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Implications of climate change for river regimes in Wales: a comparison of scenarios and models

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Abstract The paper compares the results from a range of GCM scenarios, downscaling methods and hydrological simulation techniques that have been applied to assess the impact of climate change on rivers in Wales. In spite of wide differences in scenarios and the sophistication of the methodology, there is broad agreement.

Key words climate change impacts; downscaling; river regimes; Wales

INTRODUCTION

Evidence has been gradually accruing since the early 1990s to support the view that world climates are likely to change at a faster rate over this coming century than at any time since the Hypsithermal 6000 years ago (e.g. IPCC, 2001; Jones *et al.*, 1996).

Although in global terms population increase is still likely to be the main influence on per capita water resources (Jones, 1999), the apparent inexorability of the climatic trends means that translating them into changes in water balances and river flows is essential for prudent planning of resources and risk assessment.

INITIAL SENSITIVITY STUDIES

At the first Celtic Hydrology Colloquium in Rennes, France, Holt & Jones (1996a) presented results from a sensitivity study based on three national scenarios (wettest, best estimate and driest) developed by Arnell (1992) from the initial report by the UKCCIRG (1991). These were: temperature +2.1–2.3°C, precipitation varying from no change save a 16% reduction in summer in the driest scenario, through +8% in all seasons except summer in the "best estimate" to an all-year-round 16% increase in the wettest. The Hadley Centre's (1992) high resolution UKHI model run in transient mode (UKTR) provided a fourth scenario for 2055: temperature +1.0–1.8°C, precipitation +45.0, +70.8, –23.0 and +4.8 mm, for winter, spring, summer and autumn, respectively (Holt, 1993).

Holt & Jones (1996b) applied the scenarios to three direct supply reservoirs, two sites on a regulated river and three unsupported rivers. A methodology was developed in which statistical transfer functions were derived by correlating effective precipitation for the Met Office's MORECS cells with recorded river flows for 1979 to 1991. Flows from the regulating reservoir were modelled using Welsh Water's spreadsheet model.

The results suggested reductions of the order of 25% in summer discharges under the best estimate equilibrium scenario for rivers in North Wales (Erch), mid-Wales (Ysgir) and South Wales (Taf). The Erch is less affected as it drains the high rainfall mountains of Snowdonia.

Summertime response at the two sites on the River Towy in South Wales, regulated for public water supply by the Llyn Brianne reservoir, was very similar to the natural rivers. The direct supply reservoirs also showed at least a 25% reduction in summer inflows, but those in mid-Wales and the Brecon Beacons suffer less than the Preseli reservoir, which receives only half the rainfall of the mid-Wales reservoir.

DOWNSCALING CLIMATE AND LINKING HYDROLOGICAL MODELS

Mathematical downscaling

Despite the improved spatial resolution in UKHI, the scenarios were far from basin-specific. Pilling & Jones (1999) used climatologies downscaled and interpolated to a 10 × 10 km grid for the whole of Britain produced by the Climatic Research Unit, University of East Anglia. These comprised a present-day climatology produced by Barrow *et al*. (1993) and two future climatologies: an equilibrium scenario (UKHI) for 2050 and a transient scenario (UKTR) for 2065 (Viner & Hulme, 1993a,b). Downscaling was achieved by fitting a thin plate smoothing spline to irregularly spaced station data for the present baseline (Barrow *et al*., 1993), and for the future scenarios using a standard space-filtering scheme employed by Santer (1988). These climatologies were used as input to the 17-parameter hydrological simulation model HYSIM (Manley, 1993) and the necessary surface characteristics were derived individually for each grid cell (Pilling, 1999).

For Wales, the results suggested overall that summers would have reduced runoff and winters would be slightly wetter by mid-century. UKTR was more extreme than UKHI, with summer reductions in excess of 15% over most of the Principality. This is due to higher evapotranspiration as well as lower rainfall. In winter, both models result in increased river flow. Under UKHI, Wales is divided around the middle between substantial increases in the North (15–30%) and moderate increases in the South (0–15%), with the exception of higher increases in the Brecon Beacons and Black Mountain. Under UKTR, increases are more uniformly in the moderate range.

Statistical and stochastic downscaling

A major failing in the mathematically downscaled climatologies is that they cannot take account of any topographic influences that are on a smaller scale than the spacing of the *original* data points. A statistical method of "downscaling" scenarios to catchment scale was developed by Wilby *et al*. (1998), which uses local climatological data, which implicitly incorporates the effects of local topography. This was used by

Pilling *et al*. (1998) to derive a set of hydrometeorological parameters for the headwaters of the rivers Wye and Severn in mid-Wales, first correlating airflow indices (vorticity, wind velocity and direction) calculated from the GCM output with recorded hydrometeorology from the Centre for Ecology and Hydrology's Upper Wye Experimental Basin. Transitional probabilities for dry–wet and wet–wet daily sequences were then used in a randomized sampling procedure to generate local daily weather sequences from the airflow parameters.

Pilling & Jones (2002) linked this methodology to the runoff simulation program HYSIM, in order to simulate future runoff in the 10.55 km^2 Upper Wye catchment. This provided a daily sequence of river flows, which allowed study of variability and runs and, for the first time, changes in the frequency of extreme events could be studied on the basis of physical simulations. Pilling (1999) used data from the Hadley Centre's HadCM2: HadCM2GHG, a "greenhouse gases only" scenario which has been accepted as a "medium-high" estimate of possible climate change and adopted as the industry standard for UK water company estimations; and HadCM2SUL, which incorporates the cooling effects of sulphate aerosols.

Pilling & Jones (2002) presented the HadCM2SUL results. These indicate a marked reduction in the amount and frequency of precipitation in summer and autumn by 2080–2099, combined with a shortening of the mean length of wet spells, which is most pronounced in autumn. This is accompanied by an increase in evapotranspiration, and together these result in a marked increase in the number of days with low flows in summer and autumn. A 17% reduction in mean daily discharges in summer and a 12% reduction in autumn are both significant at the 1% level. There are also increases in both high and low flows in the year as a whole, which are evident in the 5% increase in the mean annual flood (MAF) and a 17% reduction in the Q95 discharge level, both significant at the 1% level.

HadCM2, HadCM3 AND SDSM DOWNSCALING

At the second Celtic Hydrology Colloquium in Aberystwyth, Jones & Mountain (2000) applied the same methodology to the larger, 184 km^2 basin of the River Elan above the town of Rhayader in mid-Wales.

The latest work by Mountain (2004) uses A2 and B2 scenarios recently released from the HadCM3 GCM and the improved downscaling methodology, SDSM (Statistical DownScaling Model), developed by Wilby *et al*. (2002). HadCM3 has 19 atmospheric levels and improved models for convection, minor gases, aerosols and land surface properties. The IPCC scenarios A2 and B2 are not the most extreme scenarios, reaching 1310 and 915 ppmv CO_2, respectively, by 2100. A2 assumes a world population of 15 billion by 2100 and relatively slow economic growth. B2 assumes a population of 10.4 billion and more rapid economic growth. These two scenarios were singled out for discussion in IPCC (2001).

SDSM follows the same general methodology as the original approach, but it uses up to 18 airflow indices, including temperature, sea level pressure, 500 hPa and 850 hPa geopotential heights, and relative humidity, airflow velocities, vorticity and divergence, all at these three altitudes. Each predictor variable is also normalized and standardized before regression.

Comparison of HadCM2 and HadCM3

Mountain (2004) has used this approach to simulate flows in the River Wye catchment above the gauge at Ddol Farm, Rhayader (174 km^2). The results are summarized in Table 1, which only shows changes significant at the 1% level. Welsh Water's definition for a low flow at this site is less than or equal to 1.06 m^3 s^{-1}.

Table 1 Significant changes (%) in annual flow characteristics, R. Wye.

Parameter	2040–2059				2080–2099			
	HadCM2 GHG	HadCM2 SUL	HadCM3 A2	HadCM3 B2	HadCM2 GHG	HadCM2 SUL	HadCM3 A2	HadCM3 B2
Total discharge		–11	–4	+14		–7	–10	+12
Q95 discharge		–20			–18		–33	–14
Total no. low flow days	+12	+25			+30		+145	+36
Low flow spell length					+27		+89	+38
No. of low flow spells		+27					+94	
Q5 discharge	–8	–8			–7	–7		
MAF		–7					+8	+14

Despite some notable differences between scenarios, there are also some important consistencies. It is notable that changes in the Q95 discharge are all negative, i.e. discharges are lower for the lowest 5% of daily flows. One scenario shows this for mid-century, the sulphate aerosols scenario that has lower rainfall in late summer and autumn, but three of the scenarios show this for the end of the century. This is supported by the changes in the number of days with low flows, in which two scenarios show a significant reduction by 2050 and three for 2090. The length of spells of low flow also increases in three out of four scenarios for late century, whilst there is also some support for an increase in the number of low flow spells from HadCM2SUL and HadCM3A2 for mid and late century, respectively.

These all add up to reasonably consistent predictions of worsening water supply and environmental problems due to low flows as the century progresses. Changes at the high flow end seem to be of a lower order and there are some inconsistencies here. Half of the scenarios show a 7–8% reduction in the Q5 discharge, remaining consistent through the latter half of the century. The mean annual flood is less consistent, but both the newest scenarios show increases by 2080. Taken together with the last point, this perhaps suggests that there might be increases in the more extreme flood flows but not in "run-of-the-mill" high flows. Again, with total annual discharge there are differences of sign between scenarios: HadCM2SUL and HadCM3A2 show a reduction in net water resource whereas HadCM3B2 predicts an increase. In both cases, the changes remain of a similar order from mid-century onwards.

The results from the seasonal analyses on the Wye (Table 2) show an even greater consistency and confirm the trend towards increased seasonality found in the previous modelling for Welsh rivers. The most constant trend is for lower discharges in summer and autumn. Total yields in summer display a significant negative trend in all four

Table 2 Seasonal change in river flow parameters (%) for the River Wye.

Parameter and season		2040–2059				2080–2099			
		CM2 GHG	CM2 SUL	CM3 A2	CM3 B2	CM2 GHG	CM2 SUL	CM3 A2	CM3 B2
Total discharge	Win		–12		+7		–10	+9	+5
	Spr								
	Su		–11			–18	–9	–32	–20
	Aut		–14	–5			–14	–30	–13
Q95 discharge	Win								
	Spr		–13		–5	+14		–12	–6
	Su		–14			–26		–27	–16
	Aut	–10	–27		–19		–9	–45	–25
No. of low flow days	Win								
	Spr								–80
	Su				+25	+76	+8	+102	+40
	Aut	+12	+44	+63	+52			+309	+64
Low flow spell length	Win								
	Spr								
	Su					+63		+98	
	Aut							+150	+50
No. of low flow spells	Win								
	Spr								
	Su				+33			+49	+36
	Aut		+38					+191	+55
Q5 discharge	Win		–7		+4		–8	+7	+6
	Spr								
	Su							–35	–21
	Aut		–11				–12	–15	
Maximum daily flow	Win		–8	+7	+10		–9	+7	+11
	Spr								
	Su				-9	–14		–28	–18
	Aut		–9	+10	+20		–9	–9	
POT	Win				+23			+30	+17
	Spr								
	Su		–18			–21	–12	–56	–34
	Aut		–25				–28		

model scenarios for the 2080s onwards, and HadCM2SUL suggests this might begin mid-century. This is more or less matched by a reduction in the Q95 low flow discharge level of the order of 10–20%. Indeed, four models show this trend beginning in spring and more or less carrying on into autumn. This is accompanied by often quite marked increases in the number of days with low flows in summer, rising to 75–100% in some scenarios by the 2080s. Two scenarios show that this is partly due to an increase in the length of low flow spells. Two also show increases in the number of low flow spells: in HadCM3A2 the spells are both longer and more frequent.

Interestingly, high flows seem to show similar trends in summer. The HadCM3 scenarios show a marked reduction in the Q5 discharge, maximum daily flow and peaks-over-threshold (POT) by 2090. HadCM2GHG supports the latter two. There is some evidence from HadCM2SUL and HadCM3B2 that some of this might be noticeable by mid-century. None of the models show any trends counter to these. These trends are not carried over into autumn as consistently as with low flows. The beginning of the new hydrological year in September is traditionally marked by the return of more intense cyclonic storms fuelled by evaporation from the warm Atlantic Ocean. Nevertheless, there is some evidence of reductions in all three of the key parameters in the 2090s, some starting in the 2050s. But it is generally to a lesser degree than in summer, and, indeed, the HadCM3 scenarios show an actual rise in maximum daily flow in mid-century, returning to a decreasing trend later.

The changes in winter flow patterns are less marked and less consistent, but still generally opposite to those in summer. The most marked change appears to be increases in flood flows, especially apparent in peaks-over-threshold in the HadCM3 scenarios by 2080–2099, and B2 even shows this beginning 2040–2059. The HadCM3 scenarios show the same pattern, but to a lesser degree, in maximum daily flows and the Q5 discharge. The only counter trend comes from HadCM2SUL, which may be over emphasizing the cooling effects of the sulphate aerosols. Exactly the same patterns are found in total wintertime yields.

CONCLUSIONS

In spite of the wide range in models and scenarios, the results are remarkably similar. From the crudest early "sensitivity" studies to the combination of the latest Hadley Centre GCM with more sophisticated downscaling, there is an increase in seasonality creating markedly lower flows in summer/autumn and less significant increases in winter. The models also suggest increases in extreme flows at both ends of the spectrum, with increases in low flows tending to be in the summer and the higher flows tending towards winter. Along with this goes a general tendency for the changes to balance out over the year as a whole, so that there is little change in overall water resources. The main problems for water management identified in all models and scenarios are twofold: drier summers and an increased risk of floods and low flows.

This message appears remarkably robust and independent of modelling procedure. Although the more sophisticated modelling has been confined to rivers in mid-Wales, they are in keeping with the results from the earlier sensitivity studies in north and south Wales.

REFERENCES

Arnell, N. W. (1992) Impacts of climatic change on river flow regimes in the UK. *J. Inst. Water Environ. Manage.* **6**, 432–442.

Arnell, N. W. & Reynard, N. S. (1996) The effects of climate change due to global warming on river flows in Great Britain. *J. Hydrol.* **183**, 397–424.

Barrow, E., Hulme M. & Jiang, T. (1993) *A 1961-90 baseline climatology and future climate change scenarios for Great Britain and Europe. Part I: A 1961-90 Great Britain Climatology.* Climatic Research Unit, University of East Anglia, Norwich.

Hadley Centre (1992) *The Hadley Centre Transient Climate Change Experiment.* Hadley Centre, Meteorological Office, Bracknell, UK.

Holman, I. P. (2005) Regional hydrological impacts of climate and socioeconomic change in North West England, UK. In: *Water in Celtic Countries: Quantity, Quality and Climate Variability* (Proc. Fourth InterCeltic Colloq. on Hydrology and Management of Water Resources, Guimarães, Portugal, July 2005). IAHS Publ. 310. IAHS Press, Wallingford, UK (this volume).

Holt, C. P. (1993) Climate change and future water resources in Wales. PhD Thesis, University of Wales, Aberystwyth, UK.

Holt, C. P. & Jones, J. A. A. (1996a) Impact of global warming on Welsh water resources: patterns of response under equilibrium and transient scenarios. In: *Hydrologie dans les pays celtiques* (ed. by P. Mérot & A. Jigorel), 85–92. Les Colloques 79, INRA Editions, Rennes, France.

Holt, C. P. & Jones, J. A. A. (1996b) Equilibrium and transient global warming scenario implications for water resources in Wales. *Water Resour. Bull.* **32**(4), 711–721.

Intergovernmental Panel on Climate Change (IPCC) (2001) *Climate change: The Scientific Basis*. (ed. by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson). Cambridge University Press, Cambridge, UK.

Jones, J. A. A. & Mountain, N. C. (2000) Hindcasting and forecasting flows for water resource planning using an airflow-index-based weather generator and a hydrological simulation model: Elan and Wye valleys, Wales. *British Hydrological Society Occasional Paper no. 11*, 85–92.

Jones, J. A. A, Liu, C., Woo, M-K. & Kung, H-T. (eds) (1996) *Regional Hydrological Response to Climate Change*. Kluwer, Dordrecht, The Netherlands.

Jones, J. A. A. (1999) Climate change and sustainable water resources: placing the threat of global warming in perspective. *Hydrol. Sci. J.* **44**(4), 541–557.

Manley, R. E. (1993) *HYSIM user Guide*. R.E. Manley Consultancy, Cambridge, UK.

Mountain, N. C. (2004) Modelling the impacts of climate change on the hydrology of the Elan and Wye catchments, mid-Wales. PhD Thesis, University of Wales, Aberystwyth, UK.

Mountain, N. C. & Jones, J. A. A. (2002) Estimating low flow frequencies in the mid to late 21st century for two basins in central Wales. In: *Environmental Change and Water Sustainability* (ed. by J. M. García-Ruiz, J. A. A. Jones & J. Arnáez), 111–127. Instituto Pirenaico de Ecología, CSIC, Zaragoza, Spain.

Pilling, C. G. (1999) Modelling the hydrological impacts of climate change on British runoff. PhD Thesis, University of Wales, Aberystwyth, UK.

Pilling, C. & Jones, J. A. A. (1999) High resolution equilibrium and transient climate change scenario implications for British runoff. *Hydrol. Processes* **13**(17), 2877–2895.

Pilling, C. G. & Jones, J. A. A. (2002) The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye experimental catchment, mid-Wales. *Hydrol. Processes* **16**(6), 1201–1213.

Pilling, C., Wilby R. L. & Jones, J. A. A. (1998) Downscaling of catchment hydrometeorology from GCM scenarios using airflow indices. In: *Hydrology in a Changing Environment* (ed. by H. S. Wheater and C. Kirby), vol. 1, 191–208. Wiley, Chichester, UK.

Santer, B. D. (1988) *Regional Validation of General Circulation Models*. Climatic Research Unit Publication no. 9, Climatic Research Unit, University of East Anglia, Norwich, UK.

UKCCIRG (UK Climate Change Impacts Review Group) (1991) *The Potential Effects of Climate Change in the United Kingdom.* Department of the Environment, HMSO, London, UK.

Viner, D. & Hulme, M. (1993a) *The UK Met Office High Resolution GCM Equilibrium Experiment (UKHI).* Climate Impacts LINK Technical Note no. 1, Climatic Research Unit, University of East Anglia, Norwich, UK.

Viner, D. & Hulme, M. (1993b) *The UK Met Office High Resolution GCM Transient Experiment (UKTR).* Climate Impacts LINK Technical Note no. 4. Climatic Research Unit, University of East Anglia, Norwich, UK.

Wilby, R. L., Hassan, H. & Hanaki, K. (1998) Statistical downscaling of hydro-meteorological variables using general circulation model output. *J. Hydrol.* **205**, 1–19.

Wilby, R. L., Conway, D. & Jones, P. D. (2002) Prospects for downscaling seasonal precipitation variability using conditioned weather generator parameters. *Hydrol. Processes* **16**, 1215–1234.