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# ESTIMATING LOW FLOW FREQUENCIES IN THE MID TO LATE 21ST CENTURY FOR TWO BASINS IN CENTRAL WALES

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*ABSTRACT: The research reported here uses a methodology that has been developed to generate riverflow scenarios for future climate change from GCMs. The method involves simulation of daily flows to assess the degree of change in flow frequencies, lengths of low flow periods and seasonal distributions in catchments in mid-Wales under two climate change scenarios derived from the Hadley Centre HadCM2 GCM. The method consists of: (1) establishing statistical relationships between interval-scale airflow indices (vorticity, the strength of the geostrophic wind, and its zonal and meridional directional components) and recorded precipitation and potential evapotranspiration (PET) for the period of instrumental record within each catchment, (2) using the derived transitional probabilities and correlations as input to a daily Stochastic Weather Generator, and (3) inputting this synthesised daily weather sequence into a physically-based hydrological simulation model (HYSIM). Split-sample tests indicate good agreement between predicted and recorded daily flow frequencies, with a Nash-Sutcliffe efficiency criterion of 0.7 for daily flows and 0.9 for monthly totals. The results suggest that there will be increased frequency of low flow days during the summer and a slight increase in the length of individual low flow spells.*

*RESUMEN: Este trabajo utiliza una metodología que ha sido desarrollada para producir escenarios de caudal ante un futuro cambio climático a partir de Modelos de Circulación General (MCG). El método implica la simulación de caudales diarios para definir el grado de cambio en frecuencias de caudal, duración de los periodos de estiaje y su distribución estacional en cuencas de Gales Central bajo dos escenarios de cambio climático derivados del Hadley Centre HadCM2 MCG. El método consiste en: 1) Establecer relaciones estadísticas entre índices de flujo atmosférico de intervalo-escala (vorticidad, fuerza del viento geostrófico y sus componentes direccionales zonal y meridional), y la precipitación y la evapotranspiración potencial para el periodo de registro instrumental dentro de cada cuenca; 2) utilizar las probabilidades y correlaciones transicionales derivadas, como un input del Generador Estocástico de Tiempo diario; y 3) introducir esta secuencia sintética de tiempo en un modelo de simulación hidrológica de base física (HYSIM). Los tests realizados indican un buen ajuste entre las frecuencias diarias de caudal predichas y registra-*

*das, con un criterio de eficiencia de Nash-Sutcliffe de 0.7 para los cauda - les diarios, y de 0.9 para los totales mensuales. Los resultados sugieren que habrá un aumento en la frecuencia de días de caudales bajos durante el verano y un ligero aumento en la duración de los periodos de estiaje.*

**Key-words**: Hydrological modelling, Low flows, Discharge forecast, General Circulation Models, Middle Wales.

**Palabras clave:** Modelización hidrológica, Estiaje, Predicción de caudales, Circulación General Atmosférica, Gales Central.

## 1. Introduction

It has been suggested in recent climate change research that rapid changes are likely to occur over the next century both in climate and water resources (IPCC, 1996; CCIRG 1996; Jones *et al*., 1996; Arnell, 1998, 1999; Arnell and King, 1997). Future climate change is likely to have a significant effect on the hydrological regime of UK river catchments. Changes in the hydrological regime of catchments may have serious implications for water resource management and it is likely that traditional methods of water resource assessment, which commonly use past records of climate and riverflow, will no longer be adequate under changed climate conditions where flows are likely to be significantly different. It has therefore become necessary to develop some means of predicting the likely hydrological regime of catchments in the UK under a significantly different future climate.

Estimations of future riverflows are of great importance to water resource managers, allowing the development of more realistic water resource management strategies for the future. It is for this reason that research was carried out under a contract with Welsh Water to provide an assessment of estimated low flow frequencies in the mid to late 21$^{st}$ century, under possible future climatic conditions, for two basins in mid-Wales, UK. The basins are the Elan, a tributary of the River Wye, and the Wye down to the gauging station at Belmont (Figure 1). The Elan is a small upland catchment 184km$^2$ in size. It contains a system of five dams and reservoirs in its reaches, built in the mid-19$^{th}$ century to supply water to the growing population of Birmingham. The Elan catchment continues to be an important water supply system providing water for the Midlands, and also occasionally for South Wales to supplement usual water supplies here in times of shortages. The Wye to Belmont is also an important water supply catchment, 1896km$^2$ in size, mainly providing water for the local area, although since the early 1980s the Wye has acted as an additional supply of water to South Wales if required, with its flow regulated by releases from the Elan reservoirs.

In order to produce estimations of future riverflow conditions, daily time series of precipitation and potential evapotranspiration (PET) under future climatic conditions are required. At present the best available estimates of future climatic conditions are produced by General Circulation Models (GCMs). However, the current GCM output is at a spatial resolution (300x350km) which is far too coarse for catchment-scale studies, with only one model grid square covering the whole of Wales. Another problem associated

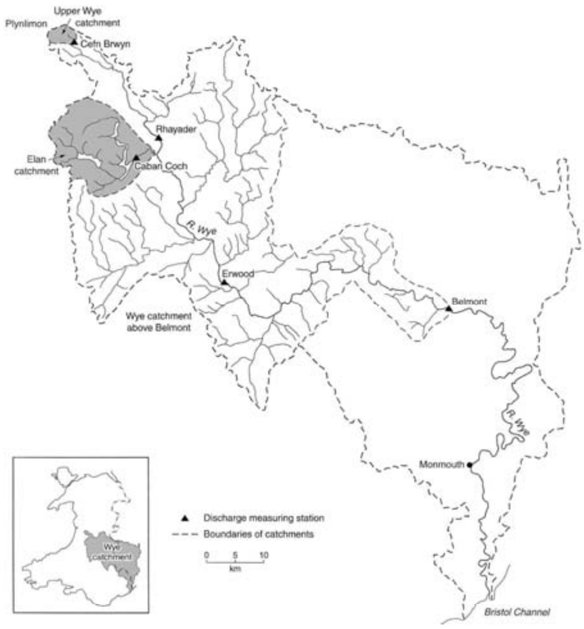


*Figure 1. The Elan and Wye catchments (inset shows location of catchments in Wales).*

with GCMs is that output of the water balance components, such as precipitation and PET, are relatively less reliable than the output of temperature and atmospheric pressure. The solution is to use a method to downscale the more reliable output of atmospheric pressure to catchment-scale precipitation and PET data to use as input to a hydrological simulation model, HYSIM (Manley, 1978, 1993). Results are presented for estimated changes in low flow frequencies in both the Elan and the Wye to Belmont, adding to previous work carried out for the Elan (Jones and Mountain, 2000).

## 2. Methodology

A statistical downscaling technique developed by Wilby *et al*., (1998) and modified by Pilling *et al*., (1998) is used to establish daily sequences of precipitation and PET under present and future climatic conditions to 2099 for use as input to a hydrological simulation model. The method combines a number of approaches, including statistical downscaling and a stochastic weather generator. The output of daily riverflows is used to assess future low flow frequencies in the Elan and Wye to Belmont catchments.

Two future climate change scenarios are used in this study, both obtained from the Hadley Centre GCM HadCM2 model. The first scenario is the HadCM2GHG which models 'greenhouse gas only' forcing of the future climate. This is also referred to as the 'Medium-High' scenario and is recommended by the UKCIP (Hulme and Jenkins, 1998) as the scenario to use if only one is to be studied. It has also been adopted as the standard scenario for water resource planning in the UK. The second scenario is the HadCM2SUL, which models greenhouse gas forcing plus the negative effect of sulphate aerosols in the atmosphere. This is a less extreme scenario, and together both should provide a suitable range of possible future riverflow conditions.

The method used to estimate future low flow frequencies consists of three stages:

1) Establish statistical relationships between meso-scale atmospheric predictor variables (vorticity, strength of the geostrophic wind, and the zonal and meridional directional components of the airflow) and the recorded precipitation and PET for each catchment.

2) Use the transitional probabilities and correlations derived from the meso-scale and local-scale data as input to a daily Stochastic Weather Generator.

3) Input generated daily weather sequences to a physically-based hydrological simulation model (HYSIM).

*2.1. Data*

The datasets used to produce the daily time series of riverflows were as follows:

1) Recorded precipitation and PET for the Elan catchment. The most representative single raingauge record was used for the present period 1976-1995 and missing data infilled where necessary from surrounding gauge records that showed a good correlation with the main gauge. Penman PET calculated by the Institute of Hydrology for the adjacent Upper Wye catchment (Figure 1) was used for the present period 1976-1995 and transposed to the similar Elan catchment where no records were available.

For the Wye to Belmont catchment, precipitation and PET data were obtained from the Meteorological Office Rainfall and Evaporation Calculation System (MORECS). Precipitation and PET data are calculated on a 40x40km grid basis. These data were found to better represent the larger Wye catchment than the PET calculated in the Upper Wye headwater research catchment and the single-site precipitation records. This probably reflects the fact that the MORECS data are averaged for an area large enough to cover the basin fully and incorporate varying landuses.

2) Recorded daily discharge supplied by Welsh Water for the present period 1976-1995 for the Elan and Wye to Belmont. One gauge record was used for the Elan at Caban Coch. For the Wye to Belmont the catchment was split into three sub-catchments and recorded flows at Rhayader, Erwood and Belmont used (Figure 1).

3) Three airflow indices, calculated from daily grid point mean sea level pressure data for the British Isles grid box are employed in the downscaling procedure. The three indices are vorticity (Z-index), the strength of the geostrophic airflow (F-index) and the zonal and meridional directional components of the airflow ($D_x$ and $D_y$ indices). Observed airflow indices for the present period 1976-1995 and airflow indices from both future climate change scenarios, for two future timeslots (2040-2059 and 2080-2099) were obtained from the Climatic Research Unit of the University of East Anglia.

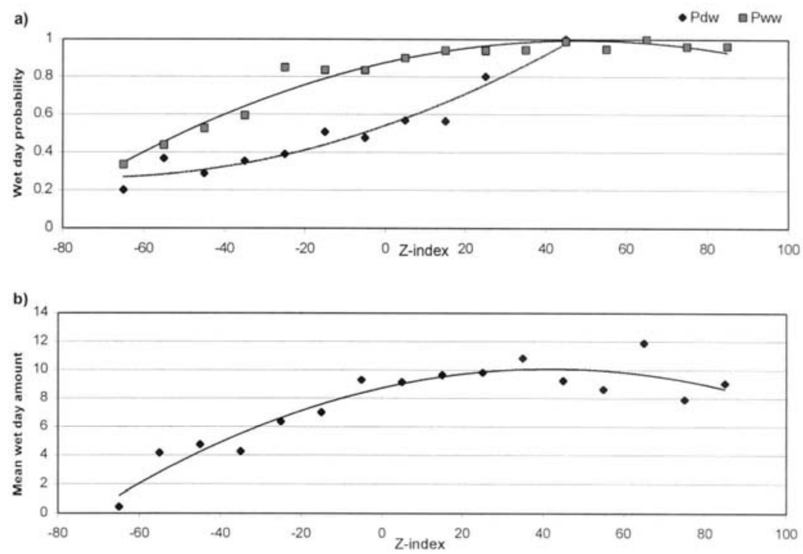


*Figure 2. Relationships of daily probabilities of precipitation (a) and daily precipitation depth (b) to vorticiy for the Elan in winter.*

### *2.2. Method*

The three main stages in the method are described below:

1) Statistical relationships:

Seasonal relationships were established for three-month seasons (winter, December to February, spring, March to May, summer, June to August and autumn, September to November) between the observed meso-scale airflow indices and the recorded catchment precipitation and PET for both the Elan and Wye to Belmont catchments, for the present period (1976-1995). Strong relationships have previously been identified between precipitation probabilities and amounts and airflow indices in the British Isles, Europe, USA and Japan (Conway and Jones, 1998, Conway *et al*., 1996, and Wilby *et al*., 1998). Second order polynomial regression equations were derived initially for precipitation probability and amount in relation to vorticity classes for the Elan catchment. The probability of a wet day following a wet day ($P_{ww}$) or a wet day following a dry day ($P_{dw}$) was found to be strongly related to the vorticity in the Elan catchment, with $R^2$ values of up to 0.95 (Figure 2).

Regression relationships were also established for precipitation probabilities and amounts for the Wye to Belmont catchment, although the relationship was significantly improved by adding the F-index (strength of the geostrophic wind) into the equation. Seasonal second order polynomial regression equations were also found to be adequate to represent the relationship between the daily PET amount and airflow indices.

However, due to weaker correlations between PET amounts and the observed airflow indices all three indices were included in the regression.

2) Stochastic Weather Generator:

The derived transitional probabilities and correlations are used as part of a stochastic weather generator which is driven by the input of daily airflow indices to produce daily sequences of precipitation and PET for present and future climatic conditions. Two different randomization techniques are employed to simulate precipitation and PET, in order to best reproduce the statistical properties of each hydrometeorological variable. The stochastic weather generator is initially used to simulate precipitation and PET for the present period 1976-1995, using the observed airflow indices as input. This provides a reference from which the significance of simulated future changes can be assessed. The stochastic weather generator is then used to simulate daily precipitation and PET series under future climatic conditions, for two time periods, 2040-2059 and 2080-2099, for the two climate change scenarios. Thirty simulation runs were carried out for both present and future time periods for each scenario. Details of the techniques are given below.

*i) Simulating daily precipitation*

Precipitation simulation is based on the transition probabilities of a wet day occurring after a wet day ($P_{ww}$) or a wet day after a dry day ($P_{dw}$), derived from the observed data sets. Simulation is carried out on a seasonal basis. The initial step is to establish whether the previous day was wet or dry, and apply the appropriate probability equation:

If wet $P_{ww} = a + bZ + cZ^2$ (for the Wye $P_{ww} = a + bZ + cZ^2 + dF + eF^2$) (1)

If dry $P_{dw} = d + eZ + fZ^2$ (for the Wye $P_{dw} = f + gZ + hZ^2 + iF + jF^2$) (2)

Daily Z-index values (for the Elan) and Z and F-index values (for the Wye to Belmont) are input into the relevant expression above to calculate the probability of rain for that day. Precipitation occurs if the probability of a wet day ($P_{ww}$ or $P_{dw}$) is more than a randomly generated number ($r_1$) between 0.0 and 1.0. The next step is to calculate the mean wet day amount ($P_z$) for the Z-index (or Z and F indices) for that day. This is done by applying the following equation:

$P_z = g + hZ + iZ^2$ (or for the Wye $P_z = k + lZ + mZ^2 + nF + oF^2$) (3)

The actual daily rainfall amount for that day is determined by taking a random sample from an exponential distribution with a mean of $P_z$:

$$P_{day} = -P_z \ln(r_2) 2r_3 \quad (4)$$

where $r_2$ and $r_3$ are linear random numbers and the term $2r_3$ is used to increase the variance around the mean, commonly used in precipitation models to improve the representation of observed precipitation series (Hay *et al.*, 1991). The procedure is then repeated for the next day.

*ii) Simulating daily potential evapotranspiration*

Daily time series of PET values are simulated in the following way, again using the derived seasonal relationships between the observed airflow indices and the observed PET values for the present period. All airflow indices are included in the second order polynomial regression equation and a first order Markov chain is incorporated, which takes account of the autocorrelation present in the evaporation series. The general expression fitted for each season is:

$$PET_i = a + PET_{i-1} + bZ + cF + dD_x + eD_y + fZ^2 + gF^2 + hD_x^2 + iD_y^2 + r \qquad (5)$$

where i represents the $i^{th}$ day in the sequence and r is the residual. The residuals are extracted from the original regression. For the simulation, daily residuals are generated by Monte Carlo sampling from a normal distribution with the same mean and standard deviation as the original residuals. Actual daily values are simulated by inputting daily Z, F, $D_x$ and $D_y$ values, the previous day's value and the stochastically generated residual. This procedure is repeated for the next day.

3) Hydrological simulation model:

The observed and simulated daily weather sequences are used as input to the 1993 version of HYSIM (Manley, 1978; 1993). HYSIM is a physically-based hydrological simulation model and takes daily precipitation and PET as the basic inputs, while the basic outputs are daily riverflow and actual evapotranspiration. The model consists of five internal stores representing interception, the upper and lower soil horizons, transitional groundwater storage and residual groundwater storage. Seventeen parameters are used in the model, nine of which are set using land use and soil survey data for the catchment. These include parameters for interception storage, impermeable surface cover, soil porosity, permeability and maximum soil moisture storage. The remaining eight parameters are set at average values recommended by Manley (1977) for UK catchments. These include the rate of discharge from soil and groundwater and the time to peak in minor channels. These initial parameters are adjusted during calibration of the model against recorded flows for a ten-year period 1986-1995. HYSIM is validated against recorded flows for another ten-year period 1976-1985. Correlation coefficients achieved between simulated and recorded flows in the validation period for the Elan are 0.85 for daily flows and 0.97 for monthly flows. For the Wye catchment a daily correlation coefficient of 0.96 and a monthly correlation coefficient of 0.99 were achieved. The Nash-Sutcliffe efficiency criterion is used to assess the success of the model. It expresses the proportion of variance of recorded flows reproduced in the simulated flows. A daily value of 0.7 and a monthly value of 0.9 were achieved for the Elan, and daily and monthly values of 0.9 were achieved for the Wye.

## 3. Results

In order to assess changes in low flow frequencies for water resource planning purposes various flow characteristics in the Elan and the Wye to Belmont have been inves-

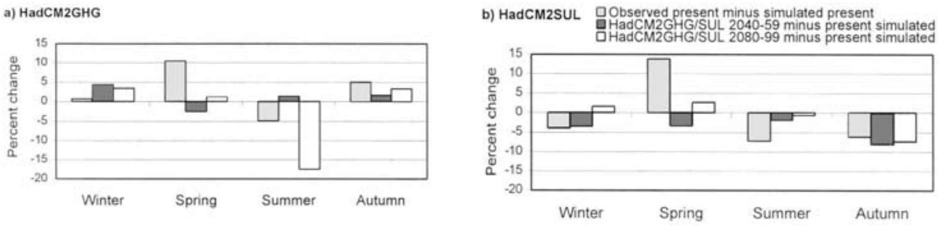


*Figure 3. Percentage changes in seasonal discharge for the Elan. The zero line is the present simulated.*

tigated. A number of these are utilised in the Institute of Hydrology's Low Flows Studies (1980) and recognized as important low flow measures, especially for water supply studies. The changes in average discharges, low flow durations, Q95 flows and low flow spell characteristics, including length and number, have been studied by taking the average results from 30 simulation runs. Results are presented for both the Elan and the Wye to Belmont, and for two future time periods (2040-2059 and 2080-2099) for two GCM scenarios, HadCM2GHG and HadCM2SUL. The results of the low flow analyses correspond to changes in the catchment hydrometeorology, with a reduction in mean daily rainfall of around 8% and an increase in daily PET of 4%.

The results presented below are discussed in terms of two types of significance. Firstly, changes modeled internally between the present simulated and future simulated values are tested for significance using the Student's t test at the 5% level. This shows significant modeled changes. Secondly, the significance is discussed in terms of the error in the model simulation between the observed values for the present period and the simulated values for the present. If the difference between these two simulations is more than the difference between the present and future simulations, this latter change is seen as insignificant in relation to the error in estimation.

*3.1. Changes in average discharges*

Figure 3 illustrates the percentage change in average seasonal discharge for the Elan by 2040-2059 and by 2080-2099, under a) HadCM2GHG and b) HadCM2SUL. Changes in winter and spring are relatively small, but some very significant changes are found in summer and autumn. Under the greenhouse gas only scenario, significant increases occur in winter discharge, of 4% by 2040-2059 and 3% by 2080-2099. A significant decrease in average summer discharge of almost 18% occurs by 2080-2099. No significant changes occur in spring or autumn. Under the greenhouse gas plus sulphate aerosols scenario, there is an increase in average winter discharge of just 2% by 2080-2099. Spring discharge is seen to decrease by 3% by 2040-2059, and although there are no significant changes in summer discharge, there is a significant decrease in autumn discharge of 8% by 2040-2059 and 7% by 2080-2099.

*Figure 4. Percentage changes in seasonal discharge for the Wye to Belmont. The zero line is the present simulated.*

Changes in average discharges for the Wye at Belmont follow a similar pattern. Figure 4 a) illustrates changes in seasonal discharges for the Wye under HadCM2GHG. There is a significant decrease in spring discharge of 4% by 2040-2059. Summer discharge decreases significantly by 20% by 2080-2099. Changes in winter and autumn discharges are not significant. Figure 4 b) shows changes in average Wye discharge under HadCM2SUL. Winter discharge decreases significantly by 7% by 2040-2059 and 6% by 2080-2099. Spring discharge decreases significantly by 4% by 2040-2059. Interestingly summer discharge is seen to increase by almost 3% by 2080-2099, although much greater decreases are seen in autumn, of 14% by 2040-2059, and almost 15% by 2080-2099.

*3.2. Changes in low flow durations*

Flow duration curve analysis has allowed an assessment of the change in the total period of time that flows fall below a specified level. Flow duration curves are useful in providing an overall view of the risk of low flows. Three flow thresholds were studied, recommended by Welsh Water as significant to low flow management in the catchment under study. For the Elan the three thresholds are $1.15m^3/s$, $1.74m^3/s$ and $2.3m^3/s$. For the Wye to Belmont the three thresholds are $8.05m^3/s$, $9.55m^3/s$ and $11.04m^3/s$. Table 1 details the change in the percentage of total Elan flows below each threshold for both the HadCM2GHG and HadCM2SUL scenarios for all seasons. Under the greenhouse gas only scenario the most notable changes occur in summer with significant increases in low flows approaching 10% by 2080-2099 for all three thresholds. Spring exhibits smaller yet significant decreases in low flows of around 4% by 2080-2099. Although changes in winter and autumn are in some cases statistically significant, the majority are small and often not significant in relation to the present day simulation error.

Under the HadCM2SUL scenario much less change can be seen. Most changes are less than the difference between the present simulated and present observed values, except in spring where decreases in low flows of around 1 or 2% are seen, as under the greenhouse gas scenario although to a lesser extent. Interestingly in autumn there are statistically significant, if relatively small (up to 3%), increases in low flows by 2040-2059. However, by 2080-2099 the trend is reversed and small decreases in low flow duration can be seen. No significant changes occur in summer under this scenario.

*Table 1. Change in the percentage of total flows below selected thresholds, Elan. Bold figures significant at 5% level. Positive values indicate more frequent low flows below the thresholds.*

| | Discharge threshold and scenario | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| **GHG** | | | | | |
| **<1.15m³/s** | Present observed minus simulated | +2.1 | +1.3 | +6.6 | -0.8 |
| | 2040-59 simulated minus present simulated | 0.0 | **-1.1** | +0.8 | **-1.1** |
| | 2080-99 simulated minus present simulated | **+0.1** | **-3.5** | **+8.9** | **-1.7** |
| **<1.74m³/s** | Present observed minus simulated | **+4.7** | +2.6 | +9.0 | +2.9 |
| | 2040-59 simulated minus present simulated | **+0.2** | -0.7 | +1.5 | -0.5 |
| | 2080-99 simulated minus present simulated | **+0.4** | **-4.4** | **+9.7** | **-1.2** |
| **<2.3m³/s** | Present observed minus simulated | **+7.6** | +3.4 | +3.3 | **+5.3** |
| | 2040-59 simulated minus present simulated | **+0.4** | -0.4 | +1.0 | **-0.8** |
| | 2080-99 simulated minus present simulated | **+0.7** | **-4.4** | **+9.2** | -1.6 |
| **SUL** | | | | | |
| **<1.15m³/s** | Present observed minus simulated | +2.1 | +2.4 | +7.6 | +1.8 |
| | 2040-59 simulated minus present simulated | **+0.1** | **+1.7** | +0.1 | **+1.7** |
| | 2080-99 simulated minus present simulated | 0.0 | -0.7 | -0.1 | **-1.9** |
| **<1.74m³/s** | Present observed minus simulated | **+4.5** | +3.3 | +9.5 | **+5.6** |
| | 2040-59 simulated minus present simulated | **+0.4** | **+1.7** | +0.9 | **+2.5** |
| | 2080-99 simulated minus present simulated | 0.0 | -1.2 | +0.7 | **-1.4** |
| **<2.3m³/s** | Present observed minus simulated | **+7.1** | +3.4 | +3.7 | **+8.8** |
| | 2040-59 simulated minus present simulated | **+0.8** | +1.5 | +1.1 | **+3.2** |
| | 2080-99 simulated minus present simulated | -0.3 | **-1.8** | +1.1 | -0.8 |

*Table 2. Change in the percentage of total flows below selected thresholds, Wye at Belmont. Bold figures significant at 5% level. Positive values indicate more frequent low flows below the thresholds.*

| | Discharge threshold and scenario | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| **GHG** | | | | | |
| **<8.05m³/s** | Present observed minus simulated | 0.0 | +2.1 | +8.5 | +5.6 |
| | 2040-59 simulated minus present simulated | 0.0 | +0.4 | **+3.9** | 0.0 |
| | 2080-99 simulated minus present simulated | 0.0 | -0.5 | **+10.2** | -1.0 |
| **<9.55m³/s** | Present observed minus simulated | +0.2 | +5.2 | +9.6 | **+9.0** |
| | 2040-59 simulated minus present simulated | 0.0 | **+1.1** | **+4.5** | -0.2 |
| | 2080-99 simulated minus present simulated | 0.0 | -0.6 | **+11.4** | -1.3 |
| **<11.04m³/s** | Present observed minus simulated | +0.3 | **+7.7** | +10.9 | **+10.6** |
| | 2040-59 simulated minus present simulated | 0.0 | **+2.1** | **+4.2** | -0.2 |
| | 2080-99 simulated minus present simulated | 0.0 | -0.8 | **+11.4** | -1.3 |
| **SUL** | | | | | |
| **<8.05m³/s** | Present observed minus simulated | 0.0 | +2.0 | +3.0 | +5.8 |
| | 2040-59 simulated minus present simulated | +0.2 | **+1.4** | -0.6 | **+3.6** |
| | 2080-99 simulated minus present simulated | 0.0 | **+0.9** | -0.8 | +0.1 |
| **<9.55m³/s** | Present observed minus simulated | +0.2 | +4.5 | +3.5 | **+9.4** |
| | 2040-59 simulated minus present simulated | +0.3 | **+2.1** | -0.5 | **+4.0** |
| | 2080-99 simulated minus present simulated | +0.1 | **+1.6** | -1.1 | +0.7 |
| **<11.04m³/s** | Present observed minus simulated | +0.4 | +6.5 | +5.1 | **+11.1** |
| | 2040-59 simulated minus present simulated | +0.5 | **+2.4** | +0.1 | **+4.3** |
| | 2080-99 simulated minus present simulated | +0.2 | **+2.1** | -1.1 | +1.2 |

Table 2 presents changes in the percentage of total flows below three key thresholds for the Wye to Belmont, for each season under both GCM scenarios. As for the Elan, under HadCM2GHG, large increases in the frequency of flows below each threshold are seen in summer, of around 11% by 2080-2099. Spring and autumn show small and on the whole insignificant changes, and in winter no change is indicated.

Under the HadCM2SUL scenario less change is seen to occur. In spring there are small statistically significant increases in the frequency of low flows of around 2% by 2080-2099, although these are not significant in terms of the simulation error for the present period. Similarly, in autumn statistically significant changes occur with increases in low flow frequencies of up to 4%, visible by 2040-2059 in this season rather than by 2080-2099. Winter and summer show no significant change in the amount of low flows below any threshold.

*3.3. Changes in the Q95*

The Q95 represents the flow equalled or exceeded by 95% of all riverflows and provides a significant and widely accepted indicator of low flow conditions. The change in the Q95 has been calculated annually and seasonally for the Elan and the Wye to Belmont, under both the HadCM2GHG and HadCM2SUL climate scenarios.

Table 3 shows changes in the Q95 for the Elan. Under the HadCM2GHG scenario there is a significant increase in the winter Q95 of 9% by 2040-2059 and 7% by 2080-2099, indicating a decrease in low flows in winter. The Q95 also increases in spring by 15%. The greatest change occurs in summer with a decrease in the Q95 of 24% by 2080-2099, indicating an increase in low flows.

Under the HadCM2SULscenario, the Q95 is again seen to increase in winter (4% by 2080-2099) and in spring (12% by 2080-2099). In summer the Q95 is seen to decrease, as under the greenhouse gas only scenario, by 11% by 2040-2059. However, by 2080-2099 an 11% increase is seen in the summer Q95 suggesting a decrease in the relative frequency of low flows by the end of the century. The autumn Q95 also follows this pattern, decreasing by 14% by 2040-2059, before increasing by 9% by 2080-2099. These

*Table 3. Percentage change in the Q95 discharge for the Elan. Bold figures significant at 5% level.*

| **Scenarios** | **Annual** | **Winter** | **Spring** | **Summer** | **Autumn** |
|---|---|---|---|---|---|
| *Greenhouse-gas only scenario* | | | | | |
| Present observed minus simulated | +1 | **-44** | +2 | **+15** | **-25** |
| 2040-59 simulated minus present simulated | -6 | **+9** | -4 | -6 | -6 |
| 2080-99 simulated minus present simulated | **-14** | **+7** | **+15** | **-24** | +2 |
| *Sulphate aerosols scenario* | | | | | |
| Present observed minus simulated | -4 | **-52** | +8 | +11 | -44 |
| 2040-59 simulated minus present simulated | **-12** | **-5** | -2 | **-11** | **-14** |
| 2080-99 simulated minus present simulated | **+13** | **+4** | **+12** | **+11** | **+9** |

trends are also reflected in annual Q95 values. Under the HadCM2GHG scenario, the annual Q95 shows a 14% decrease by 2080-2099. The HadCM2SUL scenario shows a similar trend for 2040-2059, but this is reversed by 2080-2099. This suggests that by 2080-2099 an anomalous situation has developed in which mean autumn and annual discharges have fallen significantly, but the Q95 is higher. Detailed analyses of the simulations confirm that this is indeed the case. This situation could result from either lower average discharges but fewer extreme low flows or an increase in the frequency of extreme high flows, which could result in a decrease in the *relative* frequency of extreme low flows even though average discharge is reduced. Analyses of the simulations suggest that the latter explanation best fits the situation on the Elan.

Changes in the Q95 for the Wye to Belmont can be seen in Table 4. Under the HadCM2GHG scenario changes similar to those seen in the Elan occur. In winter there is an increase in the Q95 of 10% by 2080-2099, whereas large decreases in the Q95 are seen in summer. By 2040-2059 there is a 14% decrease in average summer Q95 and a 28% decrease by 2080-2099, suggesting large increases in low flows in summer. Under the HadCM2SUL scenario the only significant change occurs in spring with an interesting 10% decrease in the average Q95. Annually under the HadCM2GHG scenario there is a large significant decrease in the Q95 of almost 11% by 2040-2059 and 19% by 2080-2099. Under the sulphate aerosols scenario by 2040-2059 there is an 11% decrease in the Q95. However, by 2080-2099 no significant annual change is seen.

The sulphate aerosol scenario therefore suggests that the trend towards lower annual Q95 is reversed by 2080-2099 in both the Wye and the Elan. However, the reversal is less extreme on the Wye. This could be related to greater orographic enhancement of extreme rainfall in the Elan basin where the Caban Coch gauging station is located 251 metres above sea level, compared to the gauging station on the Wye at Belmont which is located just 46 metres above sea level. Unlike the Elan, detailed analyses of the Wye simulations did not indicate any significant increase in extreme flood events compared with the present day.

*Table 4. Percentage change in the Q95 discharge for the Wye at Belmont. Bold figures significant at the 5% level.*

| Scenarios | Annual | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| *Greenhouse-gas only scenario* | | | | | |
| Present observed minus simulated | -5.0 | **-12.3** | **-19.3** | **+17.3** | **-25.1** |
| 2040-59 simulated minus present simulated | **-10.6** | +6.8 | **-12.3** | **-14.0** | -3.3 |
| 2080-99 simulated minus present simulated | **-18.6** | **+10.0** | +3.7 | **-27.9** | +3.7 |
| *Sulphate aerosols scenario* | | | | | |
| Present observed minus simulated | +3.8 | **-18.4** | -8.2 | **+26.6** | **-24.1** |
| 2040-59 simulated minus present simulated | **-11.3** | **-9.7** | **-9.9** | -5.1 | **-16.9** |
| 2080-99 simulated minus present simulated | +1.5 | -5.2 | -1.3 | +4.0 | -0.5 |

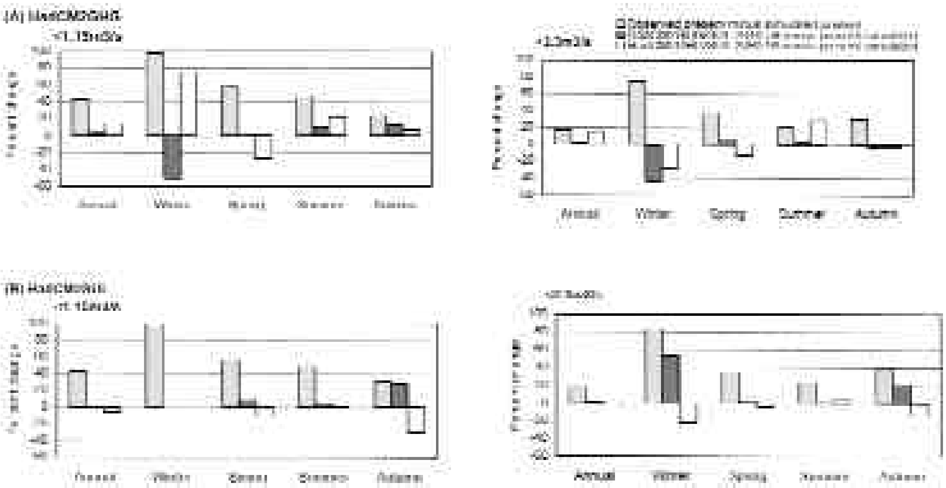


*Figure 5. Percentage change in mean duration of flow spells under a) HadCM2GHG and b) HadCM2SUL, for the Elan.*

### *3.4. Changes in low flow spell characteristics*

Of concern to water resource managers, and perhaps just as important as the total amount of time flow falls below a certain threshold, is the length of continuous periods of time that flows are below a certain value, or the length of the flow spell. Analyses were therefore carried out to assess changes in the average length of individual low flow spells below the three flow thresholds identified by Welsh Water. This was done on a seasonal basis for both the HadCM2GHG and HadCM2SUL climate change scenarios.

Figure 5 illustrates the percentage change in the length of individual low flow spells in the Elan under a) the HadCM2GHG scenario and b) the HadCM2SUL scenario, for two of the three flow thresholds. Although many changes are not significant in terms of the present day simulation error, a few significant changes can be identified. Under the greenhouse gas only scenario there is a significant decrease in spring low flow spell lengths under 1.15m$^3$/s and 2.3 m$^3$/s of around 27% and 13% by 2080-2099, although in actual terms this is approximately only 1 day. There is a significant increase in summer low flow spell lengths under 2.3m$^3$/s of almost 30% (3.6 days) by 2080-2099. Annually flow spells under 2.3m$^3$/s increase in length by 15% (1.5 days) by 2080-2099. Under the HadCM2SUL scenario autumn low flow spell lengths are seen to increase by around 20% (1 day) in 2040-2059, although a decrease in autumn low flow spell lengths is seen by 2080-2099.

Figure 6 shows the percentage change in average low flow spell lengths for the Wye to Belmont catchment, for discharges under the 8.05m$^3$/s and 11.04m$^3$/s thresholds for both climate change scenarios. Under the HadCM2GHG scenario statistically significant

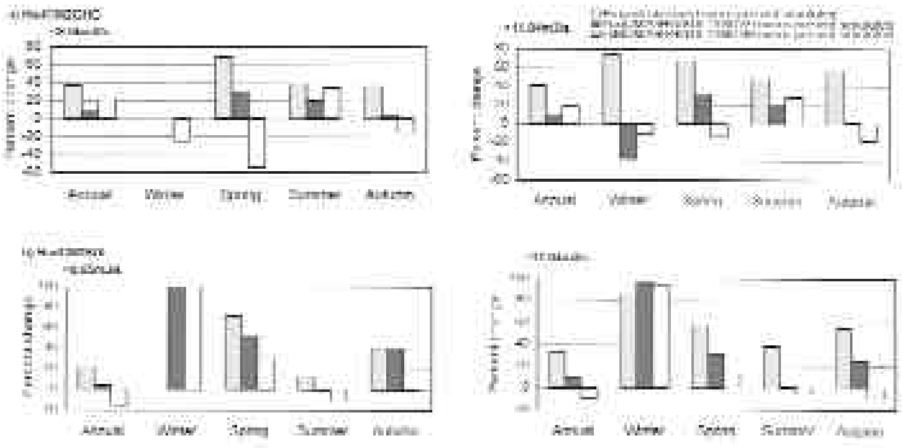

*Figure 6. Percentage change in mean duration of flow spells under a) HadCM2GHG and b) HadCM2SUL, Wye to Belmont.*

increases in low flow spell lengths of up to 3 days in summer occur by 2080-2099. Statistically significant decreases in low flow spell lengths can be seen in both winter and spring by 2080-2099, although in actual terms these increases are only around 0.5 days. Annually there is a 20% increase in the length of flow spells by 2080-2099. Under the sulphate aerosols scenario the trend in winter is reversed and increases of around 0.5 days in the average length of low flow spells under each threshold are seen. Summer and autumn exhibit decreases in low flow spell lengths by 2080-2099, although not exceeding one day. Annually by 2080-2099 for this scenario there is a 10-15% decrease in low flow spell lengths.

Analyses were also carried out on the average total number of flow spells in a year as well as the total number of days per year when flow fell below a given threshold. Less change was found in these low flow characteristics than in the average lengths of individual low flow spells described above. For the Elan catchment under the HadCM2GHG scenario the average annual number of low flow spells under 2.3m$^3$/s decreases by 5% by 2080-2099. However, under HadCM2SUL there is a 5% increase in the average annual number of flow spells under 2.3m$^3$/s by 2040-2059. For the Wye to Belmont there are no statistically significant changes in the average number of low flow spells. A few significant changes were also seen in the total number of days flow fell below each threshold. In the Elan catchment, under the HadCM2GHG scenario, there is an annual increase of 15% (6 days) in total days flow falls below 1.15m$^3$/s by 2080-2099. Under the HadCM2SUL scenario there is an annual increase of 8% (6 days) by 2040-2059 and a decrease of 6% (2 days) by 2080-2099 in days with flow below 2.3m$^3$/s. In the Wye catchment under the greenhouse gas only scenario the total number of days with flow below 2.3m$^3$/s increases annually by around 20% (8 days) and in summer by around 30% (10 days) by 2080-2099. Under HadCM2SUL increases are seen by 2040-2059 annually and in autumn by up to 35% (6 days), although by 2080-2099 no significant changes occur.

**4. Conclusions**

The results suggest that there are likely to be significant changes in low flow frequencies in the mid to late 21st century in both the Elan and the Wye catchments and since both catchments are important water supply systems the results could have significant implications for water resource managers. This supports the conclusions from previous climate change research carried out in Wales (Pilling *et al*., 1998; Holt and Jones, 1996).

Changes have been investigated under two climate change scenarios, HadCM2GHG and HadCM2SUL for two future time periods, 2040-2059 and 2080-2099. Although many aspects of low flows do not show any significant change, a number of significant changes are seen, particularly during the critical summer-autumn period. There is an increase in the seasonality of flows, with lower extremes in summer and autumn and higher extremes in winter and spring. Under the HadCM2GHG scenario the lowest flows generally occur in summer and the highest in winter, whereas under the HadCM2SUL scenario the most extreme seasons tend to be spring (high flows) and autumn (low flows). Average discharges are seen to decrease in summer in both the Elan and the Wye by up to 20% ($60m^3$/s in the Elan, $360m^3$/s in the Wye) at the end of the century under HadCM2GHG. Under the sulphate aerosols scenario the largest decreases in discharge occur in autumn by up to 15% ($550m^3$/s for the Wye). Corresponding increases in discharges in winter and spring are seen but to a much lesser extent in both catchments and under both scenarios, by around 4% ($40m^3$/s and $280m^3$/s). Although changes in annual discharges are not very large, the reductions in summer flows are likely to be particularly problematic for water management.

Low flow durations are seen to increase significantly in summer and autumn with increases of up to 10% under the HadCM2GHG scenario. Again, corresponding decreases in low flows in winter and spring are seen but to a much lesser extent. These changes are supported by changes in the Q95 where annually there are decreases of up to 14% and in summer and autumn decreases of between 15 and 20%, indicating large increases in low flows. Analyses of the characteristics of low flow spells suggest that changes in the lengths of individual flow spells are more likely than changes in the number of low flow spells or the total number of low flow days. Summer exhibits increases in the length of individual flow spells by up to 30% under the HadCM2GHG scenario. The results suggest that although the actual number of low flow spells may show a slight overall decrease, individual spells may get longer, and it is this that will pose problems for water management strategies.

The HadCM2GHG scenario can be seen to be more extreme than the HadCM2SUL scenario, and fewer significant changes were found to occur under the latter. One significant difference between the two scenarios was found in the trends in Q95, with the sulphate scenario showing a reversed trend in the latter part of the century. Some evidence was found in the Elan basin to suggest that this might result from increases in extreme flood events towards the end of the century under the sulphate scenario. If so, then this could support suggestions that there will be significant increases in the frequency of extreme events at both ends of the spectrum (Beven, 1993; Cameron *et al*., 2000). However, this must remain speculative on the present evidence. Neither scenario should be regarded as 'more likely'. Both make important assumptions about future increases in greenhouse gas concentrations and there are doubts surrounding the estimation of the sulphate aerosol concentration and cooling effect simulated in HadCM2SUL. The two scenarios have therefore been taken as best showing the range of possible outcomes and changes in low flow frequencies during the 21st century. The more extreme HadCM2GHG scenario is seen as providing a reasonable safety factor for water resource planning. It is interesting to note that frequently under the HadCM2SUL scenario the most significant changes occur by 2040-2059, fading by 2080-2099, perhaps illustrating the possible influence of large-scale weather patterns on this scenario. However, anomalously these trends are only visible in selected results for the HadCM2SUL scenario.

A large range of possible changes in low flow frequencies are estimated to occur over the next century, some more extreme than others. Although many individual years may be similar to or less extreme than at present, it is the increase in the frequency of low flows which is likely to be most problematic for water resource planning in the future.

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