The potential impacts of climate change on hydropower generation in Mid Wales

D. Carless and P. G. Whitehead

ABSTRACT

Hydropower is a potential large source of electricity supply in Wales. The Upper River Severn in Mid Wales is a typical stream where a high head hydropower scheme could be developed and the river system at Plynlimon has some of the longest records for weather and flow in Wales. A micro-hydropower potential of 99 kW is demonstrated at Plynlimon and the potential impacts of climate change are simulated to assess the effects on flows and power outputs of such schemes under climate uncertainty. Based on UK Climate Projections 2009 (UKCP09) projections, the impacts of climate change are to significantly decrease both the stream flows and energy production during summer months but to increase flows and power production in the winter, with a net tendency to cancel out over the course of a full year. A methodology for assessing impacts of climate change on hydropower is established, which could be applied more widely to other potential hydropower sites such as lowland rivers or high base flow rivers in other parts of the UK. This will be useful for developers, water companies and environmental agencies to assess hydropower potential, economic viability and environmental impacts of micro-hydropower, under future climate change.

Key words | climate change impacts, economic impacts, hydropower, IHACRES, micro-hydro, Plynlimon

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INTRODUCTION

The IPCC Fourth Assessment Report (IPCC 2007) confirmed the consensus among scientists and policy-makers that human-induced climate change is occurring and that regardless of future greenhouse gas emission reductions, substantial climate change is unavoidable. One of the most significant effects of climate change is on the hydrological cycle (Gleick 1987; Wilby *et al.* 2006; Bates *et al.* 2008). Extremes in the hydrological system in the UK during the past decades have reflected the vulnerability of our rivers to climatic fluctuations (Hannaford & Marsh 2008).

Under the Kyoto Protocol, the UK has to further reduce carbon dioxide emissions and the government has set targets for renewable energy generation. Under the Renewables Obligations strategy and the Climate Change Bill (UK Government 2008) electricity suppliers must ensure that 15% of the energy they provide to consumers in England and Wales by 2020 is derived from renewable resources. While the government's response to climate change may promote the development of small- and micro-hydro, the effects of climate change itself may affect the actual generation of hydropower. A large and increasing body of work has highlighted the potential for predicted changes in climate and, in particular, changes in precipitation and temperature, which will alter the quantity, quality and distribution of river water (Wilby *et al.* 2006; Whitehead *et al.* 2009). Furthermore, these changes have been shown to impact on the production and, consequently, the economics of large hydropower schemes (Harrison & Whittington 2002).

There have been many studies on the potential impacts of climate change on hydropower (Sweden, Andréasson *et al.* 2004; Switzerland, Hauenstein 2005; Scotland, Duncan 2010; Finland, Molarius *et al.* 2010; Greece, Mimikou &

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Baltas 1997). Most studies have focused on catchments at high altitude or high latitude where summer snow melt is a major contributor to river flows and have been too complex for cost-effective application to small and micro-hydro schemes. However, the study in Greece by Mimikou & Baltas (1997) considers a large-scale storage hydropower scheme in a Mediterranean climate where the impacts of reduced rainfall on hydropower and dam design are considered to be significant. There has also been worldwide attention on the many hydropower schemes for large-scale developments located at large dams (El-Shafie & El-Manadely 2010). However, in the UK there are very few opportunities for new storage schemes and generally only small-scale run of river schemes are viable propositions. A simple approach is needed to make practical assessments of potential micro-hydro schemes to ensure their future economic viability.

Given that these small-scale hydropower schemes typically have little or no storage, such schemes are quite vulnerable to potential changes in climate. Furthermore, they are designed using flow duration curves to set the useable flow regime, in consultation with the Environment Agency, so that there is a trade-off between utilising high flows, remaining operational during low flows and ensuring there is sufficient water to meet environmental concerns (Environment Agency 2010). Given that installations have normally only one turbine, the capability of micro-hydro to respond to changes in flow distribution is rather limited. These factors may lead micro-hydropower to be particularly vulnerable to the changes in river flow quantity and distribution that result from climate change. The economics of micro-hydro schemes means that extensive hydrological studies of climate change are really required to fully assess the future potential of hydropower schemes. Therefore, the objectives of this paper are to develop a simple repeatable methodology based on established tools and procedures and to demonstrate this methodology by applying it to a hypothetical but realistic upland hydropower scheme in Mid Wales. The analysis has been possible by making use of the extensive data sets available at Plynlimon (Neal *et al.* 2003, 2011), together with a time series analysis hydrological modelling approach, namely IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) (Jakeman *et al.* 1990). With the focus on green energy in the UK, there has been a resurgence of interest in micro-hydropower in upland Wales and the Upper Severn River System at Plynlimon is typical of a potentially viable location.

SMALL-SCALE HYDROPOWER

Generating small-scale hydroelectric power in upland Welsh streams has had a long and successful history despite falling out of favour in the second half of the 20th century as the mains network reached the remoter parts. The technology is well established with only relatively minor recent improvements to performance and reliability from new materials technology and computer-aided design and manufacture. With the recent introduction of Feed in Tariffs in the UK (UK Government 2008), the value of electricity generated has been increased and fixed for an extended period of time (20 years). The major remaining risk to investment in new plant is the expected flow in the stream and that is a function of the local rainfall patterns and hydrology and the longer-term effects of climate. In order to estimate future patterns of generation, and hence revenue flows, developers rely on either historic flow records at the site, or on modelled flow from catchment rainfall, or from scaling gauged flows from nearby similar catchments. Traditionally, flow duration curves (FDCs) are developed which provide a statistical presentation of historic flows, and it is usually assumed that future flows will have a similar statistical distribution. Essentially a static situation is assumed and the potential impacts of climate change are generally ignored. Increasingly, investors in hydropower schemes are questioning this approach and are asking, as part of their due diligence process, for further assurance that power generation, and hence economic returns will be sufficient for the schemes' success.

The amount of water which may be abstracted from a stream and fed to the turbine is determined before construction of the plant by the regulatory authorities, namely the Environment Agency in England, Northern Ireland and Wales, and by the Scottish Environmental Protection Agency in Scotland. This permitted abstraction is designed to ensure that there will be sufficient flow, and variation in flow, to ensure that the environmental health of the depleted river section is not damaged. The acceptable flow will also be based on the historic FDCs and will typically be defined by a number of related parameters. The Hands Off Flow (HOF) will define a minimum flow in the stream before any abstraction is permitted and the share over HOF will define the fraction of flow which may be abstracted. The maximum flow ($Q_{\max}$) will be the full design flow of the turbine.

CLIMATE PROOFING METHODOLOGY

A key aim of this study has been to establish a practical methodology which can be readily applied to small-scale hydropower developments in order to make technical and economic assessments of the potential impacts of climate change, and enable developers, hydrologists and investors to act with greater confidence. A seven-stage methodology has been developed to enable direct comparison of expected performance of a hydropower plant under a 'business as usual' scenario and compare this with projected performance under a range of potential climate change impacted scenarios. The methodology assumes that the river system or stream has been selected and the appropriate hydropower calculations undertaken, such that a viable scheme is possible, under current day hydrology. In order to assess the potential impacts of climate change, seven stages of analysis are proposed as illustrated in Figure 1, and as follows:

1. For the river or stream in question, develop robust sets of baseline data for an extended period (in this case 24 years) of historic daily precipitation, temperature and river flow observations at the site.
2. Build and calibrate a reliable hydrological model (in this case IHACRES) to represent the relationships between the observed data sets.
3. Calculate and apply appropriate change factors to the precipitation and temperature data sets to represent climate change as projected by UK Climate Projections 2009 (UKCP09) in the chosen scenarios (in this case 2020s medium emissions and 2050s high emissions).
4. Run the model using the modified data sets to simulate the projected daily flows at the site for each scenario.
5. Calculate monthly FDCs to give a statistical representation of the flows under baseline and changed scenarios at different times of year.

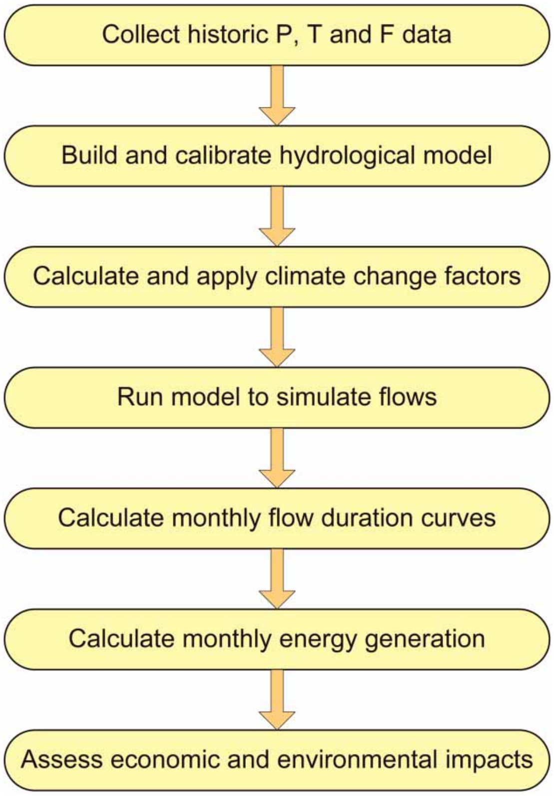

Figure 1 | A schematic diagram of the proposed methodology.

6. Calculate the monthly and annual energy generated in each scenario after having defined parameters of the hydropower plant.
7. Assess economic impacts, environmental impacts and water resource implications in the light of potential climate change.

RIVER SEVERN SYSTEM AT PLYNLIMON AND HYDROPOWER

The Plynlimon area in Mid Wales contains the headwaters of the River Severn and the River Wye with mostly forest cover in the Severn catchment. This paper is concerned with the Severn, which has two major sub-catchments, the Hafren and the Hore (Figure 2) at altitudes between 300 and 750 m above sea level. The whole area is underlain by base-poor Lower Palaeozoic mudstones, shales and grits upon which a mosaic of acid upland soils has developed.

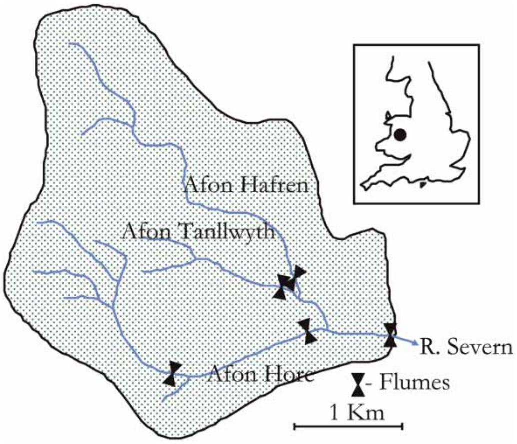

Figure 2 | The Severn catchment with the Hore, Tanllwyth and Hafren sub-catchments.

Underlying the soils in some parts of the catchment are drift deposits of boulder clay and colluvium derived from the bedrock. Most of the Upper Severn catchment is covered in plantation forest consisting mainly of Sitka spruce (*Picea sitchensis*) and Norway spruce (*Picea abies*) planted in three phases between 1937 and 1964. Prior to planting, the catchment was drained extensively by ploughing and ditching and now parts are in second rotation/planting.

The Plynlimon catchment has been the focus of a long running experiment with excellent data sets being collected and many hydrological, water quality and modelling studies (Neal *et al.* 2003, 2011; Whitehead *et al.* 2004). Catchment characteristics and hydrochemical behaviour are documented in great detail in a special issue of *Hydrology and Earth System Sciences* dedicated to the Plynlimon catchments (Neal 1997).

There are extensive records of climate and flow data at Plynlimon from a network of weather stations and an array of gauging stations, as shown in Figure 2. Analysing and combining data from a selection of weather and gauging stations, a reliable set of daily precipitation, temperature and flow data have been obtained for the Plynlimon Flume catchment covering the years 1985 to 2008. With average rainfall in the order of 2.65 m per year and an average flow in the stream of 0.58 $m^3 s^{-1}$ then a potential energy calculation suggests a micro-hydro plant of around 100 kW could be constructed utilising a head of 25 m. The potential performance of such a plant under historic and projected future climatic conditions has been assessed.

MODELLING HYDROLOGY AT PLYNLIMON – THE IHACRES APPROACH

A key requirement for any climate impact assessment is to model the catchment so that future potential changes in temperature and rainfall patterns can be translated into changing flows and hence into changing hydropower outputs. In this study, the IHACRES approach to hydrological modelling has been used because it provides a proven method of relating river flows in a defined catchment to precipitation and air temperature (Jakeman *et al.* 1990; Littlewood *et al.* 1997; Littlewood 2008).

IHACRES is a time series approach to modelling that has developed from the recursive analysis algorithms of Young (1974) and originally applied to model rainfall river flow relationships by Whitehead (1979). The modelling approach was later improved by Jakeman *et al.* (1990) and is available as a stand-alone software package which has been widely used by researchers and hydrologists in the water industry (Littlewood *et al.* 1997, Littlewood 2008; Croke *et al.* 2006). The program was later released as a more powerful IHACRES package which is now available from http://www.toolkit.net.au/ihacres. One of the benefits of this package is its ability to optimise on model structure and parameters and calibrate the model to observed flow data. However, the package is not suited for scenario analysis and a spreadsheet implementation of the model was developed for climate change scenario runs and hydropower calculations.

The overall model structure used for this study, as shown in Figure 3, consists of a rainfall loss model reflecting the losses during evapotranspiration and uptake by the soils, followed by a unit hydrograph module. This is shown at the core of Figure 3, which also gives brief descriptions of the six key catchment characteristics that are obtained from an IHACRES analysis.

The non-linear loss module was first developed by Whitehead (1979) and then modified by Jakeman & Hornberger (1993). The equations in the loss module are as follows:

$$u_k = r_k \frac{(s_k + s_{k-1})}{2},\ s_0 = 0 \tag{1}$$

$$s_k = \frac{r_k}{c} + \left(1 - \frac{1}{\tau_w(t_k)}\right) s_{k-1} \tag{2}$$

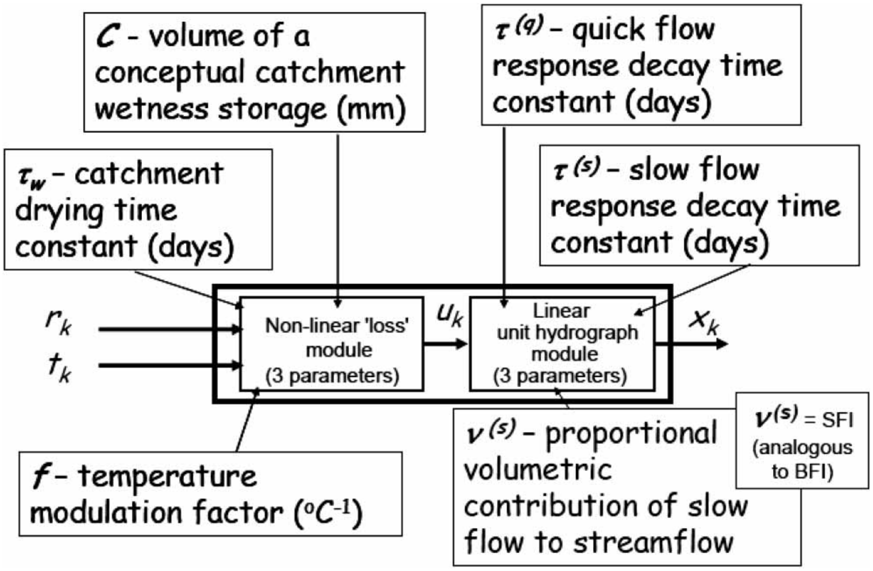

Figure 3 | Basic structure of IHACRES and the key catchment characteristics.

$$\tau_w(t_k) = \tau_w \exp(0.062 f(R - t_k)) \tag{3}$$

where s_k is a dimensionless catchment wetness index ($0 < s_k < 1$); t_k is air temperature (°C); τ_w is a catchment drying time constant (e.g., days) given by the value of $\tau_w(t_k)$ at a reference temperature, R (°C); f is a temperature modulation factor ($^\circ\mathrm{C}^{-1}$); and c is the depth of a catchment wetness store (e.g., millimetres) such that the volumes of effective rainfall and observed streamflow are the same over the model calibration period. The three catchment characteristics derived from this model are c, τ_w and f, as shown in Figure 3.

For dominant quick- and slow-response flows acting in parallel, streamflow at time-step k (Q_k) is estimated from effective rainfall (u_k) by Equation (4). Superscripts q and s in Equation (4) denote dominant quick- and slow-response flows, respectively. It is important to note that effective rainfall is the proportion of rainfall (r_k) that eventually becomes stream flow. The a and b parameters define first-order transfer functions ($-1 < a^{(.)} < 0$, $b^{(.)} > 0$), and z^{-1} is the backward-shift operator (i.e. $z^{-1}x_k = x_{k-1}$). Pure time delay, δ (i.e., $u_{k-\delta}$ instead of u_k in Equation (4)) may be important in some contexts where there is a significant groundwater response because of the lag between rainfall and the response of the river flows.

$$Q_k = \left(\frac{b^{(q)}}{1 + a^{(q)} z^{-1}} + \frac{b^{(s)}}{1 + a^{(s)} z^{-1}} \right) \tag{4}$$

The three catchment characteristics, $\tau^{(q)}$, $\tau^{(s)}$ and $\upsilon^{(s)}$ define the linear module, shown in Figure 1, and are given by Equations (5) to (7), where Δ is the data time-step (e.g., 1 day) and V is given by Equation (8).

$$\tau^{(q)} = \frac{-\Delta}{\ln\left(-a_1^{(q)}\right)} \tag{5}$$

$$\tau^{(s)} = \frac{-\Delta}{\ln(-a^{(s)})} \tag{6}$$

$$V^{(s)} = \left(\frac{b^{(s)}}{1 + a^{(s)}} \right) \left(\frac{1}{V} \right) \tag{7}$$

$$V = \frac{b^{(s)}}{1 + a^{(s)}} + \frac{b^{(q)}}{1 + a^{(q)}} \tag{8}$$

From Equation (4) it follows that modelled quick- and slow-response hydrographs, i.e., $Q_k^{(q)}$ and $Q_k^{(s)}$ for $k = 1, m$ where m is the number of time-steps in the length of record being used for model calibration, are calculated by recursive application of Equations (9) and (10), respectively, where $Q_k = Q_k^{(q)} + Q_k^{(s)}$. The quick-response hydrograph is given by recursive application of Equation (9) with $Q_0 = 0$, $u_1 = 1$ and $u_k = 0$ at all other k; similarly, for the slow-response using Equation (10).

$$Q_k^{(q)} = b^{(q)} u_k - a^{(q)} Q^{(q)k-1} \tag{9}$$

$$Q_k^{(s)} = b^{(s)} u_k - a^{(s)} Q^{(s)k-1} \tag{10}$$

The IHACRES model has been calibrated using the 1985–2009 rainfall, temperature and flow data set for the Plynlimon Flume catchment. A good fit to the observed flow data has been obtained, as shown in Figure 4 for the period 1991–1992, with an R^2 of 0.789 and a Nash–Sutcliffe statistic of 0.788. The calibration parameters for the IHACRES model are shown in Table 1. This model parameter set has been used for the climate scenario analysis.

CLIMATE CHANGE AND HYDROLOGICAL IMPACTS AT PLYNLIMON

UK Climate Projections 2009 is the latest climate model output and is the fifth generation of climate information for the UK. It provides climate change projections with greater spatial and temporal detail and is the first data set which gives probabilistic projections of future climate change (Murphy *et al.* 2009). UKCP09 reports that by the 2080s under the medium emission scenario, all areas of the UK will become warmer relative to 1961–1990 baseline conditions. Summer mean temperature in parts of southern England could increase by 4.2 °C at the 50% probability level. Precipitation patterns are projected to change significantly with more precipitation in winter (up to +33% change at the 50% probability level) and less precipitation in summer (down by −40% in the south of England at the 50% probability level). These probabilistic data are available for 23 river regions in the UK. Changes are given for seven

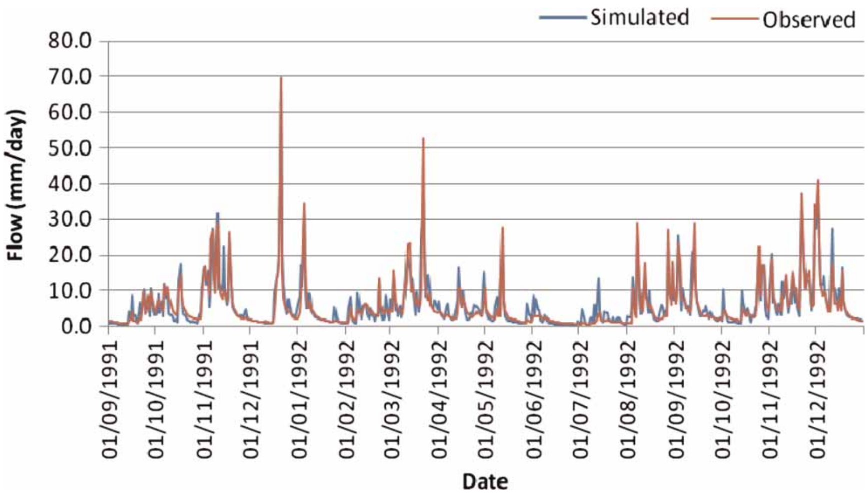

Figure 4 | IHACRES simulated and observed flow at the Plynlimon Flume catchment 1991–1992.

Table 1 | IHACRES model parameters for the Plynlimon Flume flow gauge based on data from 1985 to 2008

c (conceptual depth of a catchment wetness store in mm)	0.0057	$a^{(q)}$ (quick response recession rate)	−0.250
τ_w (catchment drying time constant in days)	2	$b^{(q)}$ (quick response peak value)	0.53
f (temperature modulation factor in °C^{-1})	1	$a^{(s)}$ (slow response recession rate)	−0.942
R (reference temperature in °C)	30	$b^{(s)}$ (slow response peak value)	0.017

future 30-year time period with ten years overlapping, covering the 2020s (2010–2039) and the 2080s (2070–2099), each with low, medium and high emission levels.

One of the significant improvements of UKCP09 over the earlier UKCIP02 is that climate modelling has been undertaken with a much finer spatial resolution using 25-km grid squares allowing finer spatial precision, compared to the earlier 200-km grid squares. The Plynlimon Flume and its catchment (8.7 km^2) are located in the southeast corner of square No. 1346, as shown in Figure 5. This square includes a significant proportion of coastal lowland and so may not be fully representative of the upland Plynlimon site. Therefore, climate change data from squares 1347, 1385 and 1386 (to the south and east) have also been used to form an average set of data for the 50-km square centred near Plynlimon. For each of the grid squares UKCP09 output data for change in mean temperature (°C) and change in precipitation (%) under a medium emissions' scenario for the 2020s (2010–2029) and high emissions' scenario for 2050s (2040–2059) were obtained for each month. A full set of 10,000 projections was taken and averaged, and from these a set of change factors for temperature and precipitation was calculated. These change factors are summarised in Table 2 and show increasing temperatures in the 2020s and the 2050s. The precipitation factors show increased rainfall in winter months and reduced rainfalls in summer months. These change factors were then applied to the Plynlimon temperature and precipitation data to generate a future climate data series to apply to the model in order to generate future flows.

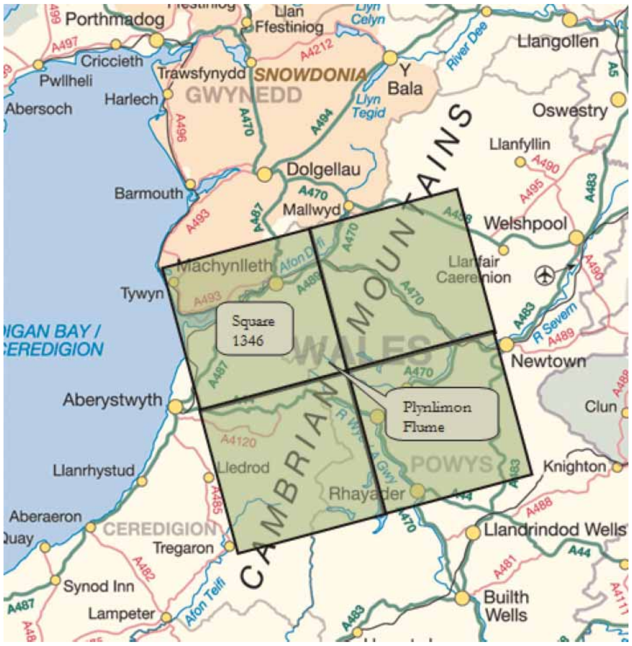

Figure 5 | The Plynlimon area and the UKCP09 grid squares.

Table 2 | Climate change factors from the UKCP09 10,000 realisations in Mid Wales for the 2020s and the 2050s for temperature and rainfall

	2020s Rainfall factors	2050s Rainfall factors	2020s Temperature change (°C)	2050s Temperature change (°C)
Jan	1.02	1.09	1.16	2.36
Feb	1.09	1.17	1.37	2.28
Mar	1.03	1.05	1.31	2.30
Apr	1.03	1.05	1.15	2.44
May	1.02	1.00	1.30	2.72
Jun	0.92	0.83	1.50	2.77
Jul	0.95	0.85	1.45	3.10
Aug	0.89	0.74	1.42	3.02
Sep	1.00	0.97	1.40	2.78
Oct	1.03	1.10	1.43	2.69
Nov	1.10	1.19	1.50	2.72
Dec	1.13	1.27	1.53	2.75

CLIMATE CHANGE IMPACTS ON HYDROLOGY

Having established a calibrated hydrological model based on reliable data, the climate change factors derived from the UKCP09 analysis were applied to the baseline daily precipitation and temperature data set by multiplying the daily rainfall data by the appropriate monthly change factor and by adding the appropriate monthly temperature change factor to the daily temperatures. Hence the projected daily weather data for the 2020s and the 2050s scenarios were calculated. The IHACRES model was re-run to generate projected daily flows, which were then averaged on a monthly basis to determine the changes in stream regime throughout the year. As shown in Table 3, the percentage changes in monthly flow indicate significant increases in flow in winter months and major reductions in summer.

Table 3 | Baseline and percentage changes in monthly flows at the Plynlimon Hore gauge site for the 2020s and the 2050s

	Baseline flow in cumecs	2020s percentage change in flow	2050s percentage change in flow
Jan	0.85	2.9	11.9
Feb	0.69	7.9	17.1
Mar	0.64	3.5	5.4
Apr	0.41	2.4	3.3
May	0.28	1.4	−1.9
Jun	0.31	−10.0	−20.5
Jul	0.37	−8.3	−22.4
Aug	0.45	−14.4	−33.3
Sep	0.50	−4.0	−11.3
Oct	0.74	0.9	7.2

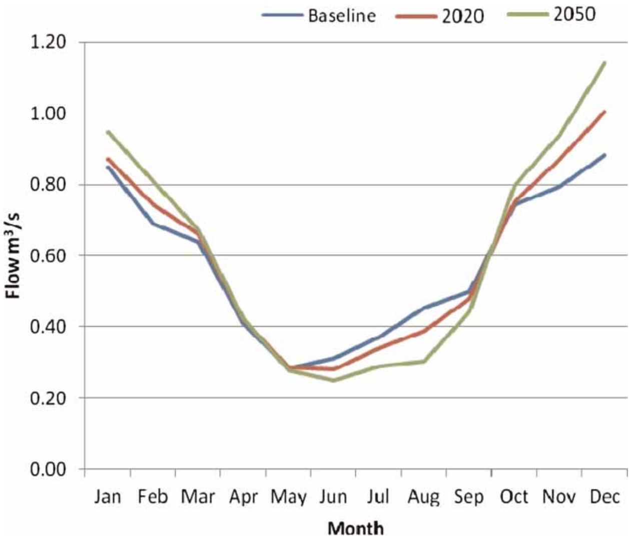

Figure 6 | The simulated monthly mean flows under baseline conditions and the two climate scenarios.

The impacts on the flows are shown in Figure 6 and indicate the seasonal pattern of flows under the baseline and future scenarios, demonstrating the shifts in flow regime, especially during summer and winter conditions. The monthly and annual flow duration curves also reflect the impacts of climate change, as illustrated in Figure 7, for the summer months showing much reduced flows.

An additional benefit of implementing IHACRES as a spreadsheet is that it is possible to evaluate the relative importance of the impacts of the rainfall and temperature changes. It is clear from the analysis that the dominant effect on flow is rainfall but, as might be expected, temperature changes also have an effect, particularly in summer months when evapotranspiration is more significant. The loss model incorporates these effects and will be catchment dependent. Thus, recalibration will be required on any other catchments, even if it is an adjacent catchment, as hydrological flow paths may be different as will vegetation types and coverage. The processes of evapotranspiration are very complex and the IHACRES approach provides a pragmatic method of simulating the losses and dynamics of flow in catchments, providing a practical way of estimating impacts for engineering and economic purposes.

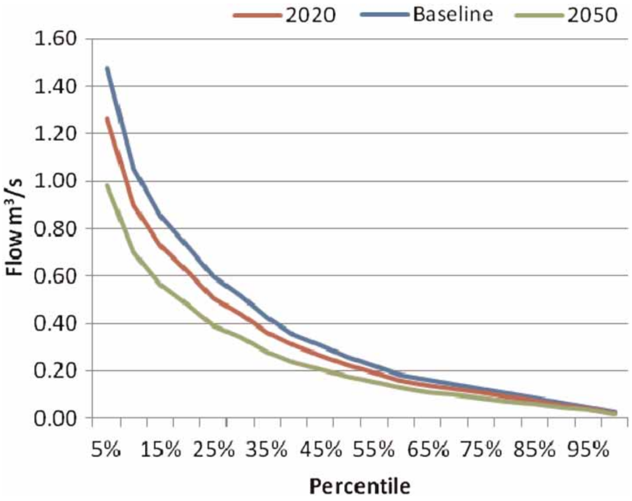

Figure 7 | The summer flow duration curves showing the effects of climate change reducing summer flows (August).

IMPACTS OF CLIMATE CHANGE ON HYDROPOWER

While it would be ideal to use data from an existing hydropower scheme, unfortunately no scheme exists for which there are sufficient data. Hence in order to assess the impact of these changes a hypothetical micro-hydro plant at Plynlimon is considered and it is necessary to define the parameters of the plant and its licensed abstraction regime. The Environment Agency has issued good practice guidelines for hydropower development (Environment Agency 2010) and, in line with this, typical values have

Table 4 | Flow control values for micro-hydropower generation at Plynlimon

Parameter	Defined by	Value
Q_{max}	Q_{mean}	0.577 cumecs
Hands off flow (HOF)	Q_{95}	0.053 cumecs
EA allowed flow	Fraction over HOF	50%
Q_{startup}	10% Q_{max}	0.058 cumecs
Head	Average net head	25 m
Efficiency	Water to grid average	70%

been chosen for the parameters based on the baseline observed flows, as shown in Table 4. Based on these values, a potential energy calculation suggests that the maximum power would be 99 kW with a capacity factor of 33% which is typical for high head schemes in Wales under these environmentally constrained operational regimes. The effect of the abstraction conditions on HOF is to further emphasise the reduction of generation in summer months, but in winter months, as the plant would already be operating at or near maximum capacity under the baseline scenario there is less opportunity to take advantage of the higher flows. Figure 8 shows the monthly mean power output from the hydropwer plant at baseline and under the two climate change scenarios. Also, from the monthly flow duration curves, the annual projected energy generated has been calculated under the baseline, 2020s and 2050s scenarios assuming that the abstraction licensing regime is unchanged, as shown in Table 5. It is noted that despite the large changes in seasonal flows, and hence energy outputs, the annual output is almost unchanged in both climate change scenarios (Table 5). This is because the loss of power output in the summer months is compensated for by the increased power in winter months. Thus it is important to consider this aspect when designing power plants so that there is sufficient capacity to take advantage of the higher winter flows.

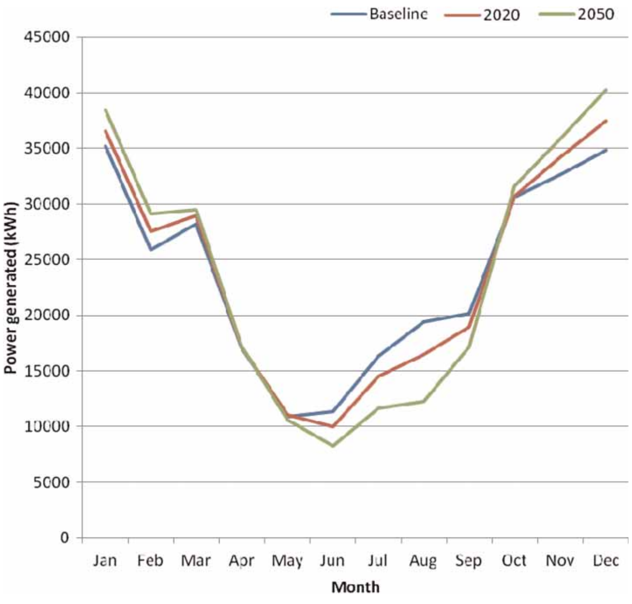

Figure 8 | The monthly power output (kWh) under baseline and climate change conditions.

Table 5 | Annual power generation under climate change scenarios

Scenario	Energy (MWh)	Capacity factor (%)
Baseline	282.7	32.6
2020s	283.8	32.7
2050s	282.1	32.5

DISCUSSION AND CONCLUSIONS

A straightforward seven-stage methodology based on robust data sets has been established to model stream flows and potential hydropower generation from which it is possible to calculate the projected impacts of climate change based on UKCP09 scenarios. This has been applied to the case of Plynlimon in upland Mid Wales where the potential performance of a hypothetical micro-hydro plant has been assessed. It suggests that there will be increases in flow and power output in winter months and significant decreases in summer months. There is a tendency to cancel out the power gains and losses over the year but this assumes there is sufficient capacity to take advantage of the higher winter flows.

If this methodology were to be applied to other UK sites, for example in other regions, on high base flow rivers, or at low head sites, it is anticipated that similar seasonal effects would be predicted but the detail and magnitude of the patterns of behaviour would be highly dependent on the specific catchment. Economic impact could be much greater, for example in southeast England where river flows may be more affected, especially in groundwater-dominated river systems. Developers and regulators of hydropower schemes might wish to consider oversizing plant to take advantage of potentially higher flows in winter months in future scenarios.

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