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PAPER

Run-of-river hydropower in the UK and Ireland: the case for abstraction licences based on future flows

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Keywords: abstraction licensing, energy policy, environmental regulation, run-of-river hydropower, water abstraction

Abstract

Run-of-river hydropower in the United Kingdom (UK) and Ireland is a small but vital component of renewable electricity generation that enhances grid diversification and resilience, contributes to the net-zero emissions targets, and provides local community benefits. Planning approval by environmental regulators for hydropower water abstraction is based on the abstraction licence conditions (ALCs) that dictate when and how much water may be taken from a given stream location. Although ALCs for non-environmentally sensitive rivers vary across England, Wales, Scotland, Northern Ireland, and Ireland, the impacts of these variations on power generation are not fully understood. Here, we investigate how ALC variations across the UK and Ireland have historically impacted water abstraction and power generation and might continue to do so under future climate conditions. Specifically, we apply five distinct ALCs combination sets, as laid out by the five environmental regulators in the region, to historical observed streamflows and future projected flows (modelled for the Representative Concentration Pathway 8.5 scenario using the EXP-HYDRO hydrological model), at 531 hydropower sites across the UK and Ireland. We then calculate the daily water abstraction potential for each hydropower site and the collective power generation potential separately for Great Britain (GB) and the Island of Ireland (IoI). Our results show that the ALCs that permit greater use of lower flows allow for more power generation than those that enable abstraction during high flow conditions. The most optimal combination of ALCs for power generation, when compared to those currently in use, increases future generation potential by 30.4% for GB and 24.4% for the IoI, while maintaining environmental protection as per the Welsh guidelines. Our results suggest that ALC policy and regulatory reforms are needed to provide optimal use of future streamflows for hydropower generation while ensuring protection for the environment is maintained.

1. Introduction

The hydropower sector provides a small but vital contribution to renewable electricity generation in the United Kingdom (UK) and Ireland, roughly 5% (DBEIS 2022) and 6.5% (SEAI 2022), respectively, for the two countries in 2021 (excluding pumped-storage systems). This contribution is further important to the grid as hydropower has a predictable and reliable power output, especially autumn through spring, that can compensate for shortfalls in other renewable generation sources in these months, such as reductions in solar power (Killingtveit 2019, Gonzalez *et al* 2023). The presence of hydropower generation, therefore, adds resilience to the overall electricity network. Small hydropower installations also provide local community benefits, as many such schemes are community funded, and the profits from the sale of electricity to the grid often fund projects for the public good (Bracken *et al* 2014, Bere *et al* 2017). In addition, hydropower has a role in moving towards national emission reduction targets, particularly in light of climate emergencies declared by the UK, Wales, Scotland, Northern Ireland, and Ireland governments within the last five years. It is, therefore, essential to clearly understand the potential contribution of hydropower to the future energy mix in the UK and Ireland.

A key area of uncertainty relating to the future contribution of the hydropower sector to renewable power generation is the impact of climate change on streamflows and, subsequently, the implications for the timing and quantity of water resources available for abstraction for hydropower. Climate change will bring warmer, wetter winters and hotter, drier summers to the British Isles (Lowe *et al* 2018). As a result, there is likely to be a clear shift in the seasonality of precipitation and streamflows (Prudhomme *et al* 2012, 2013a, 2013b, Sanderson *et al* 2012, Kay *et al* 2014a, 2014b, 2020), a pattern that has already been observed in the recent years (Steele-Dunne *et al* 2008, Hannaford and Buys 2012, Harrigan *et al* 2018). However, the picture of future change is not uniform across the British Isles, with a projected northwest-southeast divide across Great Britain (GB) (England, Wales, Scotland) in the magnitude and direction of trends in future streamflows, with increases at an annual average perspective for more westerly and northerly catchments, and decreases in the southeast (Watts *et al* 2015, Collet *et al* 2018, Dallison and Patil 2023). An east-west increasing to decreasing gradient is projected for the island of Ireland (IoI) (Northern Ireland and the Republic of Ireland) (Kay *et al* 2021, Dallison and Patil 2023). Furthermore, there is a likelihood of a greater frequency and magnitude of extreme hydroclimatic events in the future for the British Isles (Lowe *et al* 2018), such as prolonged heavy precipitation events, leading to high flows and flooding, as well as long periods of little rainfall, causing low flows and droughts.

The climate change-induced streamflow alterations have clear implications for sectors such as hydropower, particularly run-of-river type schemes, which depend highly on the instantaneous flows available in the river at any given time (Singal *et al* 2010, Anderson *et al* 2015, Sridhar *et al* 2022). Changes in the proportion of time that river systems are in states of low and high flows are particularly important for hydropower operations, as environmental regulators often restrict the use of top and bottom percentiles of streamflows (Anderson *et al* 2015, Poff 2018). Traditionally in the UK and Ireland, run-of-river hydropower schemes have licences for water abstraction that place conditions on the timing and quantity of water that it is permissible to abstract, to protect the riverine environment in the depleted reach between abstraction point and water return. The environmental regulators covering the five nations of our study, England, Wales, Scotland, Northern Ireland, and the Republic of Ireland, have different standard abstraction licence conditions (ALCs) applicable to the run-of-river hydropower schemes in non-ecologically sensitive river systems. Little reasoning or justification for the levels at which these standard ALC_S have been set is provided and we do not yet fully understand the impacts of these ALC variations on the quantity and timing of water abstraction and therefore power generation. Furthermore, given that hydropower schemes are currently designed, approved, and have ALCs set based on historical streamflows, these standard ALCs have the potential to be further deleterious to power generation over the lifetime of an installation, especially under future climate change-altered flows (Poff 2018). The potential environmental impacts of run-of-river hydropower schemes though cannot be forgotten in the quest for greater power generation. The disturbance of hydrological regime, consequences for sediment deposition and in-stream habitats (Csiki and Rhoads 2010, Kuriqi *et al* 2021, Magilligan *et al* 2021), and knock-on implications for areas such as fish spawning and macroinvertebrates (Anderson *et al* 2015, 2017, Bilotta *et al* 2016, Gibeau *et al* 2017), must be balanced against power generation changes. Regulation is important to minimise such environmental disruption, it is for this reason that this paper works within the confines of the various regulations for such systems already in place across the UK and Ireland.

Given this, and hydropower's role as part of a more sustainable and diverse future energy production system for the UK and Ireland, a clear understanding of the future contribution of the technology, and safeguarding its viability, is essential. Without this, it will be challenging to ensure the future resilience of the energy network and the successful accomplishment of emission reduction targets. Therefore, and for the first time, this paper compares the impacts of likely applied ALCs on water abstraction and power generation at over 500 hydropower abstraction locations across the British Isles for historical and future streamflows, factoring in a worst-case climate change scenario.

2. Data and methods

2.1. Study sites

Our study sites comprise 808 abstraction locations across England, Wales, Scotland, Northern Ireland, and the Republic of Ireland. These were selected from separate datasets of surface water abstractions for all purposes, provided by each nation's environmental regulatory agency (DAERA 2021, EA 2021, EPA 2021, NRW 2021, SSEPA 2021). We filtered the datasets to contain only those abstraction locations for run-of-river hydropower schemes which take water from a single source for a single purpose. We cross-referenced these

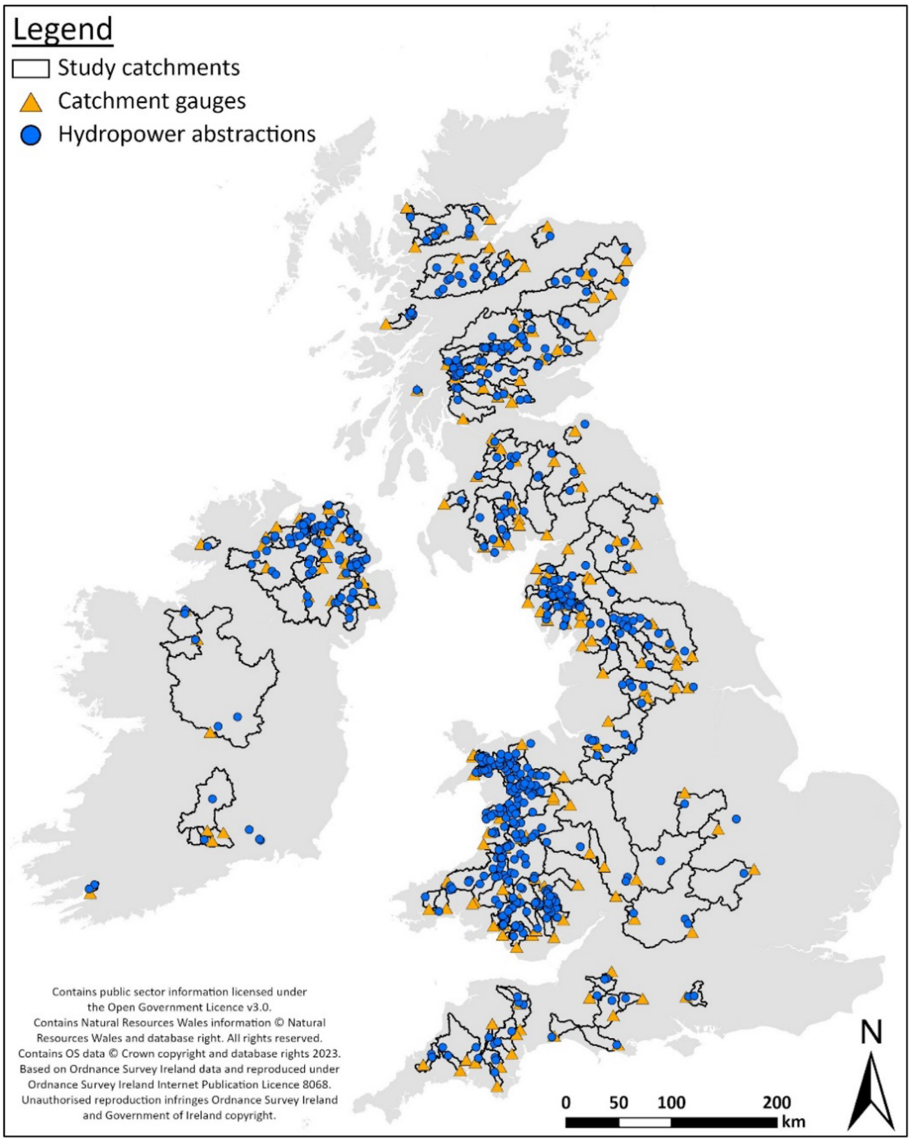

Figure 1. Locations of our study's run-of-river hydropower sites and modelled catchments. Also shown are the catchment streamflow gauges for initial hydrological modelling.

808 hydropower abstraction locations with catchments possessing sufficient historical streamflow time-series length for study and use in hydrological model calibration and validation. For England, Wales, and Scotland, this comprised 671 catchments from the CAMELS-GB dataset (Coxon *et al* 2020), specifically developed for environmental modelling and analysis, with attributes and meteorological variables provided for each catchment covering the 1970–2015 period. For Northern Ireland, we manually selected 25 catchments with near-natural flows and sufficient record length from the National River Flow Archive dataset (NRFA 2023). For the Republic of Ireland, we identified 23 catchments from the Irish Reference Network of hydrometric stations (Murphy *et al* 2013), the Environmental Protection Agency, and the Office of Public Works. Following calibration (full details in section 2.2) and cross-referencing, 531 hydropower abstraction locations within, or immediately downstream of, a total of 178 catchments remained and were taken forward for study (figure 1). This final set represents 65.7% of the initially identified hydropower abstraction locations. We believe this subset remains representative of the wider group and provides good coverage of the original geographic extent of the entire dataset.

2.2. Historical streamflow and future modelling

We obtained the historical daily mean streamflow for a single gauging point in each studied catchment for the period of 1st October 1985–30th September 2015 (30 hydrological years) from the CAMELS-GB dataset, the National River Flow Archive for Northern Ireland, and Environmental Protection Agency and Office of Public Works for the Republic of Ireland. We used this historical data to study the impact of abstraction licences on historical water abstraction and power generation potential and to calibrate the hydrological model. Using the area discharge method, we extrapolated the daily streamflow data from stream gauge locations to the individual water abstraction points (Dallison *et al* 2021).

We modelled the future daily streamflow at each study catchment using the spatially lumped version of the EXP-HYDRO hydrological model (Patil and Stieglitz 2014) and climate inputs from the worst-case future climate change scenario, Representative Concentration Pathway 8.5 (RCP8.5). This pathway represents a pessimistic future, with no downturn in global greenhouse gas emissions, and was selected to enable robust future planning of mitigation measures. EXP-HYDRO inputs include daily precipitation, air temperature, and potential evapotranspiration (PET), and it conceptualises the catchment as a bucket store with a separate snowpack storage component. The model calculates the catchment water balance based on equation (1):

$$\frac{dS}{dt} = P_r + M - ET - Q_{\text{bucket}} - Q_{\text{spill}} \tag{1}$$

where dS is catchment bucket water storage (mm), P_r is rainfall (mm day^{-1}), M is snowmelt (mm day^{-1}), ET is evapotranspiration (mm day^{-1}), Q_{bucket} is runoff from water stored in the bucket (mm day^{-1}), and Q_{spill} is bucket capacity excess runoff (mm day^{-1}). Daily streamflow is the sum of Q_{bucket} and Q_{spill}.

We chose EXP-HYDRO due to its computational efficiency, which is required to simulate streamflow for our large catchment dataset and across the twelve ensembles of future climate scenarios (further details below). Furthermore, the model was preferable due to its relatively simple data input requirements (air temperature, precipitation and PET) and its consideration of snowpack storage, which is essential for a subset of our study catchments. EXP-HYDRO has been used previously for large-scale modelling studies. For example, Patil and Stieglitz (2014) used it to simulate daily streamflow at 756 catchments across the contiguous United States. Dallison and Patil (2023) also used EXP-HYDRO to model streamflow at 585 catchments in the UK and Ireland. A detailed description of the EXP-HYDRO model is available in Patil and Stieglitz (2014).

We obtained the historical daily air temperature, precipitation, and PET data from the CAMELS-GB dataset (Coxon *et al* 2020) for England, Wales, and Scotland. For Northern Ireland and the Republic of Ireland, we sourced this data from the Europe-wide 0.1-degree resolution gridded Copernicus E-OBS dataset (Cornes *et al* 2018). We used the data from the hydrological years 1988–2005 (18 years) and from the 2006–2015 hydrological years for validation. Catchments taken forward for use in the study obtained Kling-Gupta Efficiency (Gupta *et al* 2009) scores greater than 0.6 for both calibration and validation.

Modelling of streamflows under future RCP8.5 climate change was done for 60 hydrological years (2021–2080) using the latest climate projections for the UK and Ireland, the UK Met Office Hadley Centre's 2018 UK Climate Projections (UKCP18). Specifically, the 'Regional Projections on a 12 km grid over the UK for 1980–2080' dataset (MOHC 2018) has been used, with its spatial extent covering the whole UK and Ireland study area. The 12 km resolution projections provide an ensemble of twelve regional climate model projections derived and dynamically downscaled from twelve of the fifteen members of the 60 km HadGEM3-GC3.05 global coupled model perturbed parameter ensemble (Murphy *et al* 2018). Uncertainty in the Global Climate Model ensemble members and natural climate variability between them (based on a range of plausible climate storylines) cause the 12 outputs to differ when downscaled (Kendon *et al* 2019). Various methods of bias-correction have been considered but have not been applied to the climate model output, due to varying criticisms (Ehret *et al* 2012, Maraun 2016). This is due to the disadvantages of various methods and the potential implications for the hydrological modelling output, including, the assumption that the causes of the biases are stationary, potential alteration of the climate change signal, restriction of the range of extreme values, and independent variable bias correction methods leading to potential physical inconsistency (Fung 2018). All of these issues have the possibility of impacting the climate output and modelling negatively, the assumption of stationarity of the behaviour of biases in particular has been criticised however, in relation to precipitation and evapotranspiration, and their non-stationary response to a warming climate (Ehret *et al* 2012, Maraun 2016, Fung 2018), these are key drivers of streamflow output in the EXP-HYDRO model used in this study. As with the E-OBS data, we calculated the mean of all grid squares within each catchment, providing a single future time series of precipitation, temperature, and PET for each catchment. This process was completed for each ensemble member, resulting in twelve future climate scenarios and, therefore, twelve future streamflow time series per catchment. The daily mean of these twelve streamflow outputs was calculated for each catchment, with the single resulting future streamflow output for each catchment forming the basis of the analysis presented in this paper. While this averaging dampens some of the extremes of the future modelled streamflow, this was necessary compromise against computational efficiency, with the study otherwise being infeasible. As with the historical streamflow data, we extrapolated the future projected streamflows to each studied abstraction location from the modelled point at the gauge using the area discharge method.

Table 1. Breakdown of the 178 modelled catchments and 531 studied hydropower (HP) abstraction sites by nation. Abstraction licence conditions (as set out by the five environmental regulators) applied during hydropower abstraction calculations are also shown (HoF: hands-off-flow; A_{max}: maximum abstraction volume; Q_{take}: percentage take allowed).

Nation	Modelled catchments	Modelled HP abstraction sites	Abstraction licence conditions		
			HoF	A_{max}	Q_{take}
England	60	115	Q_{95}	$1.3 * Q_{mean}$	35%
Wales	40	218	Q_{95}	Q_{mean}	70%
Scotland	52	113	Q_{95}	$1.5 * Q_{mean}$	50%
N. Ireland	18	72	Q_{80}	Q_{mean}	50%
Ireland	8	13	Q_{95}	Q_{mean}	50%

2.3. Hydropower water abstraction calculation

We calculated the daily abstractable water amount for both historical observed and future projected streamflow for each of the hydropower abstraction locations based on the standard ALCs as detailed in guidelines by the environmental regulators for each nation (SEPA 2015, EA 2016, NIEA and DAERA 2018, NRW 2020). For non-ecologically sensitive surface waters, these guidelines focus on three key components, hands-off-flow (*HoF*) volumes (*HoF*; amount of water that must be left in the river at all times), maximum abstraction rates, and percentage take (percentage of flow between *HoF* and maximum abstraction volume which can be taken), to protect low flows, high flows, and flow variability, respectively (table 1). Although ALC variations likely exist between sites within a given nation, due to the lack of site/scheme-specific details, we assumed in this study that standard ALCs are applicable for each scheme.

We calculated the values for the three ALC components for each hydropower water abstraction site based on the historical streamflow records obtained for each catchment. Then we applied the conditions to the projected future daily streamflow time series. These conditions were applied as follows; first, the surplus amount of water available for abstraction ($Q_{surplus}$) on a given day is calculated according to equation (2):

$$Q_{surplus} = Q - HoF \tag{2}$$

where Q represents streamflow volume and HoF is the required hands-off-flow volume. The result is used in the calculation of allowable daily abstraction (A_{daily}), as shown in equation (3):

$$A_{daily} = Q_{surplus} \times Q_{take} \begin{cases} 0, & if\, A_{daily} < A_{start} \\ A_{max}, & if\, A_{daily} > A_{max} \\ A_{daily}, & if\, A_{start} < A_{daily} < A_{max} \end{cases} \tag{3}$$

where Q_{take} is the percentage take, A_{start} is the minimum abstraction volume needed to start the turbine for efficient operation, and A_{max} denotes the maximum allowable abstraction volume. The resulting time series represents a daily permitted abstractable water resource record for each hydropower water abstraction site, assuming each scheme takes the maximum allowable water resource daily. In addition, we assume that each hydropower scheme operates with an impulse-type turbine. These are the predominant turbine type used in small run-of-river schemes, such as those studied (Lilienthal *et al* 2004, Cobb and Sharp 2013, Židonis *et al* 2015), due to their high efficiency at low percentages (10%–15%) of designed maximum flow (Paish 2002, Novara and McNabola 2018, Chitrakar *et al* 2020). For this reason, A_{start} has been set at 15% of A_{max} for each scheme, with A_{max} being the assumed designed maximum flow volume.

This methodology has first been applied to each hydropower site using the ALCs relevant to its location within a given nation, for example, all abstraction sites in Wales using Welsh ALCs, all in England using English ALCs, and so on. The resulting historical and future abstraction calculations act as a baseline to compare the impact of implementing other nations' ALCs. We completed these in turn for each of the five ALC sets. We then examined the daily abstractable water resource time series for each hydropower scheme under each set of ALCs by calculating three factors on an annual basis. These three factors are: (1) the number of days abstraction is possible (days A_{start} achieved), (2) the number of days maximum abstraction (A_{max}) is reached, and (3) total abstraction (A_{total}). We summed the annual totals for the five nations to give a national perspective of any changes.

2.4. Hydropower generation calculation

Due to this study's focus on run-of-river schemes and the aforementioned assumed use of impulse-type turbines, we implemented a linear relationship between calculated daily total water abstraction and daily total power generation. Owing to the high and stable level of efficiency of the impulse-type turbines across a wide range of incoming water flows, from 15% to 100% of the maximum designed flow (Paish 2002, Novara and McNabola 2018, Chitrakar *et al* 2020), no disproportionate power generation benefit is provided at higher flows. This assumption is in line with previous works that have equated runoff and streamflow change to changes in hydropower energy production (Lehner *et al* 2005, Carless and Whitehead 2013, Van Vliet *et al* 2013, Sample *et al* 2015, Schaefli 2015, Dallison and Patil 2023). In addition, due to the lack of specific hydropower scheme details, such as net head, it is impossible to calculate power implications in terms of actual energy output, only relative change via the abstraction-generation relationship. Both of the islands studied ((GB) and the (IoI)) have individual singular power transmission networks. The GB National Grid supplies power production in England, Wales, and Scotland, and the IoI Single Electricity Market to Northern Ireland and Ireland. Therefore, changes in hydropower generation are best thought of collectively for each island rather than at national levels, as power generated will contribute towards, and have a role to play in balancing and providing resilience to, those systems as a whole. For this reason, we summed the calculations of power generation changes under future climate change to show net change for the energy systems of both islands.

3. Results

3.1. Historical abstraction and power generation

3.1.1. Abstraction characteristics

The total annual hydropower abstraction for each nation is generally stable or has been increasing during the 30 year historical period studied when considering each nation under its own ALC (figure 2). However, when ALCs from other nations were applied, great water abstraction was possible in all nations except Wales. The most significant increase is seen for England, with Welsh ALCs applied, where an increase in the total abstraction of 70% across the entire period could have been achieved. Indeed, the Welsh ALCs perform best for all nations, with a 20% increase under these conditions seen for Scotland, 28% for Ireland, and 42% for Northern Ireland (figure 2). Conversely, the English ALCs performed the worst for all nations, with a decrease in total annual abstraction seen in all nations, varying between 16% and 40% across the 30 years studied (figure 2). Given that the ALCs for Northern Ireland and Ireland differ only in *HoF* volume (Q_{95} and $Q_{80,}$ respectively), this factor substantially impacts total annual abstraction. The more restrictive ALCs from Northern Ireland result in a 15% drop in total abstraction for Ireland, with the converse providing a 12% increase in abstraction for Northern Ireland (figure 2).

Differences in total annual abstraction between ALC sets disguise patterns seen in other hydropower characteristics, such as the frequency with which water abstraction for hydropower production is possible per year and the number of times the maximum allowable abstraction volume is reached. Figure 3 demonstrates that due to the nature of the ALCs in the different nations, the number of days that abstraction is possible per year is greatest under Welsh ALCs for all nations, ranging from 22.8 additional days for Ireland to 88.5 for England. While this does not necessarily relate directly to an increase in annual average abstraction, the greater consistency and frequency of generation across the year may benefit some scheme operators. Concerning the number of days that the maximum abstraction volume is reached, this is also greatest under the Welsh ALCs (figure 3) due to the lower maximum abstraction volume combined with a larger percentage take. The English and Scottish ALCs result in far few days where this maximum volume is reached, meaning less loss of abstraction from this top end of streamflows. However, this is likely at the detriment of overall abstraction potential.

3.1.2. Hydropower generation

As aforementioned, we summed the power generation totals to GB and the IoI owing to the nature of the national grid networks across the two islands. The differences seen in power generation under the different nations' ALCs broadly reflect the changes seen in annual total abstraction, owing to the linear relationship between the two, albeit somewhat dampened in magnitude. Figure 4 demonstrates how, for GB, applying the Welsh or Scottish ALCs to historical streamflows at all hydropower sites in England, Wales, and Scotland results in an increase in overall power generation (21.9% and 2.5%, respectively). The reverse is true for the ALCs of England, Northern Ireland and Ireland, where declines of 28.3%, 14.4% and 3.4% are seen in turn, compared to a status quo where each nation uses its own ALCs. For the IoI, the same differences are mostly seen. However, the size of the increase under Welsh and Scottish ALCs is larger (38.9% and 15.9%, respectively). In addition, unlike for GB, using the Irish ALCs for all catchments in Northern Ireland and Ireland increases power generation for the IoI of 9.7% compared to the status quo (figure 4).

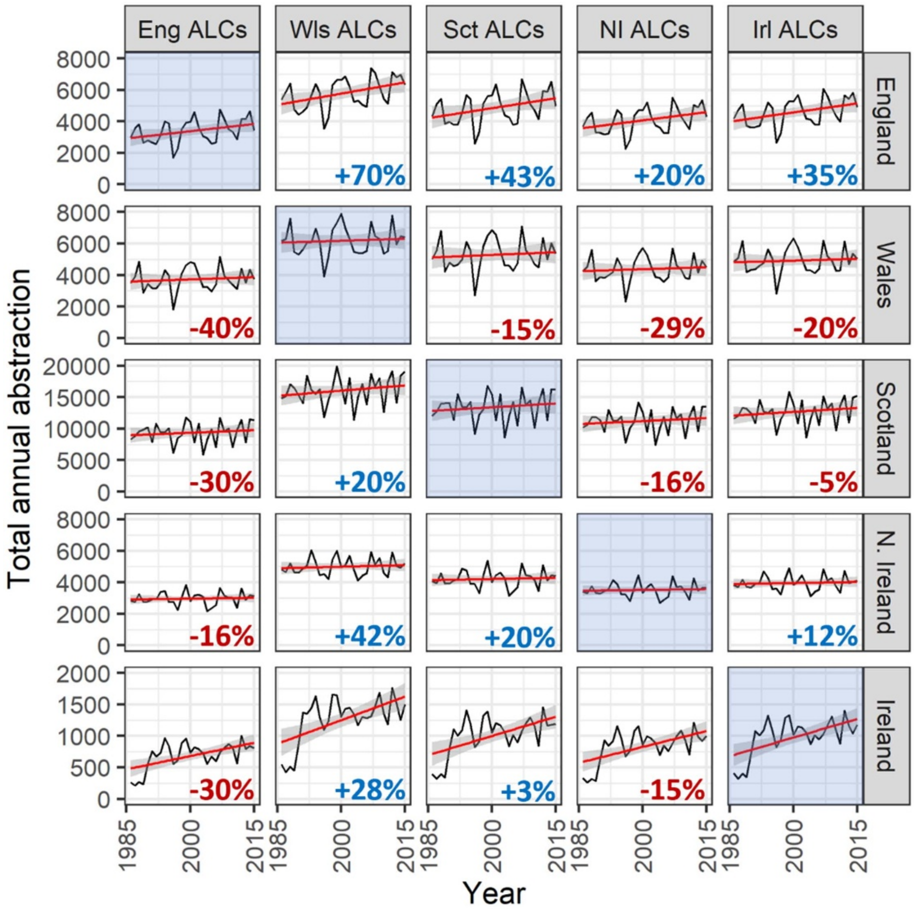

Figure 2. Total annual abstraction (1986–2015) for each of the five studied nations under abstraction licence conditions (ALCs) for each other nation. Blue highlighted boxes represent each nation's 'status quo', i.e. total annual abstraction when using their own ALCs. Quoted percentages represent a change in total abstraction for the entire 30-year study period compared to that nation's status quo.

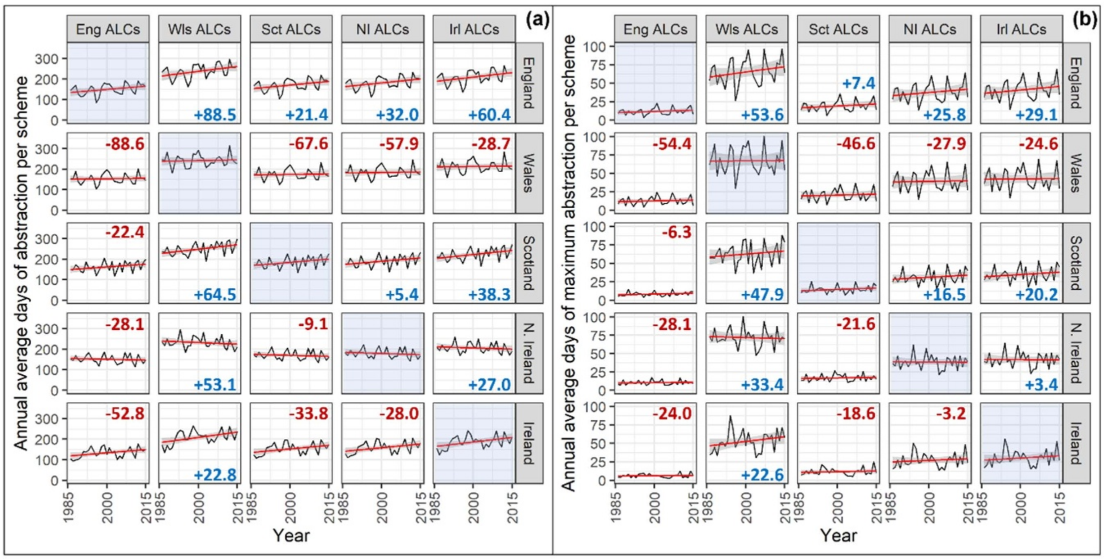

Figure 3. The average number of days per scheme per year (1986–2015) that (a) water abstraction is possible, and (b) maximum abstraction volume is reached for each of the five studied nations under abstraction licence conditions (ALCs) for each other nation. Blue highlighted boxes represent the 'status quo', i.e. when each nation uses its own ALCs. Quoted numbers for each plot represent the change in the average number of days per year compared to that nation's status quo.

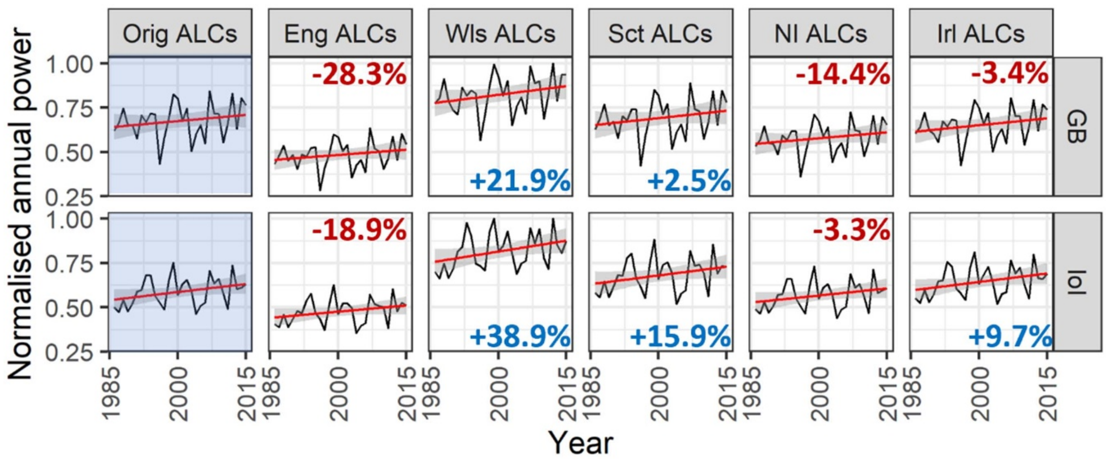

Figure 4. Normalised annual estimated power generation potential (1986–2015) for Great Britain (GB) and the island of Ireland (IoI) under abstraction licence conditions (ALCs) for each of the five nations studied. Blue highlighted boxes represent the 'status quo', i.e. power generation potential when each nation uses its own ALCs. Quoted percentages represent the change in total power generation potential for the entire 30 year study period compared to that region's status quo.

3.2. Future abstraction and power generation

3.2.1. Abstraction characteristics

The magnitude of differences between the ALCs applied to each nation, in terms of future total annual abstraction, are broadly in line with those seen for the historical period studied. Once again, the ALCs from Wales provide the largest volume of total abstraction, 23%–69% greater than the standard ALCs applied to other nations (figure 5). However, it should be noted, unlike the results for the past period, a decline can be seen in total annual abstraction across the 60 year future period under the Welsh ALCs for all nations; this is not observed for the ALCs from other nations. A further difference between the historical and future periods of study is the increase in abstraction for Scotland observed under the Irish ALCs in the future, a 2% increase compared to a 5% decline in the historical study. As before, the higher *HoF* volume in Northern Ireland is detrimental to overall total abstraction compared to Ireland, resulting in 8%–13% less abstraction in the five nations studied compared to the Irish ALCs (figure 5). Once again, the English ALCs results in the lowest abstraction across the 60 year period for all nations.

Regarding the number of days that abstraction is possible in the future, the first observation is that in all nations, under all ALCs, there is a decreasing trend across the sixty years studied (figure 6). This trend reflects declining streamflows across the study period, particularly in summer and autumn. When comparing the impact of the different ALC sets, those from Wales provide the largest number of days of abstraction on average per year, with an increase of between 65.3 and 18.0 d, compared to the status quo in other nations. A similar magnitude decrease is seen when applying the English ALCs, reducing by between 22.9 and 62.7 d (figure 6). For the IoI, the best-performing ALCs are those of Ireland, resulting in 22.6 more days of abstraction for Northern Ireland.

With regards to the number of days that maximum abstraction is reached, under the Welsh, Northern Irish, and Irish ALCs, there is a clear increase in the number of days that the maximum abstraction volume is reached across the 60 year period. Aside from this, similar differences between ALC sets, as seen in the historical analysis, are present. However, the magnitude of these differences, particularly concerning the impact of the Welsh ALCs, is often larger (figure 6). Due to the nature of the Welsh ALCs, the maximum abstraction volume is reached between 111.1 and 53.5 more days in the other four nations than under their own ALCs. The English and Scottish ALCs result in almost zero days when maximum abstraction is reached in any nation. However, a small increasing trend can be observed towards the end of the study period when the Scottish ALCs are applied (figure 6). Due to the higher implemented *HoF* volume, the Northern Irish ALCs result in fewer days of maximum abstraction in all nations than those for Ireland.

3.2.2. Hydropower generation

As is to be expected, owing to the similar differences between historical and future total annual abstraction, the magnitude and nature of change seen in annual power generation potential is analogous to the results for the historical period. The one exception to this comparability is that when applying the Irish ALCs, total power generation across the future period is greater than the status quo (by 1.9%), as opposed to the 3.9% decline seen for the historical period. Power generation for the IoI declines across the 60 year period under

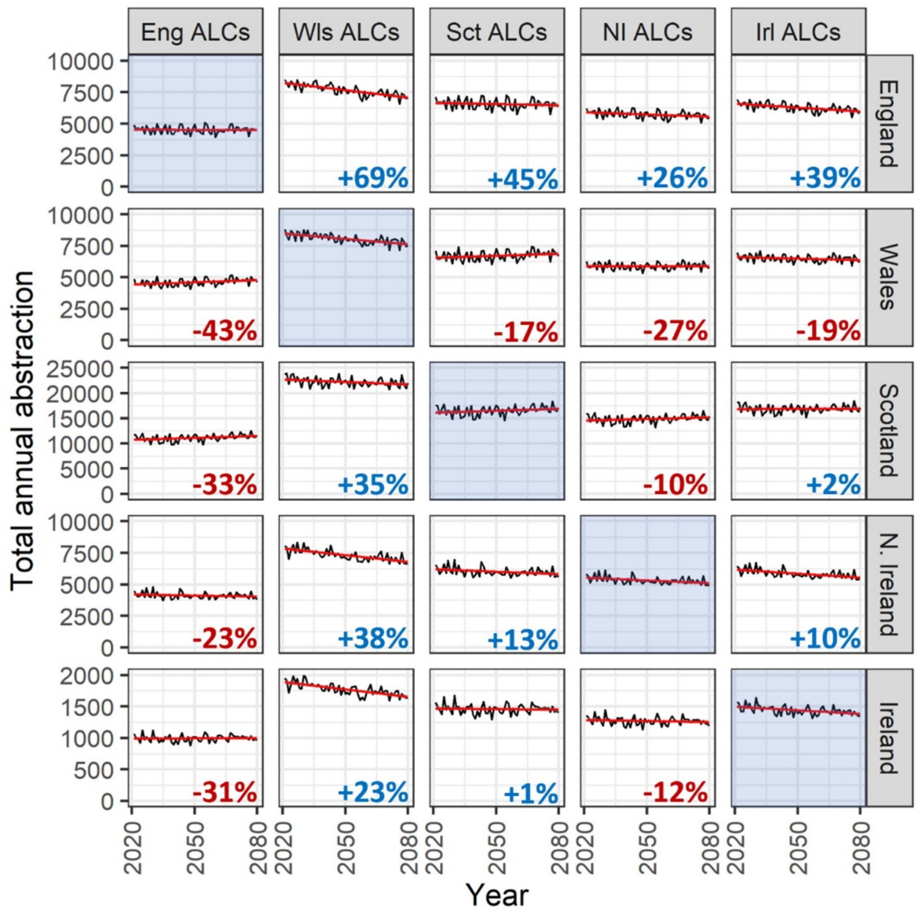

Figure 5. Total annual abstraction (2021–2080) from worst-case future climate change (RCP8.5) induced streamflows for each of the five studied nations under abstraction licence conditions (ALCs) for each other nation. Blue highlighted boxes represent each nation's 'status quo', i.e. total annual abstraction when using their own ALCs. Quoted percentages represent the change in total abstraction for the entire 60 year study period compared to that nation's status quo.

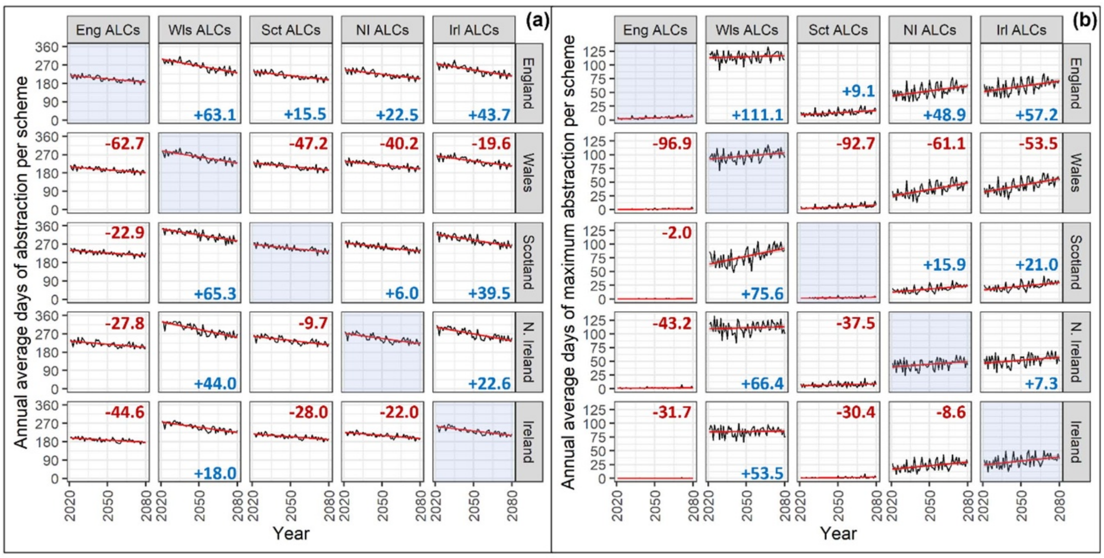

Figure 6. The average number of days per scheme per year (2021–2080) from worst-case future climate change (RCP8.5) induced streamflows for which: (a) water abstraction is possible, and (b) maximum abstraction volume is reached for each of the five studied nations under abstraction licence conditions (ALCs) for every other nation. Blue highlighted boxes represent the 'status quo', i.e. when each nation uses its own ALCs. Quoted numbers for each plot represent the change in the average number of days per year compared to that nation's status quo.

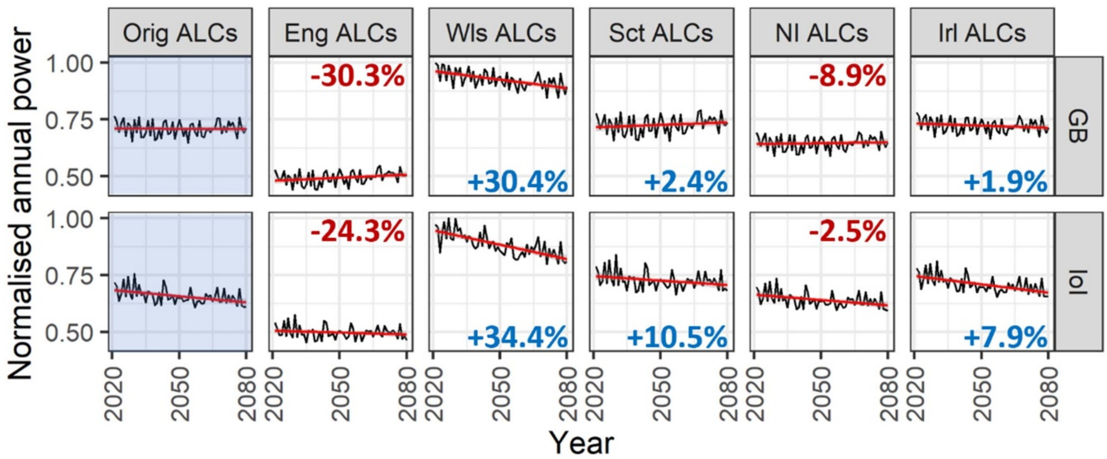

Figure 7. Normalised annual estimated power generation potential (2021–2080) for Great Britain (GB) and the island of Ireland (IoI) under abstraction licence conditions (ALCs) for each of the five nations studied, under a worst-case future climate change scenario (RCP8.5). Blue highlighted boxes represent the 'status quo', i.e. power generation potential when each nation uses its own ALCs. Quoted percentages represent the change in total power generation potential for the entire 60-year study period compared to that region's status quo.

all ALC sets, including the status quo (figure 7), linked to a general decline in abstraction over the same period, as observed in figure 5. Once again, the Welsh ALCs resulted in the greatest increase in power generation for GB and the IoI compared to the status quo of all nations using their own ALCs, with a 30.4% and 34.4% increase, respectively. The Scottish and Irish ALCs provide a larger increase in power generation for the IoI (+10.5% and +7.9%, respectively) than GB (+2.4% and +1.9%).

4. Discussion

The observed differences between the ALC sets for each nation show that the ALCs for Wales allow for more days of abstraction per year and higher overall total abstraction in both the historical and future periods (figures 2 and 5). This effect is due to this ALC set having a lower maximum abstraction volume and, therefore, lower A_{start} volume and a larger percentage take, allowing for better use of lower flows available in the river a larger proportion of the time. Making better use of these lower flows is particularly important for the future, where annual average streamflows generally decrease, irrespective of future climate scenario (Kay 2021, Meresa *et al* 2022, Dallison and Patil 2023). The ALCs of the two nations with the highest maximum abstraction volumes, England and Scotland (at 1.3 * Q_{mean} and 1.5 * Q_{mean}, respectively), result in lower annual abstraction than those for Wales for all nations and highlight the importance of the capability to use more regular low-flows over more occasional high-flows. There is consensus between these results and those of Yildiz and Vrugt (2019), who note that the lack of large water storage at run-of-river type schemes reduces the consistency of power generation seasonally. Due to the relationship between A_{start} and A_{max} (the former being set at 15% of the latter), a higher maximum abstraction volume is needed to start the turbine and begin generating electricity efficiently. This leads to fewer days per year when abstraction and power generation are possible (figures 3 and 6), compared to having a lower maximum abstraction volume with a higher percentage take, such as in Wales. However, comparing the Scottish ALCs to Ireland's, which differ only in terms of A_{max} (1.5 * Q_{mean} and Q_{mean}, respectively), it is evident that having the flexibility to use higher flows can provide some small benefits in terms of abstraction. In this two-way comparison, the higher A_{max} volume of the Scottish ALCs results in 5% more abstraction for Ireland over the historical period and 1% for the future period. For this reason, Yildiz and Vrugt (2019) note the benefits of a parallel two-turbine setup for run-of-river schemes, allowing for generation from a wider range of streamflows.

The mix of ALCs that results in least power generation has been shown to be a higher maximum abstraction volume combined with a low percentage take. This is demonstrated by the English ALCs, which have the second highest A_{max} (1.3 * Q_{mean}) and lowest percentage take (35%) and provide the lowest water abstraction and power generation for all nations in both the historical and future study periods. Indeed, when compared to the status quo of each nation using their own ALCs, applying those for England to all hydropower abstraction sites results in a 28.3% and 18.9% decline in total power generation for GB and the IoI, respectively, over the 30 year historical period. This reduction is yet larger for the 60 year future period, 30.3% for GB and 24.3% for the IoI. This combination is inferior due to the need for a greater volume of water and, therefore, streamflow to begin efficient operation of the turbine (A_{start} being proportional to

A_{max}), and a lower percentage take once the *HoF* volume has been reached. This leads to a situation, in stark contrast to that seen for the Welsh ALCs, with less use of the lower flows available in the river most often. Further contrast can be observed between the results for the English and Scottish ALCs, with the latter, despite having a larger A_{max} volume (and therefore higher A_{start}), allowing for a greater volume of water abstraction and power generation historically and in the future. In this instance, the 50% percentage take allowance, compared to the 35% allowed under the English regulations, enables more water to be abstracted once the *HoF* is reached, meaning that A_{start} is reached more regularly. In the historical period, this results in an average of 21.4 more days of abstraction per year for England under the Scottish ALCs, and 15.5 d more per year in the future period. This shows how balancing the three key ALC characteristics, alongside scheme setup and turbine design, is challenging but essential for optimising future power generation (Anagnostopoulos and Papantonis 2007, Yildiz and Vrugt 2019). A further crucial consideration here is the importance of protection for the variety of environmental reasons discussed in the introduction, as well as any stream-specific characteristics that make a one-size fits all approach to abstraction licensing impractical.

An interesting area of consideration is that depending on location, optimisation of hydropower abstraction and generation will vary between maintaining a year-round generation profile, and maximising total power generation output, even if that is more seasonal (Si *et al* 2018). In such cases, making use of the lower range of flows available for a greater proportion of the year, particularly into the drier summer period, is vital. Given the increase in the number of days per scheme that abstraction is possible for all nations, historically and in the future, under the Welsh ALCs, this combination is uniquely positioned to achieve this alternative optimisation need. Also interesting to note, as shown in figure 5, is the decline in total annual abstraction across the 60 year future period under the Welsh ALCs for all nations, which is not observed consistently under the other four ALC sets. We see the impact of this decline in abstraction in figure 7, where power generation reduces between 2021–2080 under the Welsh ALCs for both GB and the IoI. While a decline occurs under all ALC sets for the IoI, the reduction is most severe under the Welsh conditions; for GB, these and the Irish ALCs result in a decline, although it is most pronounced in the Welsh setting. While the Welsh ALCs remain the optimal mix of those studied in terms of yearly abstraction and total abstraction for the period covered, this trend suggests that as streamflows continue to change over the 21st century, the optimal ALCs for power generation will change. Indeed, by 2080, total abstraction under the Welsh ALCs is nearing the same level as that under the Scottish ALCs. This need for adaptation through the 21st century to maintain a hydropower sector fit for purpose is a conclusion also drawn in other regions, such as by Gu *et al* (2022) for China, by Viers (2011) for the United States, and by Lehner *et al* (2005) for Europe.

To our knowledge, our study is the first of its kind to quantify the impact of varying ALCs on water abstraction and power generation for the run-of-river hydropower sector globally and within the UK and Ireland region studied. However, the effects of climate change on water availability for hydropower, the sector's capability to make use of future streamflows, and its future contribution to electricity generation have been studied for the region. Our findings for individual nations, and the region as a whole, are well aligned with such works. Carless and Whitehead (2013), and Sample *et al* (2015), for example, find for Wales and Scotland respectively that currently installed hydropower schemes are not best placed to make optimal use of future projected streamflows for power generation. This is particularly true in terms of capturing winter streamflows and is reflected in the results presented in our work by the fact that under their own ALCs, a decline in the average number of days per year that abstraction is possible between 2021–2080 for both of the nations is evident (figure 6). However, Sample *et al* (2015) conclude that this leads to an overall decline in hydropower potential for Scotland, which contradicts our results, which show that despite fewer days of abstraction, there is an increase in total abstraction through the 60 year study period. This discrepancy is likely due to the use of Q_{mean} as the maximum abstraction volume in the work of Sample *et al*, as opposed to $1.5 * Q_{mean}$ as is used here, and which is based on current guidance by the Scottish Environmental Protection Agency, the environmental regulator for the region. Both papers conclude that current ALCs are limiting the ability of hydropower schemes to make best use of future streamflows for power generation. Furthermore, a study on future hydropower potential across Europe by Lehner *et al* (2005), suggests that at a UK perspective, run-of-river schemes are likely to see a relatively stable future generation, again in agreement with the results for the status quo situation in the work presented in this paper (figure 7).

Our results also suggest agreement with projections of future streamflows from other works, the consensus being for increased seasonality of streamflows, with a greater frequency and magnitude of low flows in the summer and autumn and more frequent and larger high flows in the winter and spring, for both the UK (Prudhomme *et al* 2012, Sanderson *et al* 2012, Kay 2021, Kay *et al* 2021, Dallison and Patil 2023) and Ireland (Charlton *et al* 2006, Steele-Dunne *et al* 2008, Meresa *et al* 2022, Dallison and Patil 2023). Our results correspond to these findings, with the annual average number of days that abstraction is possible decreasing in all nations under the status quo ALCs, suggesting a greater number of days of very low streamflows (figure 6). The opposite is true for the annual average number of days per year that the maximum abstraction volume is reached, with this increasing across the future period for all nations under their own ALCs (figure 6). These inclined trends suggest an increase in very high flow days, where streamflow is sufficient for maximum abstraction to occur. There is, therefore, good agreement between our future projections for hydropower generation and the above studies. Owing to this, and despite the lack of published literature on the impacts of ALCs on water abstraction and power generation, we believe our results in this area to be representative of the potential implications under a worst-case future climate change scenario, as intended. Furthermore, although this study takes a pessimistic approach in terms of future climate change scenario, the results of the historical analysis clearly highlight the potential benefit of studying and optimising water abstraction for hydropower generation, while maintaining protection for the environment. Therefore, regardless of the severity of future climate change induced streamflow alterations, the regulations surrounding water abstraction for hydropower would benefit from being reviewed across the five nations studied.

5. Conclusions

This work has shown that the ALCs placed upon run-of-river hydropower schemes can significantly impact the quantity and timing of water abstraction and power generation. The results demonstrate for the first time that balancing the different key ALC characteristics of *HoF*, maximum abstraction volume, and percentage take is crucial for optimising power generation, while maintaining protection for the environment, ecology, and stream system must also always be considered. The results, therefore, have implications for the environmental regulation and design of future schemes and those at the end of their operational lifespan. The retrofitting or alteration of currently installed and operating schemes to better use current and future streamflows with altered ALCs is more challenging and, in most cases, implausible. Owing to the semi-permanent nature of installed components, such as intake weirs and turbines, which are designed with specific operational capacities for existing conditions in mind, making changes to ALCs would prove ineffective or even potentially detrimental without alterations to these components. In addition, while this research highlights the potential for change to environmental regulations surrounding ALCs, any such changes need to be justified with carefully considered reasoning to ensure environmental protection is maintained, alongside increased hydropower generation. It is important to note that this work has presented results based on standard ALCs for non-ecologically sensitive river systems. Even greater care should be taken when licensing hydropower schemes in areas with greater ecological or environmental concerns.

We conducted this study's future-focused analysis using a worst-case future climate change scenario under RCP8.5 conditions. While this is unlikely to have significantly impacted the comparative results of the effects of the different ALCs applied (these being similar in magnitude and nature to the historical data), the streamflow generated and the trends observed in abstraction characteristics and power generation potential may be severe. Future work should seek to quantify the potential impact of various future climate change scenarios on the hydropower sectors in the UK and Ireland to provide greater insight into the sector's contribution to the renewable electricity generation mix moving forward. In addition, it should be noted that, as aforementioned, the use of a single future streamflow series averaged from the twelve model outputs, dampens the extremes of the projections. We believe, however, that the analysis presented is still a reliable indication of the likely impacts of future climate change on hydropower output from the schemes studied. Indeed, the results of this work demonstrate that future hydropower schemes should be designed with future streamflows in mind to optimise renewable electricity generation across their lifespan. In addition, while currently installed schemes are difficult to retrofit while in operation, once their lifespan has expired, there is scope to alter scheme design and components to make optimal use of future flows for power generation and review currently applied ALCs. Recommendations such as those presented in this work require a fundamental shift in the way that hydropower schemes are licensed and designed to ensure a future-proofed sector. Clearly, such changes require regulatory and policy buy-in and change to ensure a regulatory landscape that allows for a hydropower sector that is fit for the future. Environmental regulations and policymakers must recognise this need for future-proofed design to ensure maximum benefit for renewable energy generation and the scheme operators. Of course, it is also important to consider the downstream environment of hydropower-influenced river systems, ensuring that any alterations to ALCs and scheme design do not deleteriously impact the riverine environment.

Overall, it is likely that some hydropower generation has been lost historically, potentially unnecessarily, due to implemented ALCs. This will continue in the future unless changes are made in the way that hydropower schemes are licensed and designed. In addition, given the potentially substantial alterations to future streamflows due to climate change, designing new hydropower installations based on historical flows will do a disservice to future power generation. As the future total water abstraction results under Welsh ALCs demonstrate clearly, future streamflows must be considered during the design stage of such schemes to ensure optimal power generation across the project's lifetime and that the hydropower sector is fit for the future.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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CRediT authorship contribution statement

Richard Dallison: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing–Original Draft, Visualization. **Sopan Patil**: Conceptualization, Software, Writing–Review & Editing.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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