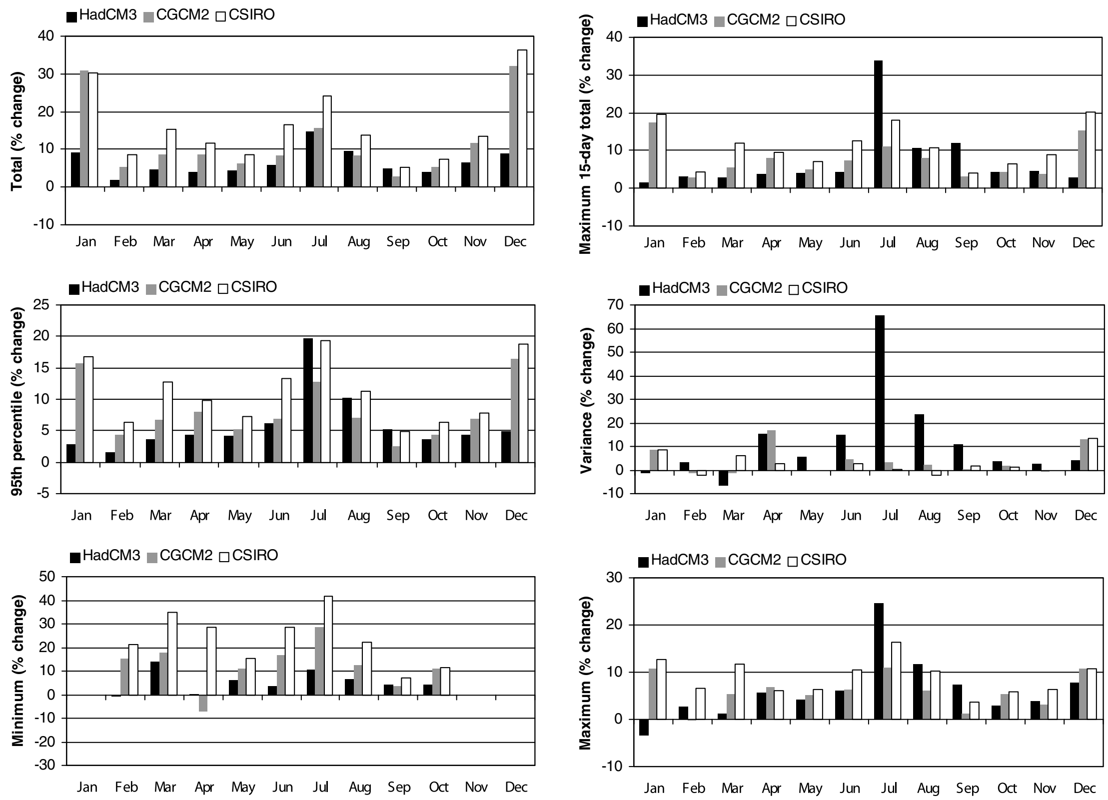

Figure 11 Changes in area-average PE diagnostics for the River Kennet between 1961 and 1990 and the 2080s under A2 emissions for three different GCMs.

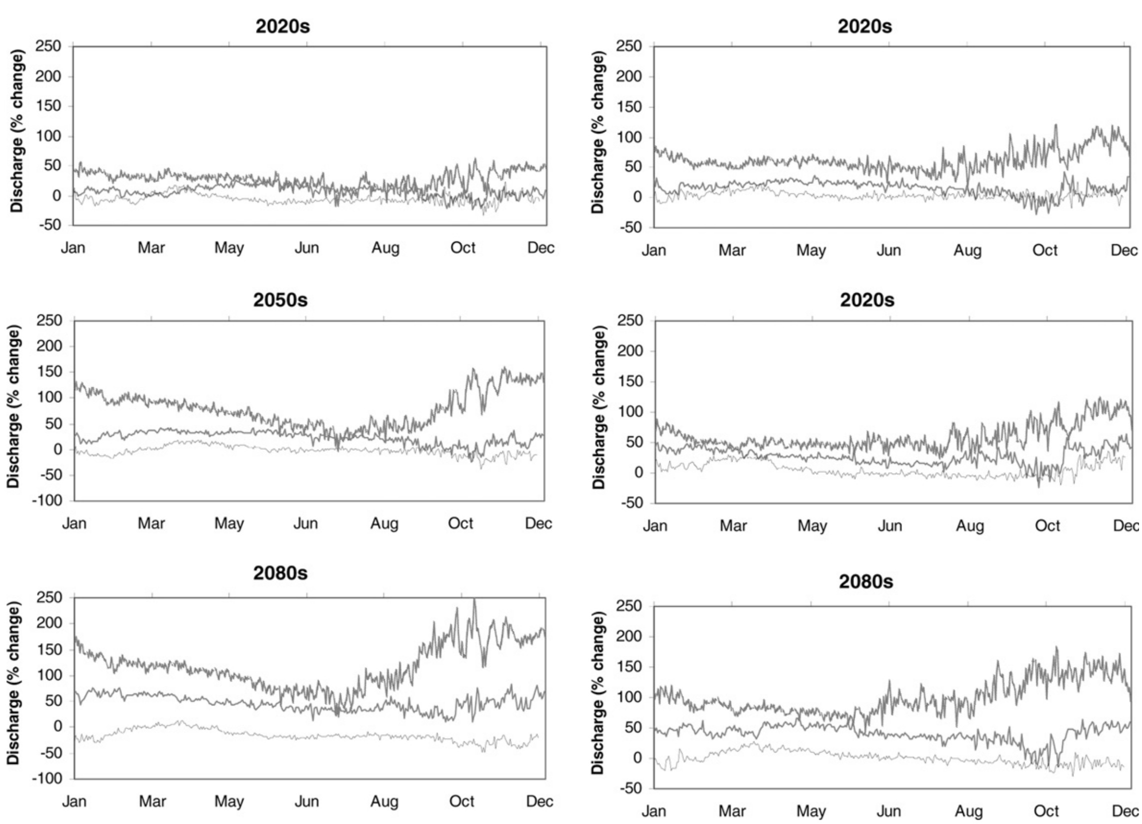

Figure 12 Percent changes in the daily discharge of the River Kennet by Julian day as predicted by CATCHMOD under A2 (left column) and B2 (right column) emissions downscaled from three GCMs (HadCM3 [black line], CGCM2 [dark grey line], and CSIRO [light grey line]) in the 2020s, 2050s and 2080s.

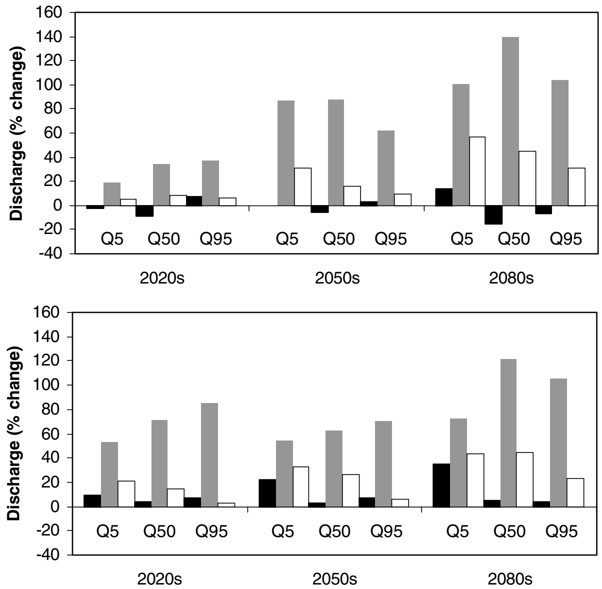

Figure 13 Changes in the daily flow quantiles of the River Kennet at Theale using daily precipitation and PE downscaled from three GCMs (HadCM3 [black bars], CGCM2 [grey bars], CSIRO Mk2 [white bars]) under two emission scenarios (A2 [upper panel] and B2 [lower panel]) for the 2020s, 2050s and 2080s. The river flow quantiles are the flows exceeded 5% [Q5], 50% [Q50] and 95% [Q95] of the time.

Table 3a Changes in downscaled winter temperatures with respect to the 1961–1990 average

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
2020s	0.5	0.4	1.0	1.5	1.6	2.0
2050s	1.4	1.0	2.5	1.7	3.0	3.1
2080s	2.5	1.1	3.2	2.3	4.5	3.9
Biases						
Mean (°C)	0.5	0.3	0.7	0.7	0.4	0.5
SD (%)	−2	14	−65	−63	−44	−42

Results are based on the median of a 20-member ensemble. Biases in the downscaled long-term mean and standard deviation of annual mean temperatures are given with respect to observations for 1961–1990.

Table 3b As in Table 3a but for downscaled winter precipitation

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
2020s	−1	4	20	23	17	16
2050s	11	12	46	14	47	30
2080s	20	15	61	40	62	39
Biases						
Mean (%)	12	13	−40	−39	−4	−2
SD (%)	−5	−2	−60	−58	−49	−34

Table 3c As in Table 3a but for downscaled winter PE

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
2020s	1	1	2	3	3	5
2050s	3	3	5	3	6	8
2080s	5	3	7	5	9	9
Biases						
Mean (%)	−7	−7	−1	−1	−2	−3
SD (%)	−85	−86	−90	−90	−89	−88

Table 4a Percent changes in downscaled summer temperatures with respect to the 1961–1990 average

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
2020s	0.5	0.6	0.8	1.1	1.1	1.8
2050s	1.7	1.7	1.9	1.3	2.3	2.6
2080s	3.7	2.4	2.7	2.1	3.6	3.3
Biases						
Mean (°C)	0.2	−0.6	0.6	0.2	−0.6	0.5
SD (%)	−14	−16	−62	−63	−23	−36

Results are based on the median of a 20-member ensemble. The biases in the mean and standard deviation of the GCM annual climatology are given relative to observations for 1961–1990.

Table 4b As in Table 4a but for downscaled summer precipitation

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
2020s	−5	6	16	28	−5	1
2050s	−11	−16	25	25	−8	18
2080s	−36	−23	54	37	15	31
Biases						
Mean (%)	1	1	10	−9	−6	−19
SD (%)	−5	−11	−37	−39	−19	−22

Table 4c As in Table 4a but for downscaled summer PE

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
2020s	1	1	3	4	5	8
2050s	3	3	8	5	11	11
2080s	8	5	10	8	16	15
Biases						
Mean (%)	−1	−1	−6	−6	−3	−2
SD (%)	−68	−69	−78	−78	−70	−66

Table 5a The percentage of days on which groundwater abstractions at Axford Pumping Station, Wiltshire are unrestricted by gauged flows at Knighton

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
1961–90	84	83	57	47	88	83
2020s	86	86	93	97	92	87
2050s	81	88	99	92	93	90
2080s	75	85	100	97	99	98

Note that observed precipitation and PE series suggest 86% days for the period 1963–1990.

Table 5b As in Table 5a except for groundwater abstraction volumes expressed as a percentage of the maximum licensed amount (5000 Ml/yr)

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
1961–90	95	95	86	83	96	95
2020s	95	96	98	99	98	96
2050s	94	96	100	98	98	97
2080s	92	95	100	99	100	99

Note that observed precipitation and PE series yield 96% of the maximum licensed amount for the period 1961–1990.

Table 5c As in Table 5b but for the standard deviation of annual abstractions expressed as a percentage of the maximum licensed amount

Scenario	HadCM3		CGCM2		CSIRO	
	A2	B2	A2	B2	A2	B2
1961–90	7	8	13	11	4	6
2020s	6	6	4	2	3	6
2050s	8	5	1	6	3	6
2080s	7	7	0	4	1	2

Note that observed precipitation and PE series yield a standard deviation of 8% of the maximum licensed amount for the period 1961–1990.

Scenarios downscaled from CGCM2 and CSIRO suggest slight increases in source output as a consequence of fewer days on which restrictions apply — both therefore point to a more favourable resource situation. In contrast, the HadCM3 B2 suggests no overall change in deployable output, whereas HadCM3 A2 indicates slightly fewer days of abstraction leading to a reduced output from 86% of the total licensed volume in the 2020s to 75% in the 2080s. Furthermore, HadCM3 suggests little change in the inter-annual variability of deployable output whereas CGCM2 and CSIRO indicate greater stability in the future (Table 5c). Of course, the future resource potential of the Kennet surface and groundwater units will also depend on environmental and water quality standards, the latter of which, is discussed below.

Water quality

The effects of long term climatic change on the extremes of nitrate and ammonium levels in the Kennet are shown in Figs. 14 and 15. The CSIRO and CGCM2 models generate rising levels of nitrate and ammonium until the 2050s and a gradual decline thereafter. This is due to increasing dilution by greater river flow volume (Fig. 13), as well as shorter residence times for in-stream nitrification. In contrast, HadCM3 generates rising nitrate and ammonium 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 the enhanced nitrification are taken into account. This increased nitrate is caused by sustained droughts during the last decade of the GCM output. Sequences of dry summers lead to the build up of nitrogen in the soil that is flushed from the land into streams when droughts break. Such high levels of nitrate are not uncommon as recorded at Teddington Weir on the Thames (i.e., downstream of the Kennet) since 1930 (Fig. 16). Concentrations at the end of the drought year of 1976 reached similar levels to the drought extremes predicted by INCA-N at 11 mg/l. Although 1976 was an extreme year, HadCM3 suggests that we may experience more such drought sequences in the future and hence the INCA-N nitrate levels are considered plausible. Extended periods of high nitrates could mean that water companies have to introduce advanced water treatment or blend sources more frequently to keep Nitrate-N below the EU legal limits of 11.3 mg/l. Also,

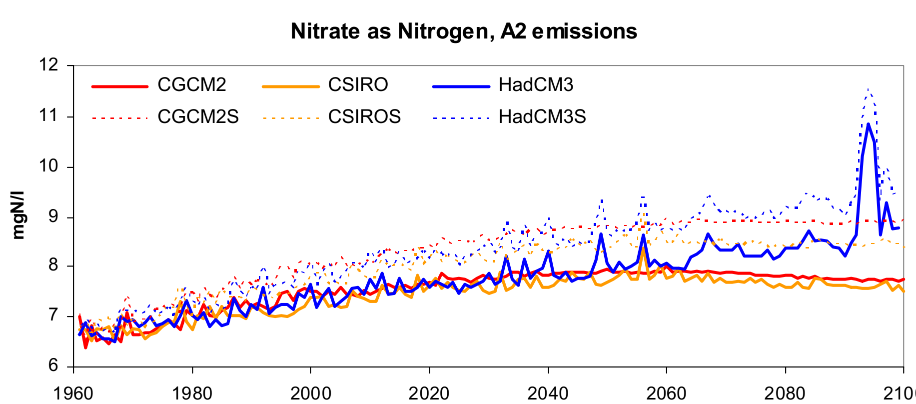

Figure 14 Effects of climate change on nitrate-N (Q05) with (dotted lines) and without (solid lines) enhanced nitrification.

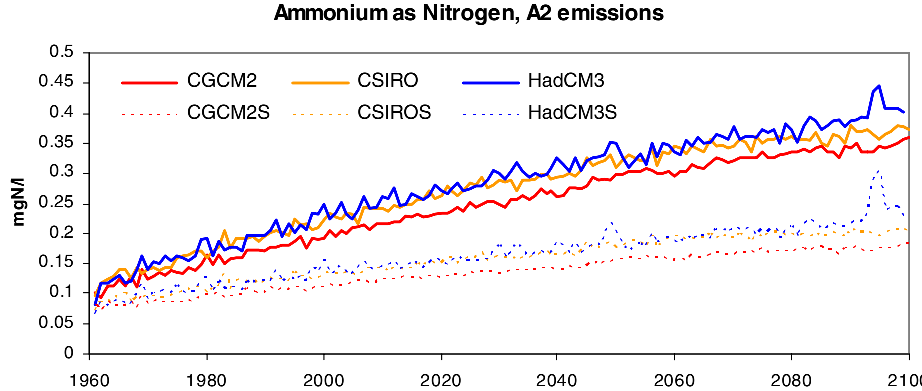

Figure 15 Effects of climate change on ammonia (Q05) with (dotted lines) and without (solid lines) enhanced nitrification.

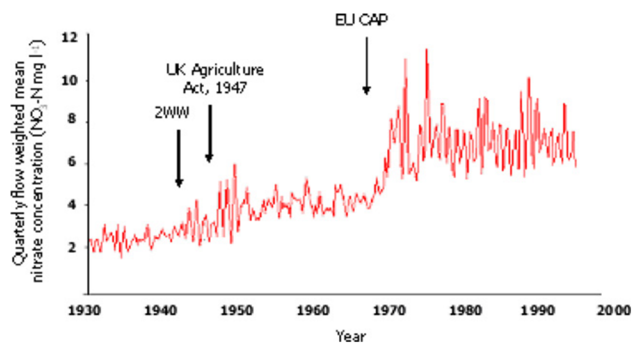

Figure 16 Long-term trends in nitrate enrichment in the River Thames, 1930—2000.

export of nitrate could have implications for other surface sources, or lead to eutrophication of downstream estuarine and coastal waters.

Discussion

The work undertaken here represents an early attempt to develop an integrated approach to climate change impact assessment by linking established models of regional climate (SDSM), water resources (CATCHMOD) and water quality (INCA) within a single framework. Trial experiments for the River Kennet illustrate how the system can be used to explore aspects of climate change uncertainty, reliability of water resources, and water quality dynamics in upper and lower reaches of the drainage network. The study was made possible by the data-richness of this LOCAR catchment as well as the legacy of earlier monitoring programmes investigating macrophytes and water quality status.

The results highlight the large uncertainty in climate change impacts due to choice of GCM compared with biases due to the water resource model. The sample of just three models (HadCM3, CGCM2 and CSIRO) and two emission scenarios (A2 and B2) showed uncertainty to be greatest during summer months. Overall, daily precipitation and PE scenarios downscaled from the A2 run of HadCM3 point to lower river flows and greater water scarcity in summer by the 2050s and 2080s. This leads to reduced deployable yield from the exemplar groundwater source, and nutrient flushing episodes following prolonged droughts, superimposed on a long-term decline in surface water quality. In contrast, scenarios downscaled from CGCM2 (and to a lesser extent CSIRO) yield wetter summers by the 2080s under both emission scenarios. Relative to the control period, these GCMs suggest increased deployable yield and less inter-annual variability in resource yield. However, rising temperatures lead to rising peak concentrations of ammonium throughout the 21st century, as well as higher nitrate concentrations until a plateau is reached in the 2050s.

Having established a prototype for integrated modelling there are now plenty of opportunities for methodological development. First, underestimation of inter-annual variability in (summer) PE for the current climate undermines confidence in future projections of the overall water balance, in particular for multi-season drought episodes. Therefore, further work is needed to better replicate periods of high PE in downscaled scenarios — part of the solution may be to locate high-quality *daily* PE data for model calibration.

Second, a more comprehensive analysis of impact uncertainty should be performed. The present study examined uncertainties arising from a relatively small sample of emission scenarios and climate model physics (i.e., choice of GCM). Uncertainties due to water resource and water quality model parameterisations and structures were not considered. Nor was the SDSM model compared with alternative empirical or dynamical downscaling approaches. Ideally, an integrating approach should enable a fuller exploration of key sources of uncertainty to determine their relative significance to the impact metric.

Third, some of the concerns about incorporating uncertainty could be addressed by moving towards a probabilistic framework. For example, conditional probabilities or weights could be assigned to different emission scenarios, GCMs, downscaling methods, impact model structure, parameter sets, etc. (as in Murphy et al., 2004; Wilby and Harris, 2006). However, it is acknowledged that a move from scenario planning (as illustrated herein) to probabilistic planning may require a step-change in thinking (Dessai and Hulme, 2003). Nonetheless, the UK water sector is one of the few policy areas, where a framework for planning with climate change scenarios has already been attempted.

Finally, the range of outputs presented for the River Kennet case study shows the versatility of integrated modelling. The framework could be applied to a broader set of policy-relevant issues. For example, the effective delivery of Water

Framework Directive objectives will need to take into account existing stresses on freshwater ecosystems as well as the potential impacts of climate change (Wilby et al., in press). Decision support tools will be needed to explore implications of changes in environmental variability for monitoring and assessment, as well as impacts on target species such as Salmon or *Ranunculus*. Anticipated reductions in atmospheric pollutants due to the EU Emission Trading Scheme and/or changes in land-use arising from reforms of the Common Agricultural Policy will also affect future loads of diffuse pollutants and nutrients. Integrated modelling provides a tool for assessing risks posed by multiple anthropogenic stresses, as well as a framework for appraising adaptation measures (as in Whitehead et al., in press). Furthermore, by placing these stresses in a wider context, there is a greater likelihood of identifying integrated solutions as well as the broader consequences of any interventions.

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