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Assessing the potential impacts of various climate change scenarios on the hydrological regime of the River Kennet at Theale, Berkshire, south-central England, UK: an application and evaluation of the new semi-distributed model, INCA

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Abstract

A new semi-distributed integrated nitrogen in catchments (INCA) model was used to attempt to assess the potential impacts of several recent Hadley Centre climate change scenarios on the hydrological flow regime of the entire River Kennet catchment to Theale, south-central England, UK. The climatically and hydrologically anomalous period 1985–1995 was used for baseline data in an attempt to: (1) represent any possible future climatic or hydrological variability not available from scenario use alone; and (2) attain maximum possible model calibration validity under future climates by simulating extremes of within-year hydrological variability. Substantial reductions in total annual runoff occurred, with an average reduction of 18.97%. Summer and late autumn soil moisture deficits (SMDs) increased in intensity, and were also found to persist for longer periods into autumn and (occasionally) winter. A generally enhanced hydrological regime of the River Kennet was simulated, with increased seasonality overall. A greater percentage of flow was observed to occur in spring and (occasionally) winter. Month-to-month variability of flow was discovered to be greater than annual changes. An average reduction in minimum annual flows

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of 46.03% occurred. Implications for catchment ecology and water resource requirements are briefly discussed. An evaluation of the new INCA model's performance as a tool for climate change impacts assessment is made.

Keywords: River Kennet; Catchment hydrology; Hydrological regime; INCA; Hydrologically effective rainfall (HER); Soil moisture deficit (SMD); Runoff; Meteorological Office rainfall and evaporation calculation system (MORECS); Groundwater recharge; Chalk aquifer; Water resources

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1. Introduction

1.1. Context

The consensus view of the contemporary scientific community is that future increases in atmospheric greenhouse gas concentrations will result in an increase in global mean temperature of approximately 0.3°C per decade (IPCC, 1990, 1992, 1995). The inefficiency of a climate change policy implemented solely within the European Union has been stressed (Rotmans et al., 1994), and the concept of a global commitment to warming due to the response lag in oceans is generally accepted. One of the most significant and important effects of climate change will be on the hydrological cycle and annual water balances (Gleick, 1987; Arnell et al., 1990, 1994, 1997; Arnell, 1992a,b, 1993; Arnell and Reynard, 1993; Beran et al., 1993; Wilby et al., 1994; Meteorological Office, 1997). Extremes in hydrological variability in the UK during the past decade have emphasised the sensitivity of our water resource systems to climatic fluctuations. It has been suggested that all regional mitigation strategies should be based on an assessment of the impacts of climate change (Arnell and Reynard, 1993). Therefore, providing scientific information relevant to policy makers and of use to water resource managers is a primary reason for climate change impacts assessment (Arnell and Reynard, 1993).

1.2. The 'GreenHouse Effect' and climate change

The physics of the 'GreenHouse Effect' are known, and well publicised (e.g. IPCC, 1990; Viner and Hulme, 1997). Several 'greenhouse gases' are transparent to incoming short-wave radiation but serve as insulators by blocking a proportion of out-going long wave terrestrial radiation, having a warming effect on the lower atmosphere (Fig. 1). This is an entirely natural mechanism, without which global surface temperatures would be approximately 33°C cooler than actually recorded (Arnell et al., 1990, 1994; Arnell, 1992b, 1993; Rotmans et al., 1994). The atmospheric concentrations of the principle 'greenhouse gases' (water vapour, carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons), with the exception of water vapour, have been, and are increasing as a direct result of anthropogenic activities (IPCC, 1990; Arnell, 1992b). Hence the 0.6°C increase in mean global surface air temperature since the industrial age is unlikely to be entirely natural (Viner and Hulme, 1997).

Although climate change scenarios differ significantly, global average surface temperature is expected to be approximately 1.8°C warmer than present (IPCC, 1990, 1995). Such a change would represent a rate of global surface air temperature increase far higher than experienced during recorded climatic history (Arnell, 1992a).

The significance of short-term trends as representative of long-term climate change should be treated with caution (Howarth et al., 1996). Wigley and Jones (1987) conclude that the only statistically significant precipitation trend during the late 1970s and 1980s in England and Wales was an increase in the frequency of extreme dry summers and wet springs. The identification of trends in some long-term data series has also proved difficult. Robson et al. (1998) suggest that whilst there has been no statistically significant trend in national flood frequency or magnitude since 1870, flood magnitudes and frequencies are clearly cli-

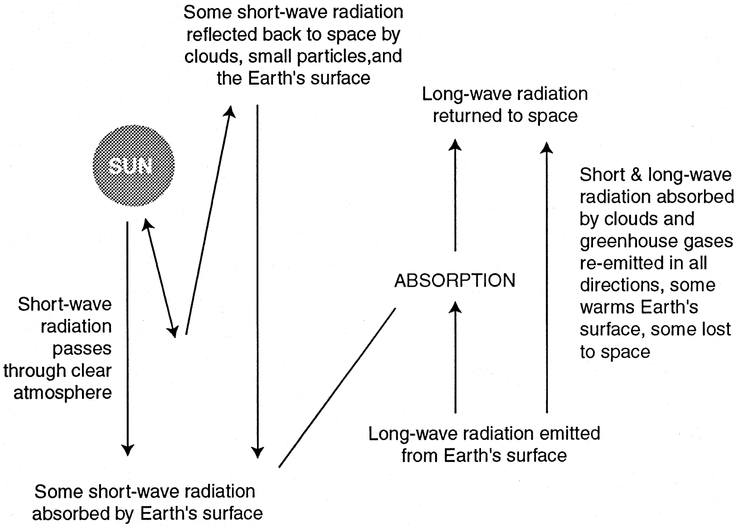

Fig. 1. Simplified mechanisms of the ‘GreenHouse Effect’ [adapted from Viner and Hulme (1997)].

matically driven. The possibility of climatically-driven flood cycles has also been acknowledged (Robson et al., 1998). Thus, natural variability partly explains historical (and inherently, any future) hydrological changes.

1.3. Climate change and hydrological processes in south-central England

The timing, frequency, magnitude, and intensity of precipitation events will be significantly affected by climate change (Hulme and Jenkins, 1998). Changes in the dominant circulation types over England and Wales during the past 20 to 30 years may be a likely indication of climate change (Bardossy and Plate, 1992; Sweeney and O'Hare, 1992; Wardlaw et al., 1996). Although the magnitude of changes in potential evapotranspiration depends on regional changes in indices such as windspeed, humidity, and net radiation, this is likely to increase over many areas of south-central England. Changes in the stomatal resistivity of some C3 plants under atmospheric CO_2 enrichment may serve to reduce potential evapotranspiration, however (CCIRG, 1991; Arnell, 1992b, 1993; Beerling et al., 1992).

Changes in soil infiltration rates due to summer cracking or winter gleying will reduce the total volume of groundwater available for maintaining flow (Arnell, 1992a; Wilkinson and Cooper, 1993).

Significant changes in surface runoff (and thus streamflow) have been notoriously difficult to detect; changes in vegetation and water resource management systems may well overwhelm any historical signal (Arnell, 1992b; Loaiciga et al., 1996). It has, however, been possible to reconstruct annual runoff from England and Wales back as early as 1728 (Marsh and Littlewood, 1978). It is the general scientific consensus that there has been a recent increase in hydrological variability and contrast between winter and summer surface runoff ratios with wetter winters and springs, and drier summers. Analyses of the long-term UK Hydrometric Series and surface runoff patterns in maritime western Europe have revealed surface runoff patterns broadly consistent with most climate change scenarios (Marsh, 1995; Green et al., 1996). The timing and magnitude of surface runoff and streamflow is generally expected to change under climate change (Gleick, 1987; Loaiciga et al., 1996). Catchments in south-central England will probably experience a greater concentration of runoff and streamflow in winter and spring months than at present (Arnell et al., 1990; Arnell and Reynard, 1993; Boorman and Sefton, 1997). Catchments in the south and east of England, with a relatively low percentage of rainfall contributing to runoff, are most likely to experience the greatest changes in annual hydrology (Nemec and Shaake, 1982; Chiew et al., 1995; Boorman and Sefton, 1997), and such changes are likely to significantly alter the aquifer recharge season (Wilkinson and Cooper, 1993; Wardlaw et al., 1996).

2. The study catchment: the Kennet Valley

2.1. General catchment overview

Located in south-central England, the Kennet Valley has an area of approximately 1033 km^2 to Theale gauging station (UK Grid 4649 1708, Ordnance Survey prefix SU), and encompasses parts of Wiltshire, Hampshire, and Berkshire. The River Kennet is a typical chalk stream that flows in a predominantly easterly direction to its confluence with the River Thames at Reading, Berkshire. Maximum stream length is 98 km from the source to its confluence (NRA, 1994). The River Kennet has an average base flow index of 0.95 along its course (Howarth et al., 1996). The main tributaries of the River Kennet are the River Lambourn (joining from the north-west), and the River Enbourne (joining from the south-west) and the Rivers Dun, Shalbourne, Aldbourne, and Og (Fig. 2).

2.2. Catchment topography

The River Kennet is a very low gradient stream, dropping from 190 m above Ordnance Datum (OD) at its source near Marlborough to 50 mOD at its confluence in Reading, a drop of only 140 m in 98 km (NRA, 1994). The northern interfluve of the catchment is represented by the Berkshire Downs, which have an average height of 200 mOD in the west, and 150 mOD in the east (NRA, 1994). The southern interfluve is represented by the Hampshire Downs that reach heights of 270 mOD. The Marlborough Downs represent the western interfluve, reaching heights of approximately 290 mOD. Catchment topography is illustrated in Fig. 3.

2.3. Catchment hydrology

2.3.1. Catchment rainfall characteristics

Catchment hydrology is driven by rainfall, percolation, and baseflow, leading to spring peaks

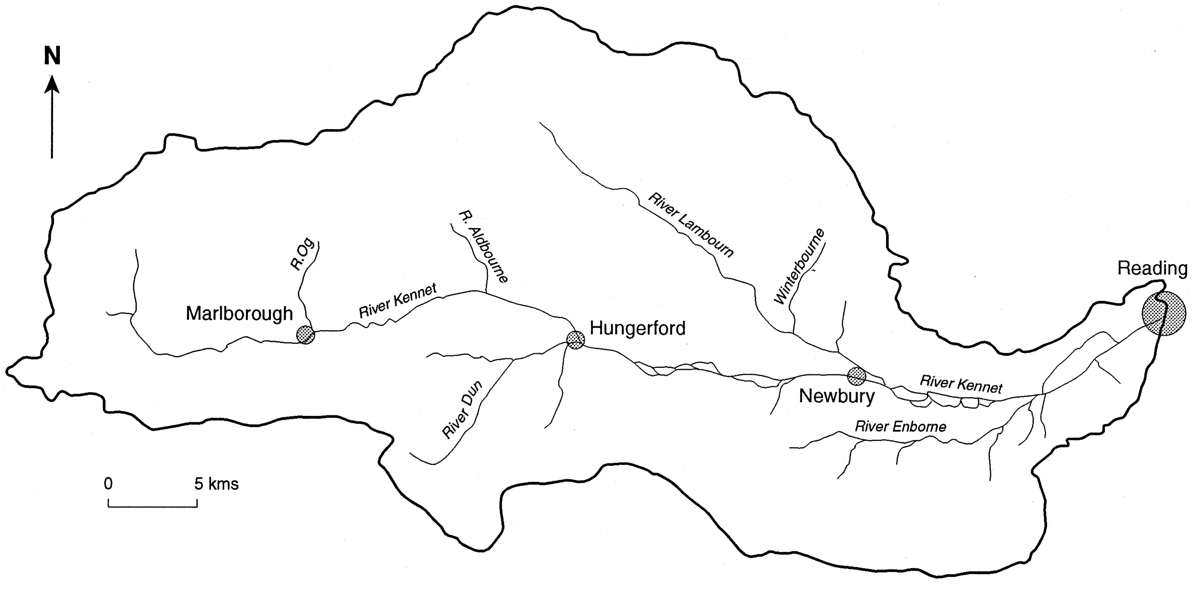

Fig. 2. Catchment overview.

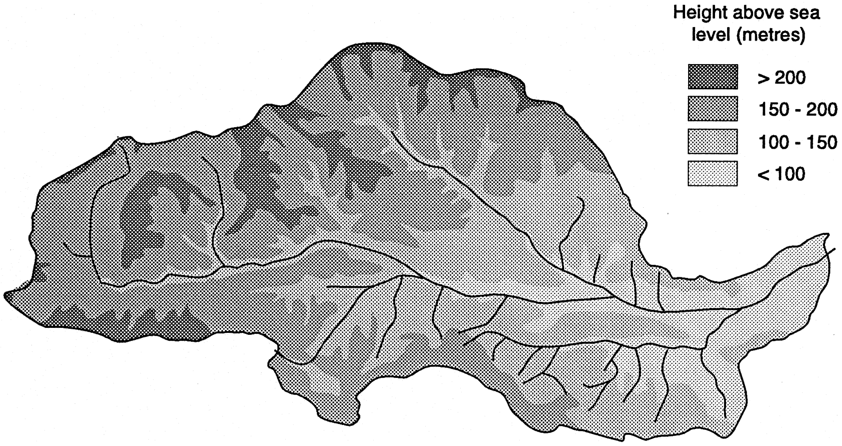

Fig. 3. Catchment topography.

and autumn troughs (Howarth et al., 1996). The standard average annual rainfall (SAAR) for the whole catchment is 764 mm/year, with a range from 900 mm/year on the Hampshire Downs to 650 mm/year in Reading (NRA, 1994). The ratio of annual precipitation to runoff determines a catchment's susceptibility to low flows and droughts (Arnell, 1992a). This ratio for the Kennet catchment is such that the system is considered to frequently suffer from low flows (Wilby et al., 1994). Flows also recover rapidly with 'flashy' response characteristics (Howarth et al., 1996). The River Kennet is a baseflow dominated stream, and consequently relies heavily on subsurface flow (Freeze, 1972). Snow-melt is not thought to significantly influence the hydrology of the River Kennet (Arnell et al., 1990, 1994; Arnell 1992a,b; Arnell and Reynard, 1993).

There are 55 Sites of Special Scientific Interest (SSSI) within the catchment, and much recent concern has focused on the protection of catchment ecology. Due to the River Kennet's susceptibility to low flows, and the sensitivity of many aquatic macrophytes and brown trout to low river flows, identifying potential changes in the flow regimes of the whole Kennet system is now a salient challenge.

2.4. Catchment geology

2.4.1. The Upper Cretaceous chalk

The underlying solid lithology of the Kennet Valley is 80% pervious Upper Cretaceous chalk (Institute of Hydrology, 1998b). The chalk is overlain in the south-east of the catchment by the sands and impervious Tertiary clays of the London Basin Syncline, providing the River Enbourne with a responsive catchment. The Cretaceous chalk is the main aquifer in the catchment, and is very important nationally, providing 53% of total groundwater abstractions in England and Wales in 1977 (British Geological Survey, 1993). The combination of the high transmissivity and low specific yield of the chalk endow the characteristics of the Kennet's main aquifer with rapid responses to recharge and abstraction (British Geological Survey, 1993). As a consequence of the chalk's aquifer properties, many of the River Kennet's tributaries have a BFI in excess of 0.9 (Institute of Hydrology, 1998b). All of the streams within the catchment rely heavily upon subsurface groundwater maintenance, with the possible exception of the responsive River Enbourne.

3. The hydrological model

3.1. Integrated nitrogen in catchments (INCA)

INCA is a new model created by staff at the Aquatic Environments Research Centre, University of Reading, UK. INCA was initially developed for the assessment of multiple sources of nitrogen in catchments. The model is process based and uses reaction kinetic equations to simulate the main processes operating (Whitehead et al., 1998). INCA can be applied to catchments as a semi-distributed simulation, and incorporates an inbuilt multi-reach structure for river systems (Whitehead et al., 1998).

3.2. The flow model

The flow model within INCA consists of three components. (1) The Meteorological Office rainfall and evapotranspiration system (MORECS; Thompson et al., 1981) is used to calculate daily hydrologically effective rainfall (HER), and to also calculate daily SMDs which fulfil two of the three input requirements of the model; the third being daily average temperature (Whitehead et al., 1998). (2) The effects of land surface and topography on flow are simulated through a semi-distributed approach that allows the dynamics and characteristics of each subcatchment to be identified and incorporated into the whole model (Whitehead et al., 1998). (3) The simulation of flows through water reservoirs in the soil and groundwater reactive zones (Whitehead et al., 1998). A knowledge of residence times and flow rates in these reactive zones is essential to the simulation process (Whitehead et al., 1998). These rates can be manually adjusted through the model parameters.

When interest lies solely in simulating river flows, relatively simple hydrological flow models, such as that used in INCA, are most effective (Arnell, 1992a). Indeed, the problems of some more complex models are that hydrological changes may be masked (Wilkinson and Cooper, 1993). In essence, hydrological models have the potential to evaluate the ideographic hydrological sensitivities of catchments (Gleick, 1986). The advantages of using such models are that they incorporate soil moisture characteristics, permit the estimation of various hydrological parameters over various time scales, and provide relatively accurate estimates of simulated flows when compared to observed flows (Gleick, 1987). Indeed water balance models have been described as one of the most versatile, flexible, and widely used tools for hydrological analysis (Gleick, 1987; Gan and Burgess, 1990). In contrast, empirical models are constrained by their low temporal resolution and inability to simulate individual hydrological events (Wilby et al., 1994). Empirical models are also developed under current climates and therefore their statistical relationships may be violated by changing climatic conditions. According to Gleick (1987) in order to be of value for impact assessment and to water resource planners, a suitable model must fulfil the following criteria. Primarily the model should focus on short-term time steps (INCA is a daily mass balance model). Secondly the model should have the ability to incorporate GCM output scenarios (INCA's input requirements are daily average temperature, HER and SMD, which can all either be derived or calculated from GCM output). Thirdly, the model should provide information on hydrological variables (INCA input of daily HER and SMD, and output of flow distribution statistics and daily flow simulations, can be presented graphically). The advantage of using daily input data is that differences in extreme flows can be appreciated, when compared to using models that require monthly input (Arnell, 1992a).

3.3. Catchment data for INCA calibration and validation

MORECS (Thompson et al., 1981) was used to provide average daily SMD, HER, and temperature for the Kennet catchment for the period 1985–1995.

Daily observed flows were obtained from the National River Flow Archive (Institute of Hydrology, 1998a) using gauged data from stations at Marlborough, Knighton and Theale.

Reach boundaries were selected at confluences, gauging stations and effluent input sources. Subsequent areas were derived using the Institute of Hydrology Digital Terrain Model (DTM). The DTM derived subcatchment data are presented in Table 1. Reach river lengths and the six subcatchment land-use percentages are given in Table 2.

4. Model calibration and validation

The method of model calibration follows the

Table 1
Kennet Valley subcatchment information

Reach number and gauging stations	Catchment to (UK Grid, Ordnance Survey prefix SU)	Sub-catchment area (km^2)	Sub-catchment SAAR (mm)	Sub-catchment PE (mm)	Estimated annual sub-catchment runoff (mm)	Estimated mean flow ($m^3 s^{-1}$)
1	410000 174250	22.3	821	525	326	0.2
2	409700 169950	36.8	818	525	323	0.6
3	415500 168750	53.4	817	524	323	1.1
4 (Marlborough)	418700 168600	24	817	523	324	1.4
5	424500 170250	83.6	809	518	322	2.2
6 (Knighton)	429500 171100	81.6	800	518	314	3
7	436200 168100	143.9	796	520	308	4.3
8	443000 166800	82	791	521	303	5
9	447200 167200	16	790	521	302	5.2
10	452000 166150	274.4	771	523	283	7.3
11	457000 166300	23.3	769	524	280	7.5
12	462000 168750	173.8	770	525	280	9
13 (Theale)	464900 170850	22	769	526	278	9.139

recommendation of Arnell (1993) that model calibrations can be assumed to be valid under future climates, with a greater degree of confidence, if the model is calibrated against historical years of an ‘extreme’ hydrological nature. The years 1989, 1990, 1991, 1992, and 1995 were therefore chosen as calibration years due to their extreme within-year hydrological variability (Cannell and Pitcairn, 1993; Marsh et al., 1994; NRA, 1994; Marsh, 1995). An evaluation of model performance, and suitability for impacts assessment, can be achieved by simulating extreme hydrological variability during model calibration (Arnell, 1993). The rather more hydrologically ‘average’ years 1985, 1986, 1987, 1988, 1993, and 1994 were chosen for model validation.

Table 2 illustrates that 68% of the Kennet catchment is described as arable. MORECS data calculated using a dominant land cover of spring barley was therefore used as INCA input data. Calibration (1992) and validation (1985) INCA results are presented in Figs. 4 and 5, respectively. Input data for 1985 are presented in Fig. 6. Simulated flow statistics are compared with observed values, with simulated percentage errors, in Table 3.

In order to quantify the effects of climate change perturbations on the flow statistics with an acceptable degree of accuracy, it was necessary to isolate which of the above statistics were simulated within either a 90% or 95% level of confidence. The effect of climate change on these flow statistics could therefore be inferred with similar accuracy. Table 4 isolates the most accurately simulated flow statistics.

The results suggest that the INCA model simulates the general flow regime of the River Kennet very efficiently. However, the model has a tendency to generalise daily flow trends, only simulating well the moderate to high peaks in flow. Indeed, some peaks are not simulated at all (Figs. 4 and 5). MORECS data often over-estimates daily SMD, therefore leading to an under-estimation of daily HER. The minimum level of model efficiency is that the general flow trends and peaks in flow were adequately simulated throughout the calibration/validation period 1985–1995. This is with the exception of the validation year 1988, in which flow simulation was unacceptably poor.

INCA tends to simulate maximum annual flows better than annual minima. Nine of the 11 calibration/simulation years simulated maximum annual flows with less than a 5% margin of error. Only 2 of the 11 years simulated minimum flows to this degree of certainty (1985 and 1994). The model also simulates the range in annual daily flows very well, again with 9 of the 11 years within a 5% margin of error (Tables 3 and 4).

INCA is occasionally poor at simulating low summer flows. This is probably due to a failure to recognise the high percentage of baseflow contribution to the River Kennet during periods devoid of HER as a result of the MORECS overestimation of daily SMD. Therefore, during sustained periods without daily HER, INCA fails to replicate the subtle day-to-day variations in flow resulting from fluctuations in baseflow discharge into the stream. The model tends to simulate the rapid baseflow response to sudden recharge more efficiently.

A number of general concluding remarks on the INCA model's ability to simulate observed flows can be made:

1. The simulated hydrographs for validation years tend to be more accurate than those of calibration years. The simulated flow distribution statistics (Tables 3 and 4) confirm this.
2. There does not appear to be any consistency in model simulation errors. Both over-estimates and under-estimates of low and peak flows occur.
3. The model tends to simulate annual flow regimes better than day-to-day flow variability.

Table 2
River reach and land class information for the Kennet Valley

Reach	Reach river length (m)	Reach BFI	Land-use class percentages (%)					
			Forest	Short vegetation (ungrazed)	Short vegetation (grazed, not fertilised)	Fertilised short vegetation	Arable	Urban
1	6350	0.95	0	0	13	4	83	0
2	4100	0.95	0	0	0	3	97	0
3	9760	0.95	2	0	0	10	88	0
4	6060	0.95	13	0	4	13	62	8
5	6900	0.95	2	0	0	6	90	2
6	6800	0.95	1	0	0	4	92	3
7	8430	0.92	12	0	3	5	79	1
8	8560	0.92	9	0	14	9	67	1
9	5310	0.92	0	0	17	33	22	28
10	6230	0.87	4	0	8	3	82	3
11	6800	0.87	9	0	9	26	39	17
12	7510	0.87	16	0	25	17	41	1
13	3990	0.87	13	0	35	9	39	4
Totals (%)	86 800		6	0	10	11	68	5

Table 3
INCA calibration and validation (1985–1995): comparison of observed and simulated flows (cumecs) and percentage errors (%) for the River Kennet at Theale[a]

	1985 (Val)			1986 (Val)			1987 (Val)		
	Obs	Sim	% Error	Obs	Sim	% Error	Obs	Sim	%Error
Mean	10.087	11.03	9.3	10.766	11.85	10	10.04	11.76	17.1
Max	32.7	31.51	−3.7	27.4	27.16	−0.08	32.3	32.07	−0.07
Min	4.79	4.86	1.4	4.55	5.01	10.1	4.43	3.47	−27.6
Median	9.5	9.96	4.8	10.2	11.52	12.9	9.54	12.18	27.67
Range	27.91	26.65	−4.7	22.85	22.15	−3.1	27.87	28.6	2.6
S.D.	4.4505	4.68	5.1	4.2804	4.78	11.7	4.0338	4.69	16.3
	1988 (Val)			1989 (Cal)			1990 (Cal)		
	Obs	Sim	% Error	Obs	Sim	% Error	Obs	Sim	% Error
Mean	10.181	9.92	−2.6	7.0046	8.5	21.3	8.6435	10.24	18.4
Max	40.3	28.39	−42	34.5	30.12	−14.5	44.1	40.16	−9.8
Min	4.37	2.43	−80	3.08	1.93	−59	3.1	1.4	−121
Median	7.295	9.18	26	5.71	7.31	28	5.75	7.68	33.6
Range	35.93	25.97	−38	31.42	28.2	−11.4	41	38.75	−5.8
S.D.	36.4994	5.45	−19.2	3.9518	5.61	41.7	7.2982	8.51	16.6
	1991 (Cal)			1992 (Cal)			1993 (Val)		
	Obs	Sim	% Error	Obs	Sim	% Error	Obs	Sim	% Error
Mean	6.0423	6.84	13.2	7.34	7.91	7.8	11.568	12.37	6.9
Max	26.1	25.15	−3.7	33.2	34.26	3.2	35.5	35.6	0.028
Min	3.25	2.74	−18.6	3.07	2.64	−16.3	4.8	4.32	−11
Median	5.61	6.12	18.6	4.97	5.04	1.4	9.58	11.24	17.3
Range	22.85	22.41	−1.9	30.13	31.62	4.9	30.7	31.28	1.8
S.D.	2.5749	3.22	25	6.03	7.05	17	5.9456	5.74	−3.6
	1994 (Val)			1995 (Cal)					
	Obs	Sim	% Error	Obs	Sim	% Error			
Mean	12.371	14.13	14.2	12.125	14.4	18.8			
Max	8.1	36.32	−4	39.9	39.1	−2			
Min	4.38	4.2	−4.2	3.43	4.36	27.1			
Median	9.49	12.47	−4.9	7.7	11.59	50.5			
Range	33.72	32.12	−4.9	36.47	34.75	−4.9			
S.D.	7.6803	7.91	2.9	9.5935	9.34	−2.7			

[a] *Abbreviations:* Val, validation year; Cal, calibration year; Obs, observed flow; Sim, simulated flow.

As a tool for climate change impacts assessment, INCA's daily flow model has much potential. The integration of its water quality model is an additional advantage. The ability to simulate periods of several consecutive years would, however, be an advantage to climate change impacts assessment. INCA would also benefit from the ability to display flow distribution statistics in a monthly, rather than annual format.

5. Climate change scenarios

5.1. Scenarios used

Climate change scenarios were derived from output data of the Hadley Centre for Climate Prediction and Research Circulation Models 1 and 2 (HadCM1 and HadCM2). HadCM1 data were derived from experiments conducted by the

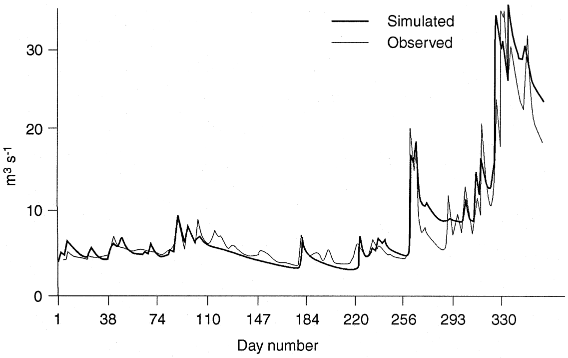

Fig. 4. INCA simulation of the River Kennet at Theale (Reach 13): 1992 calibration.

Climate Change Impacts Research Group (CCIRG), in 1996. Eight HadCM2 experiments were run by the Hadley Centre. Four experiments considered the warming effects of greenhouse gas forcing alone (scenarios HadCM2 GG), and four experiments included the cooling effects of atmospheric sulphur aerosols in addition to greenhouse gas forcing (scenarios HadCM2 GS). All three scenarios are for the period around 2050. The HadCM2 scenarios used in this study represent mean values derived from the four HadCM2 GG experiments (scenario HadCM2 GGx), and mean values derived from the four HadCM2 GS experiments (scenario HadCM2 GSx). The climate change scenarios were obtained from the DETR-funded LINK project (Viner and Hulme, 1997) at the Climate Research Unit in Norwich.

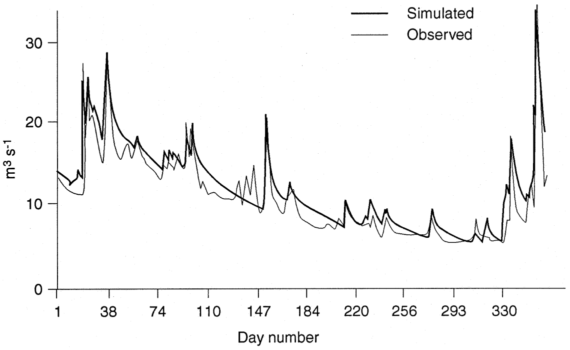

Fig. 5. INCA simulation of the River Kennet at Theale (Reach 13): 1985 validation.

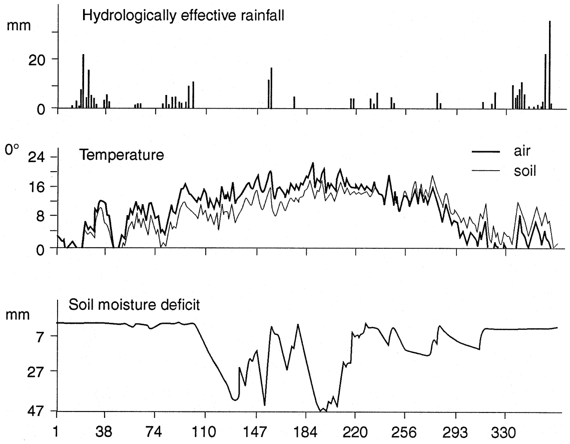

Fig. 6. River Kennet at Theale: 1985 validation.

The three scenarios obtained had been 'disaggregated' (resolution was increased to 0.5 × 0.5° grid squares) to provide data for the location of the Kennet Valley in south-central England and subsequently values for several sites within the catchment were given. These were simply aver-

Table 4
Simulated distribution statistics within the 95% and 90% level of certainty[a]

Simulated flow statistic	1985 (Val)	1986 (Val)	1987 (Val)	1988 (Val)	1989 (Cal)	1990 (Cal)	1991 (Cal)	1992 (Cal)	1993 (Val)	1994 (Val)	1995 (Cal)
Mean	YES	YES		*YES*					YES		
Max	*YES*	*YES*	*YES*		YES	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
Min	*YES*									*YES*	
Median	*YES*				*YES*			*YES*		*YES*	
Range	*YES*	*YES*	*YES*		YES	*YES*	*YES*	*YES*	*YES*	*YES*	*YES*
S.D.	YES								YES	*YES*	*YES*

[a] *Abbreviations:* Val, validation year; Cal, calibration year. *YES*, simulated distribution statistics within the 95% level of certainty; YES, simulated distribution statistics within the 90% level of certainty.

Table 5
Scenarios (a) HadCM1 (CCIRG, 1996), (b) HadCM2 (GGx) and (c) HadCM2 (GSx)

Change in:	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(a) HadCM1												
Rainfall (%)	8.4	7.26	5.89	−6.63	4.09	−0.41	1.01	−11.73	−7.94	5.27	17.57	2.65
PE (%)	16.91	13.15	5.74	10.21	2.02	6.63	2.29	11.91	17.5	8.62	0.43	7.26
Temperature (°C)	1.15	0.6	0.93	0.49	0.93	0.79	0.87	1.2	1.31	0.87	0.71	0.98
(b) HadCM2 (GGx)												
Rainfall (%)	9.47	13.96	4.36	7.47	1.95	−3.28	−15.75	−9.04	1.07	5.63	14.59	14.88
PE (%)	−19.63	−11.77	−1.12	1.75	3.67	2.08	7.92	15.35	17.14	8.05	−15.4	−29.9
Temperature (°C)	1.38	1.45	1.285	1.22	1.23	0.99	1.37	1.63	1.56	1.5	1.53	1.6
(c) HadCM2 (GSx)												
Rainfall (%)	6.29	7.06	2.28	4.05	2.7	0.5	−6.72	−6.47	−1.71	3.69	8.07	6.67
PE (%)	−13.4	−7.23	−0.06	2.08	2.34	1.89	5.71	12.16	11.79	4.52	−6.57	−14.83
Temperature (°C)	0.99	1.14	0.88	0.78	0.84	0.71	1.14	1.28	1.11	1.01	1.13	1.04

aged to provide scenarios for the whole catchment. These values represented deviations from mean monthly meteorological parameters at present. The three climate change scenarios are thus presented in Table 5a–c.

5.2. Scenario application

The INCA model requires an input of daily time series data. The three climate change scenarios offer monthly perturbations only as the use of daily GCM output is not recommended. Therefore monthly scenario changes were applied to the existing daily baseline climate data, thereby perturbing each day of the month by the same monthly scenario value. The additional advantage of this assumption is that changes in daily flow extremes would, theoretically, be more efficiently simulated in relation to applying monthly data only (Arnell, 1992b).

Scenario SMD was calculated using a cumulative daily equation. MORECS over-estimation of baseline SMD resulted in an exaggeration of daily scenario SMD until saturation of the soil profile occurred. Reductions in total runoff (sum of annual HER) for most scenario years, were therefore obtained. Despite these problems, the individual characteristics of the three scenarios were not, however, entirely lost. There were significant differences in the results of applying the three scenarios, and the magnitude of seasonal hydrological changes also varied.

The changes in total annual catchment runoff for each scenario year were generally all in line with the average equilibrium scenario changes in runoff calculated for the River Lambourn (a main tributary of the River Kennet) obtained over a 30-year baseline period used in Arnell and Reynard (1993). Their ‘Best Guess’ equilibrium scenario changes in average annual runoff for the Lambourn catchment ranged from −2% to −21% (Arnell and Reynard, 1993). Most of the baseline years perturbed by the three scenarios produced changes in total annual runoff within this range for the entire Kennet catchment. Arnell and Reynard’s (1993) ‘Driest’ equilibrium scenario changes in average annual runoff for the Lambourn catchment were as much as −37%. Only the scenario year 1989 (under all three scenarios) produced reductions in runoff in excess of this figure.

6. INCA simulation of changes in the flow regime of the River Kennet at Theale, under various climate change scenarios

An example of the effects of perturbing the baseline climatology with the three climate change scenarios on the flow regime of the whole Kennet

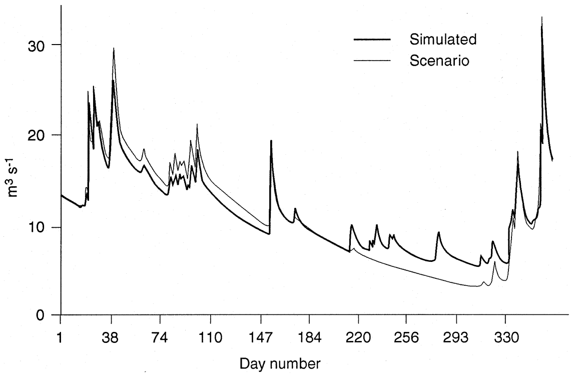

Fig. 7. INCA simulation of the River Kennet at Theale (Reach 13): 1985 vs. GGx85.

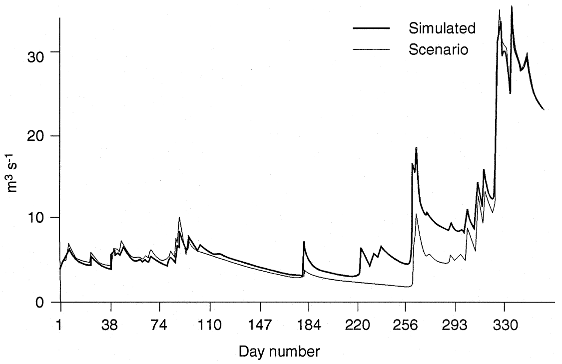

Fig. 9. INCA simulation of the River Kennet at Theale (Reach 13): 1992 vs. HadCM1 (1992).

system to Theale is provided by Figs. 7 and 8 (validation year 1985), and Figs. 9 and 10 (calibration year 1992). An example of changes in input data is given in Fig. 11. This shows changes in baseline year 1985 under scenario HadCM2 GSx and should be compared with Fig. 6.

Scenario changes in the flow statistics of the River Kennet are compared to observed values, with percentage changes, in Table 6. Only the flow statistics simulated with the maximum of a 10% margin of error during INCA calibration and validation are included in Table 6. Scenarios for years 1989 and 1990 are excluded as the reductions in total annual runoff and increases in total annual SMD were too excessive to be considered realistic.

The HadCM1 scenario consistently produced the most dramatic hydrological changes. The HadCM2 scenario incorporating the effects of sulphate aerosols (GSx) consistently produced more conservative changes than the scenario forced with greenhouse gases only (GGx). Specific hydrological changes in the example scenario years 1985 and 1992 are discussed in detail below.

6.1. 1985: Changes in runoff +0.006% (GGx) to −7.6% (HadCM1)

Mean annual flow at Theale increased under all scenarios with a maximum of 7.8% (GGx) and a minimum of 4.2% (HadCM1). Maximum annual flow values increased by 1.5% for one scenario (GGx) but were reduced by 0.4–7.5% under scenarios GSx and HadCM1, respectively. Reduc-

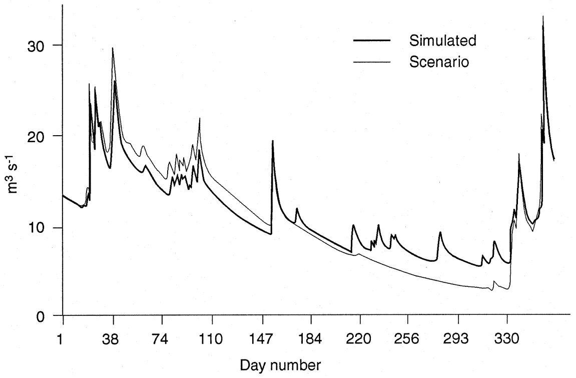

Fig. 8. INCA simulation of the River Kennet at Theale (Reach 13): 1985 vs. scenario GSx85.

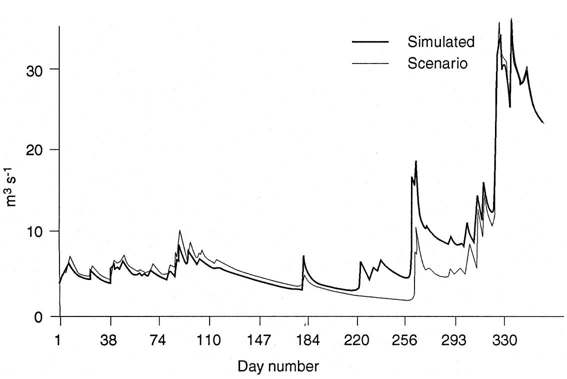

Fig. 10. INCA simulation of the River Kennet at Theale (Reach 13): 1992 vs. scenario GSx92.

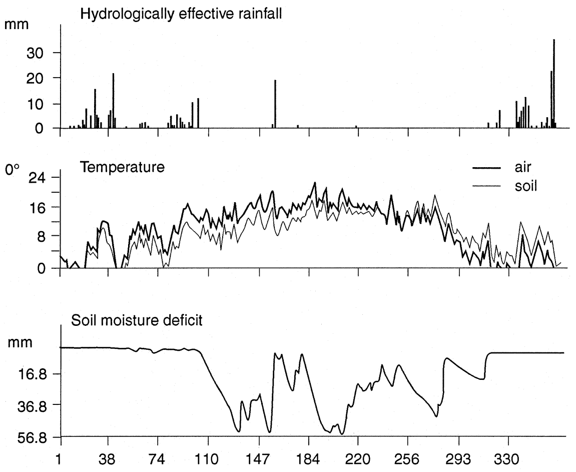

Fig. 11. River Kennet at Theale: scenario GSx85.

tions in minimum annual flow ranged from 50.7% (GGx) to 41.3% under the GSx scenario. Maximum reductions in flow of approximately 5 m^3/s^{-1} occur around day 280. The range in annual flow for baseline year 1985 increased by 0.02% (HadCM1), 7.2% (GSx), and 10.5% (GGx). As expected, these changes imply an increase in seasonality and extremes of hydrological regime (Arnell and Reynard, 1993; Loaiciga et al., 1996). Annual standard deviation from mean flows increased under all scenarios when compared to the 1985 value, ranging from 43.1% (GGx) to 34.6% (GSx). Again, the GSx scenario produced the more conservative changes. Increases in the magnitude of median flows (Q50) ranged from 7.4% (GGx and GSx) to 2.5% (HadCM1) and possibly reflect winter and spring flow increases. A visual assessment of the changes in the flow regime results in distinct changes in seasonality: flows are increased mainly in spring (days 0–147) and are reduced significantly during days 220–330. Increased HER and soil saturation after day 330 leads to smaller increases in flow. However, changes during these days are significantly less under scenario HadCM1. The loss of peaks in flow between days 220 and 330 reflect HER day losses due to SMD increases (a combination of climate change and MORECS SMD over-estimation).

6.2. 1992: Changes in runoff −1.1% (GGx) to −8.8% (HadCM1)

Mean flow values for this year increased by 1.3% under GGx, but were reduced by 2.9% and 7% under GSx and HadCM1, respectively. Maximum flows occurred between days 330 and 366 and increased under all scenarios from 4% (GSx) to 10.5% (GGx). Q50 under GGx and GSx increased by 3.2% and 1.4%, respectively, but was reduced by 5.5% under HadCM1. However, annual flow range for the River Kennet at Theale increased under all scenarios from 9.3% (GSx) to 16.3% (GGx). The spring of 1992 was exceptionally dry, but the low flows, however, were ameliorated under all scenarios, with slightly larger increases under GGx. Flow was reduced at around day 100 under HadCM1, and decreased flows reached a minimum between days 221 and 260 during which increased SMDs accounted for the loss of peaks in flow that occurred in 1992. Slight increases in the peak flows between days 300 and 366 were observed. Under scenarios GGx and GSx, flows fell below those observed for 1992 after day 184. The only significant difference between these two scenarios for this year was that spring and winter increases in flow were slightly greater under GGx, whereas, there was no visible difference between the GSx flows and observed 1992 flows around the peaks between days 330 and 366. Maximum reductions in flow of approximately 6 m^3/s^{-1} occur around day 270. All scenarios showed increasing seasonality.

7. Conclusions

By incorporating the hydrologically extreme period from 1985 to 1995 into a baseline climatology, an attempt has been made at representing the effects of hydrological variability under feasible climatic scenarios during the middle of next century. This is an additional characteristic of this study not available by relying solely on mean monthly climate change scenarios. The effect of these scenarios was simulated using a new model

Table 6
Flow distribution statistics for the River Kennet at Theale: observed compared to scenarios, with percentage changes (%) and levels of confidence (90% or 95%)

	1985	GGx	% Change	GSx	% Change	Hadcm1	%Change
Mean (90%)	10.087	10.87	7.8	10.78	6.9	10.51	4.2
Max (95%)	32.7	33.21	1.5	32.55	−0.4	30.41	−7.5
Min (95%)	4.79	2.36	−50.7	2.64	−44.9	2.44	−49
Median (95%)	9.5	10.2	7.4	10.2	7.4	9.74	2.5
Range (95%)	27.91	30.85	10.5	29.91	7.2	27.97	0.02
S.D. (90%)	4.4505	6.37	43.1	5.99	34.6	6.08	36.6
	1986	GGx	%Change	GSx	% Change	HadCM1	%Change
Mean (90%)	10.766	11.56	7.4	10.65	−1.1	10	−7.7
Max (95%)	27.4	25.32	−8.2	23.32	−17.5	23.5	−16.6
Range (95%)	22.85	22.16	−3.1	20.13	−13.5	20.9	−9.3
	1987	GGx	% Change	GSx	% Change	HadCM1	%Change
Max (95%)	32.3	27.92	−15.7	28.93	−11.6	28.42	−13.6
Range (95%)	27.87	25.09	−11.1	25.99	−7.2	25.73	−8.3
	1988	GGx	%Change	GSx	% Change	HadCM1	%Change
Mean (95%)	10.181	15.49	52.1	15.43	51.5	15.15	48.8
	1991	GGx	%Change	GSx	% Change	HadCM1	%Change
Max (95%)	26.1	27.84	6.7	26.9	3.1	26.84	2.8
Range (95%)	22.85	26.33	15.2	25.33	10.8	25.47	11.5
	1992	GGx	%Change	GSx	% Change	HadCM1	%Change
Mean (90%)	7.3403	7.44	1.3	7.13	−2.9	6.86	−7
Max (95%)	33.2	36.68	10.5	34.53	4	34.8	4.8
Median (95%)	4.97	5.13	3.2	5.04	1.4	4.71	−5.5
Range (95%)	30.13	35.03	16.3	32.95	9.3	33.49	9.8
	1993	GGx	%Change	GSx	% Change	HadCM1	%Change
Mean (90%)	11.568	11.21	−3.2	11.12	−4	10.63	−8.8
Max (95%)	35.5	37.2	4.8	36.55	2.9	37.05	4.4
Range (95%)	30.7	34.3	11.7	33.25	8.3	34.09	11
S.D. (90%)	5.9456	6.97	17.2	6.64	11.7	6.77	13.9
	1994	GGx	%Change	GSx	% Change	HadCM1	%Change
Max (95%)	38.1	36.66	−3.9	36.89	−3.3	37.73	−1
Min (95%)	4.38	2.57	−41.3	2.5	−43	2.31	−47.3
Median (95%)	9.49	11.79	24.2	9.79	3.2	9.19	−3.3
Range (95%)	33.72	34.09	1.1	34.4	2	35.41	5
S.D. (95%)	7.6803	9.8	27.6	9.03	17.6	9.18	19.5
	1995	GGx	%Change	GSx	% Change	HadCM1	%Change
Max (95%)	39.9	41.33	3.6	40.56	1.6	40.42	1.3
Range (95%)	36.47	39.43	8.1	38.72	6.1	38.59	5.8
S.D. (95%)	9.5935	11.04	15.1	10.73	11.8	10.69	11.4

(INCA). The changes in the annual flow regime and water balance of the River Kennet at Theale have generally been in agreement with ranges proposed in previous studies, for similar regions.

Total annual SMD was found to increase for all study years, under all scenarios. A persistence of daily SMD values later into the autumn, and occasionally winter, was found to occur when compared with observed trends for the baseline period. Some years in future decades may experience much more severe and persistent post-summer SMD values than at present.

Changes in the total annual surface runoff (the sum of annual HER) in the Kennet catchment under the three scenarios was found to substantially decrease under most scenarios. A greater percentage of HER occurred in spring and winter, suggesting a tendency towards increased seasonality of runoff in the Kennet Valley during the middle of next century.

Under the three scenarios an enhanced and protracted hydrological regime was recognised consistently throughout the study years. Flows generally increased during spring and winter, and substantial summer and autumn decreases in flow were observed. Flows were especially increased in spring, although this maybe a result of the flow distribution characteristics of the baseline years. Flows were especially reduced during autumn, which is likely to be a genuine characteristic of future climatic changes; increased SMD values frequently persisted into autumn, thus minimising autumn HER. The findings of Arnell et al. (1990, 1994, 1997), Arnell (1992a,b) and Arnell and Reynard (1993), generally support these conclusions.

Runoff changes for most scenario years were within the range simulated by Arnell and Reynard (1993) under their 'Best Guess', and 'Driest' scenarios for the River Lambourn. An average reduction in total annual runoff of 17.9% was calculated for future 'average' years and 20.04% for future 'dry' years. Reductions in summer and autumn flow, and therefore runoff, appeared to be much greater than annual changes. This finding was consistent under all three scenarios, and most years. The following findings occurred mainly as a result of these calculated changes in scenario total annual runoff.

An average increase in mean annual flow of 1.5% was calculated for future 'average' years, with an average decrease of 2.9% for future 'dry' years. An average reduction in annual minimum flows for future 'average' years of 46% was witnessed, suggesting a significant reduction in average low flow values. Changes in the minimum flow values for future 'dry' years were not available at the 90% level of confidence. However, clear reductions in minimum flows are visible under all 'dry' scenario years (in the simulated hydrographs). However, low flows such as those experienced during spring 1992 were ameliorated under all three scenarios. An average increase in the annual range of flow values of 2% for future 'average' years, and of 12% for future 'dry' years was calculated. This suggests increased seasonality and hydrological variability. Changes in future flow regimes are likely to present themselves more evidently as month-to-month variations in flow, rather than progressive annual changes.

The most important implication of these findings for the main aquifer of the Kennet catchment is that the average recharge period at present (approx. 6 months) could be reduced to as little as 5 or even 4 months under the simulated changes in flow regime (Wilkinson and Cooper, 1993). Increased storage is unlikely under the simulated hydrological changes for a number of reasons. A combination of decreased total annual runoff, a reduction in the duration of periods of high annual flow, and increases in periods of low flow will reduce the total amount of water available for aquifer replenishment, under all scenarios. This reduction may be further exaggerated by reduced summer and autumn infiltration rates due to soil cracking and capping (Arnell, 1992a,b), and a possible increase in frequency of periods of abrupt, intense convective rainfall, where rainfall rates inherently exceed infiltration rates (Howarth et al., 1996).

Even a broad indication of changes in the hydrological regime of rivers under potential climate changes are useful to water resource planners (Arnell, 1992b). From a planning perspective, the chalk aquifer of the Kennet catchment is less robust to climate change than other aquifers: quick responses to changes provide less time for adaptation strategies to take effect (Wilkinson and Cooper, 1993). Substantial reductions in summer and autumn flows will almost certainly result in less water for agricultural and industrial purposes within the Kennet Valley. Therefore, the likely impacts of future climate changes need to be incorporated into the strategies of policy makers (Minnery and Smith, 1994). Of particular relevance is the 5–629 Ml/day^{-1} forecasted strategic water deficit for the Thames Region by Sherriff et al. (1996). Concerns over resources in the Kennet Valley should be raised due to the future expectations of water supply customers, the long-term effect of demand management, and that current use of, and investment in, groundwater resources are far from efficient or optimal (Foster and Grey, 1997; Smith, 1997).

The acceptable flow regime required to fulfil both human and environmental requirements should be described by how frequently a river's flow regime falls below set human and environmental thresholds (Evans, 1997). The results of this study suggest that future flow regimes of the River Kennet would most likely fall below such thresholds more frequently than at present. If this occurred, the ecological status of the River Kennet (especially, of aquatic macrophytes, and fish populations such as brown trout) could significantly decline.

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