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# Future impacts of river flow on hydropower generation in Great Britain

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## ABSTRACT

Climate change is likely to alter Great Britain's water resource availability for hydropower generation. This affects hydropower production due to uncertainty around the timing and magnitude of water availability, particularly run of river (RoR) schemes that lack the storage capacity to buffer seasonal flow variability. This study examines the likely future changes on RoR potential at locations across GB using the enhanced future flows (eFLaG) dataset. Results show that annual river flows are projected to increase in winter and spring but reduce in summer and autumn. This has an impact on RoR potential with a projected decrease in the near (2030–2059) and far future (2050–2079) for both summer (−19%, −32%) and autumn (−11%, −19%) throughout GB. Therefore, results indicate a decrease in the annual RoR potential in GB. This study underscores the importance of incorporating climate change considerations in the planning and operation of RoR schemes to ensure sustainable energy generation. This could be achieved by upgrading existing turbines to handle higher flows or designing new turbines capable of accommodating larger discharges to fully utilise the increased flows during winter. However, this should be done with consideration of the technical limitations and the opportunities for optimisations for system generation.

**Key words:** climate change, hydropower, run of river

## HIGHLIGHTS

- Climate change disrupts Great Britain's (GB's) water resources, impacting hydropower through increased variability.
- The study focuses on future water availability, especially for storage-limited run of river (RoR) schemes.
- Using the enhanced future flows (eFLaG) dataset, research maps future RoR hydropower changes in GB.
- Results show reduced annual river flows near RoR sites, with varied trends impacting hydropower.

## GRAPHICAL ABSTRACT

## 1. INTRODUCTION

Climate change is a multifaceted global phenomenon that poses a significant threat to critical infrastructure, as evidenced by increasing occurrences of extreme weather events (Pörtner *et al.* 2022). The Organization for Economic Cooperation and Development (OECD) emphasizes the importance of designing, building, and operating infrastructure to anticipate and adapt to changing climate conditions, as well as retrofitting existing infrastructure to enhance climate resilience (OECD 2018). Climate change is increasingly impacting global water resources through a complex interplay of variables that are altering the hydrological cycle and water availability (Caretta *et al.* 2022). From shifting precipitation patterns to the melting of glaciers and polar ice caps, these changes contribute to altered water availability, quality, and distribution, posing substantial challenges to water resources worldwide (European Commission 2023).

In Great Britain (GB), climate change is altering river flows and water resource availability, including changes to seasonal, spatial, and temporal patterns, and to extreme events, leading to increasing uncertainty of water availability (Watts *et al.* 2015; IPCC 2021; King *et al.* 2023). Based on future projections, it is expected that river flows will decrease in spring and summer, contrasted with a slight increase in winter flows, with a mixed picture for autumn flows (Werritty 2002; Christierson *et al.* 2012; Prudhomme *et al.* 2012; Watts *et al.* 2015; Kay 2021). These projected changes in river flows across GB are likely to impact hydropower production, particularly run of river (RoR) schemes that do not have the ability to store water, like reservoir hydropower, during seasonal changes. Many regions are experiencing altered precipitation patterns, leading to more frequent and severe droughts that reduce water availability for hydropower dams (Paltan *et al.* 2021). Conversely, some areas are seeing an increase in extreme precipitation events, resulting in high river flows that can damage hydropower infrastructure or necessitate operational changes to mitigate flooding risks (Kim *et al.* 2022). Although annual river flows may remain largely unchanged, increased interseasonal variability may mean a lower energy output from hydropower installations that lack storage, like RoR hydropower (Williams *et al.* 2022). In the summer months, capacity factors (defined as the ratio of the actual electrical output of a power plant to its maximum potential output if it operated at full capacity continuously during the same period) may decrease by 15–40% due to lack of precipitation and lower flows (Sample *et al.* 2015). However, in winter, even if flows increase, the installed penstocks and turbines might not be able to take advantage of these higher flows (Boca *et al.* 2022).

Although this issue has been studied using a few case studies of a few catchments across GB (Carless & Whitehead 2013; Dallison *et al.* 2021) and in other regions of the world (e.g., Casale *et al.* 2020; Duratorre *et al.* 2020), there is a general gap in knowledge of the effects of interseasonal variability on hydropower production, particularly for RoR schemes, and there are no known UK/GB-wide studies that quantify the effects of climate change on RoR hydropower. Within GB, Carless & Whitehead (2013) and Dallison *et al.* (2021) assessed the potential impacts of climate change on hydropower generation at various RoR schemes in the Severn, Conwy, and Tywi catchments in Wales. These studies determined changes in monthly energy output and changes in annual trends in the number of days with the minimum abstraction volume required to start and the maximum permitted abstraction volume achieved for the future. However, Carless & Whitehead (2013) used the UKCP09 climate projections, which are now outdated. Although the climate projections used by Dallison *et al.* (2021) are the most up-to-date projections for the UK (UKCP18; Lowe *et al.* 2018), this study only focuses on two catchments in Wales and determined trends in abstraction volumes, not direct changes in hydropower production.

Outside of GB, Duratorre *et al.* (2020) determined future changes in projected mean monthly values of energy, discharge, and snow melt in the Italian Alps. They concluded that energy production would depend on changes on a monthly scale, rather than upon yearly flows, because of the threshold effect given by RoR scheme installed capacity. Bocchiola *et al.* (2020) assessed the hydropower potential of RoR schemes in the Himalayas using two indicators: average number of days per year with daily energy supply below the demand (system failure) and the maximum daily energy deficit in 1 year. Similar to Duratorre *et al.* (2020), they concluded that the changes in snowmelt will affect the streamflow into the RoR schemes with changes to hydropower production. Furthermore, Bocchiola *et al.* (2020) and Li *et al.* (2020) show that some RoR schemes in Dudh Koshi Basin of Nepal in Pearl River Basin, China, may be unable to meet their energy needs for some days each year due to insufficient storage. Carvajal *et al.* (2017) and Casale *et al.* (2020) determined the climate change effects on both RoR and reservoir hydropower in different regions (Ecuador and Afghanistan) using different metrics (seasonal power generation changes and annual generation output changes). Both studies emphasise the importance of using reliable climate projections to reduce uncertainty in future projections. Another approach used to determine future changes in hydropower potential is the power duration curve (de Oliveira *et al.* 2017). This approach provides insights into reservoir hydropower potential but fails to consider seasonal variations, which are crucial for understanding the full extent of climate change impacts on hydropower production.

Furthermore, climate change modelling involves various sources of uncertainty (Eccles *et al.* 2019; Yalcin 2024), such as parametric uncertainty (uncertainty associated with key parameters used in climate models, such as climate sensitivity or the rate of output growth), model uncertainty (climate models are simplified representations of the complex earth system, and there are inherent uncertainties arising from our incomplete understanding of the climate system and the need to approximate certain processes (e.g., cloud formation, convection) due to computational limitations), scenario uncertainty (imperfect knowledge of future socioeconomic and technological trajectories, which determine future greenhouse gas emissions and land-use changes) and natural variability (climate models also need to account for natural fluctuations in the climate system, such as the El Niño-Southern Oscillation (ENSO), and other modes of variability, which can obscure long-term trends, particularly at regional scales).

There is a need for more robust and reliable projections to accurately assess the impacts of climate change on RoR hydropower generation. The third Climate Change Risk Assessment (CCRA) (Climate Change Committee 2021) emphasizes the impact of climate change on water availability and, consequently, energy supply that is dependent on water. The Third National Adaptation Programme (NAP3) (HM Government 2023) recognizes the significance of renewable energy, including hydropower, in contributing to climate resilience and emphasizes the need to ensure the resilience of renewable energy infrastructure against climate impacts. Carless & Whitehead (2013) and Dallison *et al.* (2021) highlight the need for updated climate projections to minimise climate change modelling uncertainty and understand the full extent of the effects of climate change on RoR hydropower production across GB. Outside of GB, Carvajal *et al.* (2017) and Casale *et al.* (2020) show that changes in snowmelt and streamflow will likely affect RoR energy supplies, potentially leading to insufficient storage and system failures in some areas; this has yet to be assessed across GB. The limitations of previous studies and lack of a GB-wide analysis suggest the need for a comprehensive study that incorporates impacts, up-to-date climate projections, and considers both annual and seasonal changes in hydropower production to provide an accurate assessment of the potential impacts of climate change on RoR hydropower generation.

The aim of this study is – for the first time – to determine the future changes on RoR hydropower potential across the whole of GB. Specifically, the enhanced future flows (eFLaG) dataset, offering nationally consistent hydrological projections for river flow, groundwater level, and groundwater recharge based on the latest UKCP18 climate projections for the United Kingdom, is incorporated with an existing database of RoR potential locations (Golgojan *et al.* 2024) to delineate the intricate relationship between future climate-induced alterations in river flows and their consequential impact on RoR hydropower potential across GB. This study is structured as follows: Section 2 presents the methodology used to validate simulated future flows and to determine the changes in river flows and hydropower potential; Section 3 presents the key findings of this study; Section 4 discusses the implications of the results and compares them to previous studies; and, finally, Section 5 concludes the findings of this study and possible implications for RoR developers and operators across GB.

The main objectives of this study are as follows:

1. To assess the potential impacts of climate change on river flow patterns across GB.
2. To evaluate how these changes in river flow could affect the hydropower potential of RoR schemes.

This study seeks to answer the following research questions:

1. How are temperature and rainfall pattern changes influencing river flows, both now and in the future, including seasonality and low environmental flows ($Q_{95}$)? (addressed through objective 1)
2. What are the effects of climate change on RoR hydropower schemes, including power and energy output? (addressed through objective 2)

## 2. METHODS

The eFLaG future flow dataset (Hannaford *et al.* 2022) and an existing database of RoR potential locations (Golgojan *et al.*, 2024) were used to determine the effects of climate change on river flows and in RoR hydropower potential across GB. eFLaG is a nationally consistent hydrological (river flow, groundwater level, and groundwater recharge) projection for the United Kingdom, based on the latest UK Climate Projections (UKCP18) considering a high emission scenario RCP8.5. The eFLaG dataset utilises the UKCP18 dataset and applies a bias correction to its 'Regional' 12 km projections. These projections are then used as input for four river flow models (GRJ4, GRJ6, probability distributed model (PDM), and G2G) to simulate flows at 200 river catchments.

The GR4J (Génie Rural à 4 paramètres Journalier) and GR6J (Génie Rural à 6 paramètres Journalier) models, part of the airGR suite for R software, offer simple yet effective tools for hydrological modelling, with automatic parameter optimisation facilitating their widespread application across diverse catchments. GR4J, with its four free parameters, has been successfully utilised globally for hydroclimate research and operational forecasting in the United Kingdom, demonstrating robust performance. On the other hand, GR6J, a six-parameter variant, was specifically developed to enhance low-flow simulation and groundwater exchange, gaining traction in UK water resource applications. In the study by Hannaford *et al.* (2022), both models were employed and calibrated using the modified Kling–Gupta efficiency as the error criterion, ensuring a comprehensive evaluation of simulated versus observed flows across the flow regime. The calibration process included square-root-transformed flows and did not incorporate the CemaNeige snowmelt module, relying instead on a simple snow module to preprocess climate data based on temperature.

The PDM is a widely utilised lumped rainfall–runoff model, offering flexibility in configuring various catchment flow regimes. It incorporates soil water storage and runoff production mechanisms, allowing for the representation of surface and groundwater pathways. PDM employs nonlinear storage equations or linear reservoir cascades to route water, with options for groundwater extensions and multiple hydrological response zones within catchments. Under the eFLaG project, single-zone PDM models with a daily time step were employed, with model initialisation based on observed flow data and parameter estimation performed using an automatic calibration procedure. Multiple parameter combinations were systematically tested to optimise model performance, focusing on achieving zero bias and maximising the modified Kling–Gupta efficiency.

Finally, G2G, which is a distributed model used to examine the spatial coherence and variability of floods and droughts at various scales, from catchment to national was run with initialisation from observed rainfall and potential evapotranspiration (PET) for historical and climate model-driven scenarios, covering periods from 1963 to 2080. The G2G dataset includes 186 of the 200 eFLaG catchments, excluding some due to geographical and technical reasons.

The regional climate projections were created by running the Hadley Centre global climate model and regional climate models (HadGEM3-GC3.05 and HadREM3-GA705) with perturbed parameters. This results in 12 high-resolution (12 km) climate projections that are consistent spatially across the United Kingdom. The projections cover the time period of December 1980–November 2080. For all the models, evaluation was undertaken in two stages:

Stage 1 evaluated the performance of model simulations driven by observed climate data against river flow and groundwater observations using various metrics (Nash–Sutcliff efficiency ($R^2$ efficiency), Nash–Sutcliffe efficiency log flows, Nash–Sutcliffe efficiency square-root flows, modified Kling–Gupta efficiency (square-root flows), absolute percent bias, mean absolute percent error, absolute percent error in $Q_{95}$, low-flow volume, and absolute percent error in the mean annual minimum on a 30-day moving average). A full description of the metrics used can be found in Table 2 in the study by Hannaford *et al.* (2022).

Stage 2 assesses the models' performance when driven by climate model outputs, comparing statistical characteristics such as river flow and groundwater level duration curves, low-flow/low-level metrics, and seasonal recharge values over a common baseline period. This comparison considers the range of variability within climate model ensembles, acknowledging that historical weather events are one realisation of natural variability.

Hannaford *et al.* (2022) summarised the evaluation metrics performance across all catchments. The GR4J model showed good performance overall, though there were some outliers in drought metrics, particularly in the southeast and London. The GR6J model performed slightly better than GR4J, especially in low-flow catchments. The PDM model achieved very good scores, particularly for low-flow and drought indicators. The G2G model also performed well, but generally lower than GR and PDM models, as it was not calibrated to individual catchments and simulates natural flows, whereas the other models included artificial impacts implicitly through calibration. This calibration distinction means PDM and GR models better replicate observed flows. The eFLaG dataset has been instrumental in providing valuable insights into the potential impacts of climate change on river flows and groundwater future droughts, contributing to informed decision-making and policy development.

## 2.1. Data

Alongside the eFLaG dataset presented earlier, a dataset of RoR hydropower schemes was used. Golgojan *et al.* (2024) identified potential locations for RoR hydropower schemes across GB, providing a dataset of potential RoR schemes that are technically and financially feasible and realisable. In this study, the term *technically feasible* refers to RoR schemes that can have a penstock and a turbine installed, whereas *financially feasible* refers to the technically feasible schemes that are also financially viable, meaning a positive net present value at the end of a scheme's lifespan. *Realisable schemes* exclude the financially viable schemes, which are in an environmentally protected area. The potential RoR locations (Golgojan *et al.* 2024) dataset includes details such as installed power, design flow, head, intake and powerhouse coordinates, penstock diameter, initial cost, and net present value for each potential RoR scheme.

### 2.1.1. Selection of run of river locations

In the present study, we use the RoR locations identified in the study by Golgojan *et al.* (2024) that are in proximity to eFLaG gauges. The potential RoR schemes from Golgojan *et al.* (2024) are spread throughout GB; however, the eFLaG set consists of river flow projections at limited river gauge locations (Hannaford *et al.* 2022). Therefore, only the RoR locations in proximity to those river gauges were selected for this study. The technically feasible potential RoR locations from Golgojan *et al.* (2024) were used for this study because they provide all the information needed to carry out the analysis.

First, maps from Golgojan *et al.* (2024) were examined to identify RoR intake locations that are close (less than 1 km radius) to the gauged stations from the eFLaG dataset. Once these locations were determined, a database was created, incorporating the RoR intake characteristics (e.g., design flow, turbine type, head). The $Q_{40}$–$Q_{95}$ flow was then calculated for the eFLaG gauges and compared to the design flow for the RoR schemes next to it. If the difference between the design flow of the RoR scheme and the $Q_{40}$–$Q_{95}$ flow of the eFLaG gauge was $\pm 10\%$, the RoR scheme was selected. By following these steps, the study identified appropriate RoR locations that closely aligned with the observed flow patterns at the nearby eFLaG gauged stations. Figure 1 shows the geographical location of the RoR schemes and nearby eFLaG gauges.

## 2.2. Validating the simulated future flows

Although the simulated flows from the eFLaG dataset were previously validated using various metrics (Section 2.1), in this study, the eFLaG future river flows (simulated flows at 200 river catchments) (Hannaford *et al.* 2022) were validated using the National River Flow Archive (NRFA) observed flow dataset (NRFA 2021) at the same locations for a time period ranging from 1963 to 2018, matching the period suggested for validation in the study by Hannaford *et al.* (2022).

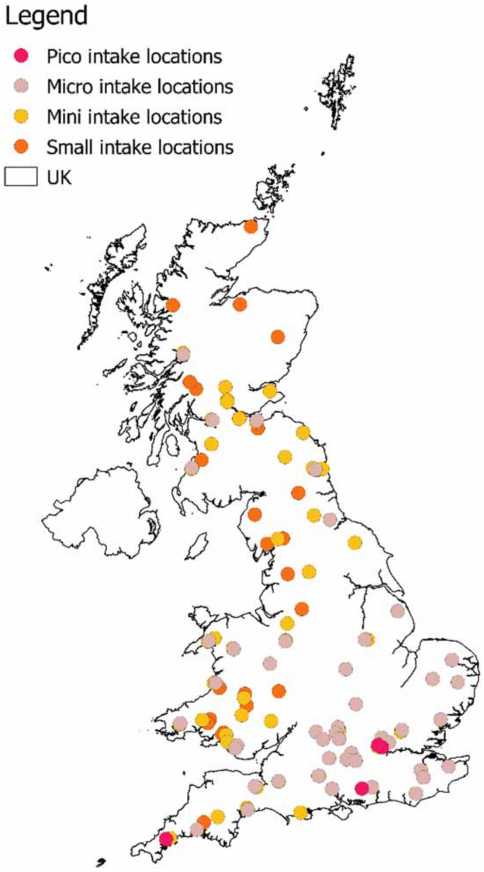

**Figure 1** | The location of potential run of river schemes intakes. Classified by size in pico, micro, mini and small run of river (Golgojan *et al.* 2024).

The coefficient of determination ($R^2$) was used to determine how well the simulated flows predict the gauged flows since this was not used by Hannaford *et al.* (2022). $R^2$ is the proportion of the variation in the dependent variable that is predictable from the independent variable(s). It provides a measure of how well-observed outcomes are replicated by the model based on the proportion of total variation of outcomes explained by the model (Steel & Torrie 1962). Bell *et al.* (2018) recommend that the comparison between simulated and observed flows should be made using statistics over long periods of time, rather than time-series. Therefore, the high ($Q_5$ – the flows that is exceeded 5% of the time), medium ($Q_{40}$, $Q_{50}$, and $Q_{60}$), and low or environmental ($Q_{95}$) simulated eFLaG flows were compared to the observed corresponding exceedance flows from NRFA (2021) at all the eFLaG stations for the four hydrological models: G2G, GR4J/GR6J, and PDM (Supplementary Material). Only the predicted future flows using the hydrological model with the highest $R^2$ values were used for the next part of the analysis.

## 2.3. Changes in future river flows

Three 30-year time slices were analysed from the eFLaG simulations: baseline (1980–2009), near future (2030–2059), and far future (2050–2079). The near future and far future time slices were compared against the baseline time slice to assess potential future changes in flows. The time-series of monthly mean flows were used to derive seasonal mean flows for each time slice, using the standard seasons (winter: December–February, spring: March–May, summer: June–August, autumn: September–November). Percentage changes in daily, monthly, annual, and seasonal river flows for the near future and far future were calculated relative to the baseline period.

The design flow for RoR schemes was based on $Q_{40}$ and $Q_{95}$ (flows with an exceedance probability of 40 and 95%, respectively) (Golgojan *et al.* 2024); therefore, the percentage changes in these types of flows were also calculated. Moreover, changes in days with flows below the $Q_{40}$ flow and the environmental flow ($Q_{95}$) were also determined. The minimum flow level needed to maintain the health and integrity of a river and its ecosystems is known as the environmental flow, usually $Q_{95}$. This is typically used to set requirements for maintaining the environmental flow, so it is essential to assess any changes in this flow for RoR operation.

## 2.4. Changes in future run of river hydropower potential

### 2.4.1. Baseline and future hydropower potential

Changes in future (2030–2059 and 2050–2079) hydropower potential relative to the baseline period (1980–2009) were calculated based on annual and seasonal differences between available power and energy. The difference between historical and future hydropower potential was typically calculated using annual percentage differences (Carless & Whitehead 2013; Carvajal *et al.* 2017; Casale *et al.* 2020). However, these do not capture the seasonality of changes or more subtle changes such as days when the flows are too low to produce electricity. The differences between monthly, seasonal, and annual power generation were based on average power generated during the baseline and future periods. Therefore, to get a complete picture of changes in hydropower potential, the differences in total energy generated during the baseline and future periods were also calculated.

RoR hydropower potential was calculated based on available daily power using the following formula:

$$P_{\text{daily\_baseline}} = \frac{g \cdot \rho \cdot \eta \cdot Q_{\text{baseline}} \cdot H}{1,000} \tag{1}$$

where $P_{\text{daily\_baseline}}$ is the available power in kW; $g$ is the acceleration due to gravity and is equal to 9.81 m/s$^2$; $\rho$ is the water density and is equal to 1,000 kg/m$^3$; $\eta$ is the turbine efficiency, $Q_{\text{baseline}}$ is the daily baseline flow through the turbine and is calculated as the simulated daily flow from the eFLaG set, and $H$ is the available head between the intake and the powerhouse. If the daily flow was above the design flow of the RoR scheme, the flow used in Equation (1) was the design flow (maximum flow captured at the RoR intake). The turbine efficiency, $\eta$, differs based on the turbine type and its efficiency curve (Sinagra *et al.* 2014; Dellinger *et al.* 2016; Pereira 2021). For the near (2030–2059) and far future (2050–2079), the available power was calculated using the predicted future flows from the eFLaG dataset (Equation (2))

$$P_{\text{daily\_future}} = \frac{g \cdot \rho \cdot \eta \cdot Q_{\text{future}} \cdot H}{1,000} \tag{2}$$

where $P_{\text{daily\_future}}$ is the available power in kW and $Q_{\text{future}}$ is the average daily flow in the future (average from all the Regional Climate Models (RCMs)).

For the energy calculation, the following equations were used for the baseline (Equation (3)) and the future (Equation (4)):

$$E_{\text{daily\_baseline}} = P_{\text{daily\_baseline}} \cdot 24 \ \ \text{h} \cdot \text{Cf} \tag{3}$$

$$E_{\text{daily\_future}} = P_{\text{daily\_future}} \cdot 24 \ \ \text{h} \cdot \text{Cf} \tag{4}$$

where $E_{\text{daily\_baseline}}$ and $E_{\text{daily\_future}}$ are the daily energy produced for the baseline and the future, respectively, in kWh; Cf is the capacity factor, set at 40% for this analysis, based on the work by Sample *et al.* (2015) and DUKES statistics (DUKES 2022).

The monthly power and energy for the baseline (Equations (5) and (7)) and the future (Equations (6) and (8)) were calculated using the following formula:

$$P_{\text{monthly\_baseline}} = \frac{\sum_{1}^{n} P_{\text{daily\_baseline}}}{n} \tag{5}$$

$$P_{\text{monthly\_future}} = \frac{\sum_{1}^{n} P_{\text{daily\_future}}}{n} \tag{6}$$

$$E_{\text{monthly\_baseline}} = \sum_{1}^{n} E_{\text{daily\_baseline}} \tag{7}$$

$$E_{\text{monthly\_future}} = \sum_{1}^{n} E_{\text{daily\_future}} \tag{8}$$

where $P_{\text{monthly\_baseline}}$, $P_{\text{monthly\_future}}$, $E_{\text{monthly\_baseline}}$, and $E_{\text{monthly\_future}}$ are the mean monthly power and total energy for each month of the year and $n$ is the number of days for each month. The seasonal power and energy were calculated by averaging the monthly power for each season, respectively, adding the monthly energy for each season.

The annual power and energy for the baseline (Equations (9) and (11)) and the future (Equations (11) and (12)) were calculated using the following formulas:

$$P_{\text{annual\_baseline}} = \frac{\sum_{1}^{m} P_{\text{monthly\_baseline}}}{m} \tag{9}$$

$$P_{\text{annual\_future}} = \frac{\sum_{1}^{m} P_{\text{monthly\_future}}}{m} \tag{10}$$

$$E_{\text{annual\_baseline}} = \sum_{1}^{m} E_{\text{monthly\_baseline}} \tag{11}$$

$$E_{\text{annual\_future}} = \sum_{1}^{m} E_{\text{monthly\_future}} \tag{12}$$

where $\mathrm{P}_{\text{annual\_baseline}}$, $\mathrm{P}_{\text{annual\_future}}$ are the mean power, $\mathrm{E}_{\text{annual\_baseline}}$, $\mathrm{E}_{\text{annual\_future}}$ are the total energy for each year for the baseline, respectively, future periods and m is the number of months per each year. The differences between the baseline and future power and energy (daily, monthly, seasonal, and annual) were calculated as percentage differences.

## 3. RESULTS

### 3.1. Simulated flows validation

All hydrological models evaluated in this study were found to demonstrate high accuracy in predicting simulated flows, particularly with respect to percentile flows. Table 1 provides an overview of the model performance, highlighting the overall precision of each model in predicting flows. All models predict percentile simulated flows with $R^2 > 0.9$. However, the G2G hydrological model exhibits relatively lower accuracy compared to the others (for the $\mathrm{Q}_{95}$ flow, $R^2$ is less than 0.7, which is considered the upper limit for a good $R^2$ value) (Moore *et al.* 2013).

Figure 2 presents a graphical representation of the simulated versus observed percentile flows for gauge 2001 as an example. A comparison between the daily simulated and observed flows for the same gauge can be found in the Supplementary Material (Figure S1). The results indicate that most models accurately simulate percentile flows, except for the G2G hydrological model, which shows deviations from the observed values. The performance was generally lower than for GRJ4, GRJ6, or PDM hydrological models because the G2G is not usually calibrated to individual catchments, and G2G

**Table 1** | $R^2$ value for percentile flows for each hydrological model from the eFLaG dataset

| Hydrological model | $R^2$ | | | | | |
|---|---|---|---|---|---|---|
| | $Q_5$ | $Q_{20}$ | $Q_{40}$ | $Q_{50}$ | $Q_{60}$ | $Q_{95}$ |
| G2G | 0.988 | 0.988 | 0.966 | 0.949 | 0.930 | 0.693 |
| GR4J | 0.996 | 0.998 | 0.994 | 0.993 | 0.995 | 0.961 |
| GR6J | 0.997 | 0.999 | 0.998 | 0.998 | 0.999 | 0.993 |
| PDM | 0.996 | 0.999 | 0.998 | 0.998 | 0.998 | 0.993 |

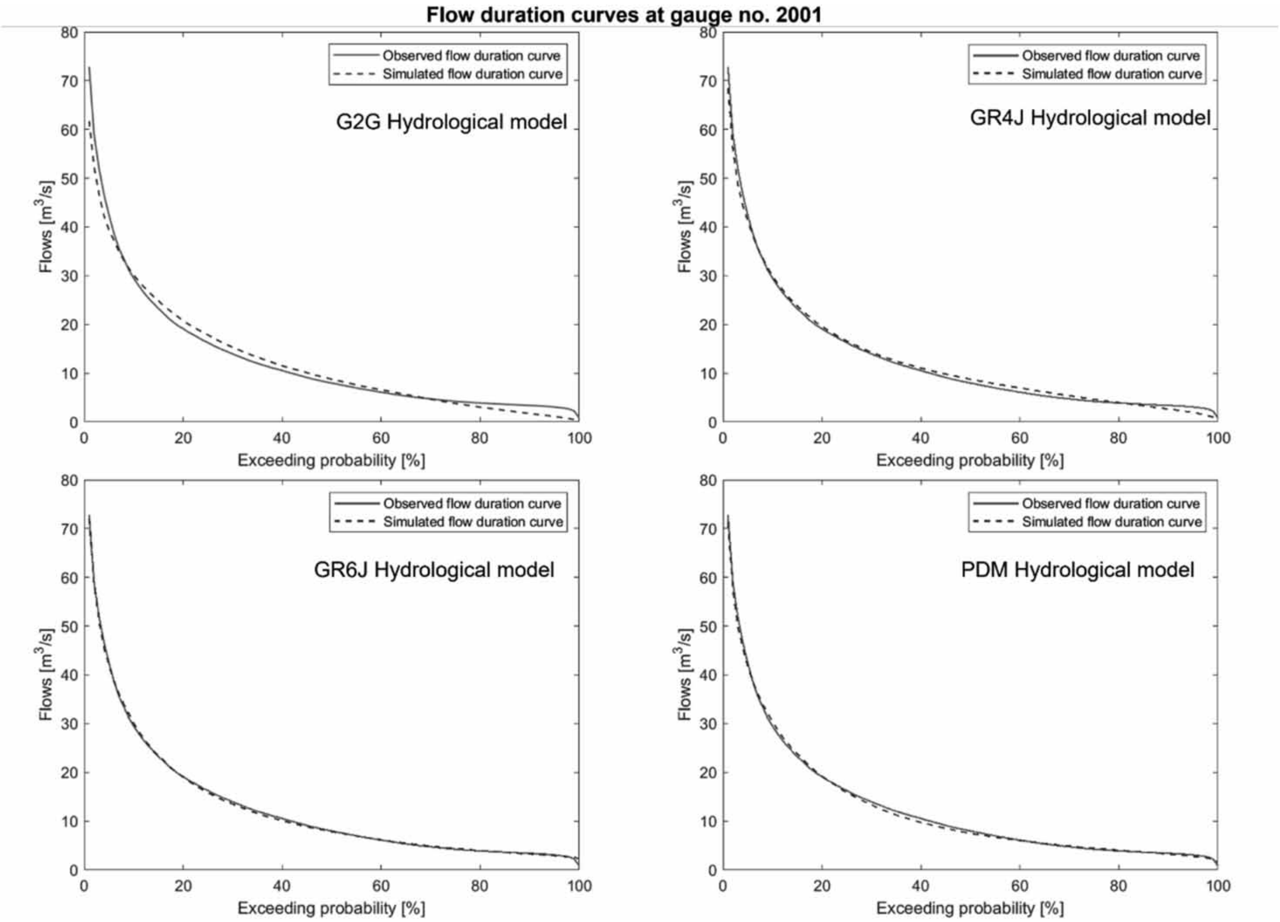

**Figure 2** | Simulated and observed flow duration curves at gauge no. 2001.

simulates natural flows, whereas the lumped models (GRJ4, GRJ6, and PDM) were calibrated to the observations used for performance assessment (Hannaford *et al.* 2022). In catchments with a high degree of anthropogenic disturbance, the G2G model often exhibits lower performance in simulating observed flows. This is primarily because the G2G model is designed to simulate natural hydrological processes on a grid basis, without calibration to specific catchments. As a result, it does not explicitly account for localised human activities that can significantly alter natural flow patterns.

Human activities, such as urbanisation, agricultural practices, industrial water use, and reservoir management, can greatly influence the hydrological cycle. For instance, reservoirs can alter the timing and volume of river flows, urbanisation can increase surface runoff and reduce infiltration, and agricultural practices can change groundwater recharge and discharge patterns. These anthropogenic factors can lead to significant deviations from natural flow patterns, which are not captured by the G2G model.

In contrast, lumped hydrological models such as GR4J, GR6J, and PDM are calibrated using observed flow data from specific catchments. This calibration process allows these models to implicitly account for the effects of human activities, as they are fitted to match observed flows that include these influences. Consequently, the lumped models are better able to replicate observed flows in catchments with significant anthropogenic disturbances.

**Figure 3** | Monthly percentage changes in river flows at the gauging station near RoR schemes. The baseline flows are the flows simulated using the GR6J hydrological model for the period 1980–2009. The near future flows are the mean for all the regional climate models (RCMs) simulated flows for the period 2030–2059. The maps below show the highlighted in grey the catchments where the gauges are in each column. Furthermore, the ID is equivalent to the gauge number, which is based on the NRFA system, consisting of the hydrometric area number, followed by three further digits (e.g., the IDs 21022 and 21024 correspond to hydrometric area 21, also known as the Tweed catchment). The legend refers to percentage change in mean monthly flows in the future from the baseline.

**Table 2** | Mean changes in the future (near future: 2030–2059; far future: 2050–2079) from the baseline (1980–2009) of different metrics for the eFLaG gauges near potential run of river hydropower schemes

| | **Change from the baseline** | |
|---|---|---|
| **Metric** | **Near future (%)** | **Far future** |
| Annual mean flow | −4.51% | −4.56% |
| Spring mean flow | −3.13% | +6.87% |
| Summer mean flow | −26.34% | −37.06% |
| Autumn mean flow | −17.59% | −27.43% |
| Winter mean flow | +2.81% | +9.86% |
| Design flow ($Q_{40}$) | −2.60% | −4.70% |
| Environmental flow ($Q_{95}$) | −16.40% | −23.30% |
| Days with flow below $Q_{40}$ | +3 days/year | +5 days/year |
| Days with flow below $Q_{95}$ | +21 days/year | +34 days/year |

This difference in performance is particularly evident in regions with high levels of human activity, such as the south and east of GB. Here, the G2G model's inability to simulate artificial influences results in lower performance metrics compared to the lumped models.

## 3.2. Future changes in river flows

In the near future (2030–2059), annual river flows near RoR hydropower locations are anticipated to decrease by approximately −4.51%, while in the far future (2050–2079), they may decrease by approximately −4.56% compared to the baseline (1980–2009). Seasonally, river flows are projected to increase in winter and spring. However, there is a notable decrease in flows during the summer months, which may extend into autumn across most regions (Figure 3).

The design flow (considered $Q_{40}$ in this analysis) decreases by −2.6% in the near future and by −4.70% in the far future. Furthermore, the days where the flow is below $Q_{40}$ may increase by 3 days per year on average in the near future and by 5 days per year in the far future (Table 2). These changes are more significant for environmental flows (considered $Q_{95}$ in this analysis). The results show that the environmental flows may decrease by −16.40% in the near future and by −23.30% in the far future. The average number of days with flows below minimum environmental flow level show a strong increase in the future (+21 days/year in the near future and +34 days/year in the far future). Regional disparities exist, with year-round decreases in the south and increased river flows in all seasons, except summer in the north.

## 3.3. Future changes in run of river hydropower potential

Results show that most of the RoR locations analysed (presented in Figure 1) have a reduced power and energy output in the near and far future (Table 3). Overall, the decrease in available power is −5.06% in the near future and almost double in the far future (−8.46%). Despite this, some locations using RoR technology are experiencing an increase in available power. Specifically, micro RoR location with ID 4698 is showing a notable power output increase of 13.77% in the near future and 8.72% in the far future. However, when looking at the corresponding eFLaG gauge (ID 63001), it is apparent that annual river flows are decreasing (−4.56% in the near future and −4.23% in the far future). This suggests that the increase in power output is likely due to seasonal increases in river flows. It is important to note that this particular micro RoR location is the only one among the selected RoR locations with an Archimedean Screw turbine as the technically feasible turbine solution, which has higher efficiencies on a wider range of river flows compared to other more common turbines such as Francis and Pelton (YoosefDoost & Lubitz 2020). Nevertheless, seasonally, most RoR locations may see an increase in available power in the near and far future in winter (Figure 4). The exception is locations in the southern and south-eastern parts of GB, which may have a decreased power output all year compared to the baseline. In spring and winter, there is a modest increase in power output (less than 2%) in the near and far future (Figure 5), while summer and autumn show a significant decrease in power output (up to −32.33% in the far future in summer). This is due to this type of hydropower's dependence on river flows (Mosier *et al.* 2016). There is a clear split between future available power of the north-western potential RoR schemes and the south-eastern ones in all seasons (Figure 4). In

**Table 3** | Percentage difference between near (2030–2059) and far future (2050–2079) available power for the 30-year time slices from the baseline (1980–2009)

| RoR intake ID | Baseline available mean power (kW) | Near future available mean power (kW) | Far future available mean power (kW) | Difference near future from baseline (%) | Difference far future from baseline (%) |
|---|---|---|---|---|---|
| 22350 | 3.39 | 3.04 | 2.87 | −10.33 | −15.42 |
| 26433 | 3.52 | 3.21 | 3.05 | −8.96 | −13.32 |
| 108693 | 5.96 | 5.21 | 4.77 | −12.57 | −19.91 |
| 115426 | 1.66 | 1.61 | 1.57 | −3.36 | −5.78 |
| 2190 | 49.14 | 47.15 | 46.12 | −4.05 | −6.15 |
| 4698 | 44.45 | 50.57 | 48.33 | 13.77 | 8.72 |
| 5872 | 47.26 | 47.57 | 47.64 | 0.66 | 0.80 |
| 7126 | 68.78 | 65.53 | 64.01 | −4.73 | −6.95 |
| 8876 | 16.10 | 16.10 | 15.88 | 0.00 | −1.33 |
| 11592 | 46.22 | 46.58 | 45.79 | 0.77 | −0.93 |
| 14619 | 76.60 | 76.23 | 75.97 | −0.48 | −0.82 |
| 17098 | 5.69 | 5.43 | 5.25 | −4.65 | −7.71 |
| 17975 | 55.38 | 51.37 | 50.11 | −7.23 | −9.52 |
| 21114 | 69.86 | 63.87 | 60.72 | −8.57 | −13.09 |
| 22243 | 12.19 | 11.10 | 10.57 | −8.96 | −13.32 |
| 22477 | 25.96 | 24.53 | 23.52 | −5.50 | −9.39 |
| 24048 | 60.94 | 53.44 | 51.06 | −12.30 | −16.21 |
| 27390 | 65.42 | 60.66 | 57.48 | −7.28 | −12.14 |
| 28249 | 19.55 | 18.36 | 17.42 | −6.09 | −10.93 |
| 30764 | 25.77 | 25.58 | 24.82 | −0.72 | −3.69 |
| 30912 | 80.13 | 77.35 | 74.77 | −3.47 | −6.69 |
| 37423 | 32.01 | 28.83 | 27.36 | −9.93 | −14.52 |
| 42834 | 50.12 | 46.68 | 44.53 | −6.86 | −11.17 |
| 43958 | 37.98 | 34.89 | 32.75 | −8.15 | −13.76 |
| 46202 | 6.39 | 5.39 | 5.07 | −15.65 | −20.57 |
| 50701 | 20.37 | 18.96 | 17.97 | −6.93 | −11.79 |
| 51679 | 22.47 | 20.96 | 20.65 | −6.72 | −8.10 |
| 53056 | 37.34 | 34.07 | 32.10 | −8.75 | −14.05 |
| 54007 | 43.12 | 39.47 | 37.73 | −8.45 | −12.49 |
| 55023 | 26.81 | 26.39 | 25.41 | −1.58 | −5.24 |
| 58075 | 51.30 | 47.04 | 45.23 | −8.29 | −11.82 |
| 59803 | 61.30 | 57.34 | 54.35 | −6.46 | −11.34 |
| 60966 | 44.62 | 42.58 | 41.97 | −4.57 | −5.94 |
| 76933 | 8.80 | 7.60 | 6.92 | −13.71 | −21.43 |
| 83774 | 21.11 | 19.84 | 19.00 | −6.02 | −10.01 |
| 85083 | 9.85 | 8.44 | 7.78 | −14.32 | −21.06 |
| 99121 | 9.62 | 9.30 | 9.06 | −3.36 | −5.90 |
| 101092 | 17.87 | 15.82 | 14.90 | −11.43 | −16.61 |
| 106546 | 38.52 | 37.78 | 37.30 | −1.92 | −3.18 |
| 131120 | 15.88 | 12.88 | 11.48 | −18.85 | −27.70 |
| 154321 | 41.51 | 38.51 | 37.25 | −7.23 | −10.26 |

(*Continued.*)

**Table 3** | Continued

| RoR intake ID | Baseline available mean power (kW) | Near future available mean power (kW) | Far future available mean power (kW) | Difference near future from baseline (%) | Difference far future from baseline (%) |
|---|---|---|---|---|---|
| 160647 | 14.94 | 13.83 | 13.30 | −7.42 | −10.93 |
| 166579 | 63.75 | 62.12 | 61.46 | −2.57 | −3.60 |
| 209114 | 13.97 | 12.71 | 12.09 | −9.01 | −13.51 |
| 4084 | 295.16 | 286.11 | 279.70 | −3.07 | −5.24 |
| 4453 | 168.53 | 169.63 | 169.85 | 0.65 | 0.78 |
| 4570 | 139.78 | 128.46 | 122.42 | −8.10 | −12.42 |
| 7071 | 153.00 | 146.31 | 143.18 | −4.37 | −6.42 |
| 7940 | 109.81 | 107.72 | 106.28 | −1.90 | −3.21 |
| 8170 | 96.39 | 99.49 | 98.09 | 3.22 | 1.77 |
| 9359 | 152.17 | 144.34 | 136.39 | −5.15 | −10.37 |
| 10792 | 160.28 | 145.37 | 135.54 | −9.30 | −15.43 |
| 12523 | 133.38 | 127.48 | 125.17 | −4.42 | −6.15 |
| 12770 | 228.78 | 230.04 | 225.91 | 0.55 | −1.25 |
| 16018 | 129.48 | 119.94 | 115.20 | −7.37 | −11.03 |
| 17815 | 231.29 | 222.93 | 217.45 | −3.61 | −5.98 |
| 18458 | 264.61 | 252.88 | 242.86 | −4.43 | −8.22 |
| 19856 | 119.87 | 116.87 | 114.19 | −2.50 | −4.74 |
| 21194 | 167.89 | 148.99 | 140.44 | −11.26 | −16.35 |
| 21998 | 307.24 | 301.83 | 295.28 | −1.76 | −3.89 |
| 22118 | 176.52 | 159.18 | 154.27 | −9.82 | −12.60 |
| 23125 | 372.39 | 340.62 | 323.89 | −8.53 | −13.02 |
| 23467 | 419.91 | 395.79 | 377.08 | −5.74 | −10.20 |
| 23993 | 334.74 | 311.90 | 304.61 | −6.82 | −9.00 |
| 24111 | 613.05 | 580.89 | 553.87 | −5.25 | −9.65 |
| 24333 | 243.42 | 245.72 | 242.98 | 0.94 | −0.18 |
| 25410 | 102.07 | 95.50 | 90.21 | −6.44 | −11.62 |
| 28224 | 507.45 | 512.20 | 498.50 | 0.94 | −1.76 |
| 32402 | 632.20 | 590.18 | 555.02 | −6.65 | −12.21 |
| 34073 | 130.13 | 129.31 | 125.48 | −0.63 | −3.58 |
| 35184 | 788.67 | 787.30 | 767.47 | −0.17 | −2.69 |
| 45222 | 190.51 | 177.33 | 168.87 | −6.92 | −11.36 |
| 47749 | 117.28 | 105.35 | 99.80 | −10.17 | −14.90 |
| 49626 | 118.92 | 111.70 | 104.48 | −6.07 | −12.14 |
| 53277 | 126.11 | 114.98 | 108.21 | −8.83 | −14.19 |
| 54422 | 716.45 | 714.77 | 687.46 | −0.23 | −4.05 |
| 57212 | 172.89 | 164.32 | 161.78 | −4.96 | −6.43 |
| 63923 | 227.62 | 204.06 | 191.57 | −10.35 | −15.84 |
| 107208 | 658.60 | 623.36 | 601.17 | −5.35 | −8.72 |
| 113697 | 156.65 | 154.36 | 152.83 | −1.46 | −2.44 |
| 189463 | 312.17 | 304.42 | 291.14 | −2.48 | −6.74 |
| 2078 | 1,087.13 | 1,098.92 | 1,099.38 | 1.08 | 1.13 |

(*Continued*.)

**Table 3** | Continued

| RoR intake ID | Baseline available mean power (kW) | Near future available mean power (kW) | Far future available mean power (kW) | Difference near future from baseline (%) | Difference far future from baseline (%) |
|---|---|---|---|---|---|
| 2509 | 1,326.01 | 1,354.77 | 1,328.94 | 2.17 | 0.22 |
| 5831 | 832.20 | 854.86 | 869.88 | 2.72 | 4.53 |
| 8564 | 762.76 | 742.39 | 724.78 | −2.67 | −4.98 |
| 9988 | 1,604.53 | 1,522.05 | 1,510.45 | −5.14 | −5.86 |
| 10911 | 868.42 | 793.33 | 755.10 | −8.65 | −13.05 |
| 11448 | 849.75 | 859.66 | 845.68 | 1.17 | −0.48 |
| 18667 | 2,831.22 | 2,825.12 | 2,814.03 | −0.22 | −0.61 |
| 18896 | 5,316.39 | 5,020.60 | 4,813.32 | −5.56 | −9.46 |
| 18944 | 897.38 | 873.78 | 845.25 | −2.63 | −5.81 |
| 20693 | 1,297.00 | 1,313.19 | 1,265.97 | 1.25 | −2.39 |
| 22277 | 1,397.25 | 1,302.14 | 1,228.24 | −6.81 | −12.10 |
| 25548 | 1,885.71 | 1,961.06 | 1,958.68 | 4.00 | 3.87 |
| 27404 | 2,378.79 | 2,290.19 | 2,238.49 | −3.72 | −5.90 |
| 30466 | 1,146.18 | 1,051.15 | 989.03 | −8.29 | −13.71 |
| 33633 | 1,421.29 | 1,398.71 | 1,363.28 | −1.59 | −4.08 |
| 34822 | 5,570.15 | 4,991.19 | 4,661.17 | −10.39 | −16.32 |
| 44301 | 1,464.71 | 1,340.68 | 1,261.17 | −8.47 | −13.90 |
| 59684 | 1,343.32 | 1,291.19 | 1,256.46 | −3.88 | −6.47 |

autumn, for example, potential RoR locations in the Scottish Highlands are projected to have an increased power output, while all other potential RoR locations are projected to experience a decrease, with more than 50% decrease for RoR locations in southeast.

RoR systems can be classified by installed capacity in pico (less than 5 kW), micro (between 5 and 100 kW), mini (between 100 kW and 1 MW), and finally, small (between 1 and 5 MW). Looking at each type of RoR hydropower (micro, mini, pico, and small) (see Golgojan *et al.* (2024), the seasonal changes differ based on the RoR scheme size (Figure 6). The biggest decreases in available power are in summer for all types of RoR locations, with the biggest decrease for small RoR schemes (−45.17%) in the far future. However, small RoR schemes also benefit from the biggest increase (8.54% in the far future and 6.05% in the near future) in winter compared to the baseline.

Comparing future seasonal changes in flows with the seasonal changes in RoR hydropower power output shows a clear relationship (Table 4). The changes in seasonal flows and hydropower production are closely related, indicating a clear correspondence between decreased river flows and diminished power output in summer and autumn in both the near and far future compared to the baseline. In spring, however, while river flows are projected to decrease in the near future, power output is expected to increase relative to the baseline. This may be due to fluctuations in monthly and daily flows during the spring months (March–May) (Figure 3). In comparison, in winter, river flows show an increase of 9.86% in the far future relative to the baseline, while RoR power output shows an increase of only 1.70%. This is likely due to the RoR limiting characteristics, such as turbine and penstock size that cannot take advantage of higher winter flows. The size of the turbines and penstocks determines how much water can pass through the system and how efficiently the energy can be harnessed from the flowing water. If the turbines and penstocks are designed to handle lower flow rates that are typical during other seasons, they might not be able to fully exploit the increased water flow during winter.

## 4. DISCUSSION AND POLICY IMPLICATIONS

This study on the impacts of climate change on RoR hydropower potential across GB holds wider significance in the context of evolving energy landscapes and climate adaptation globally. The anticipated decrease in summer flows observed in this study corresponds with trends identified in various global regions (Van Vliet *et al.* 2013; Ali *et al.* 2019), emphasising the

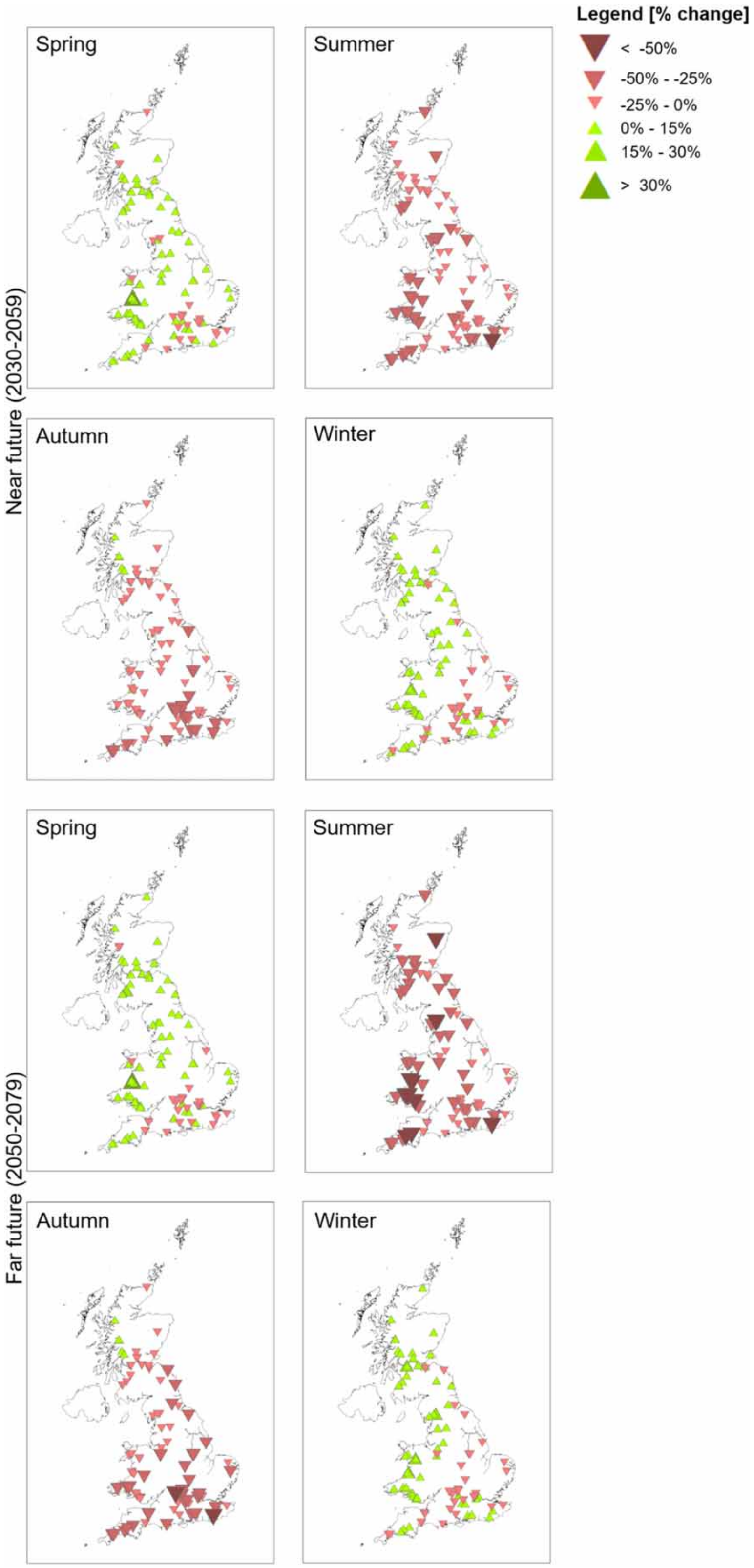

**Figure 4** | Percentage changes in seasonal available power for the RoR schemes selected in the near future (2030–2059) and far future (2050–2079) from the baseline (1980–2009).

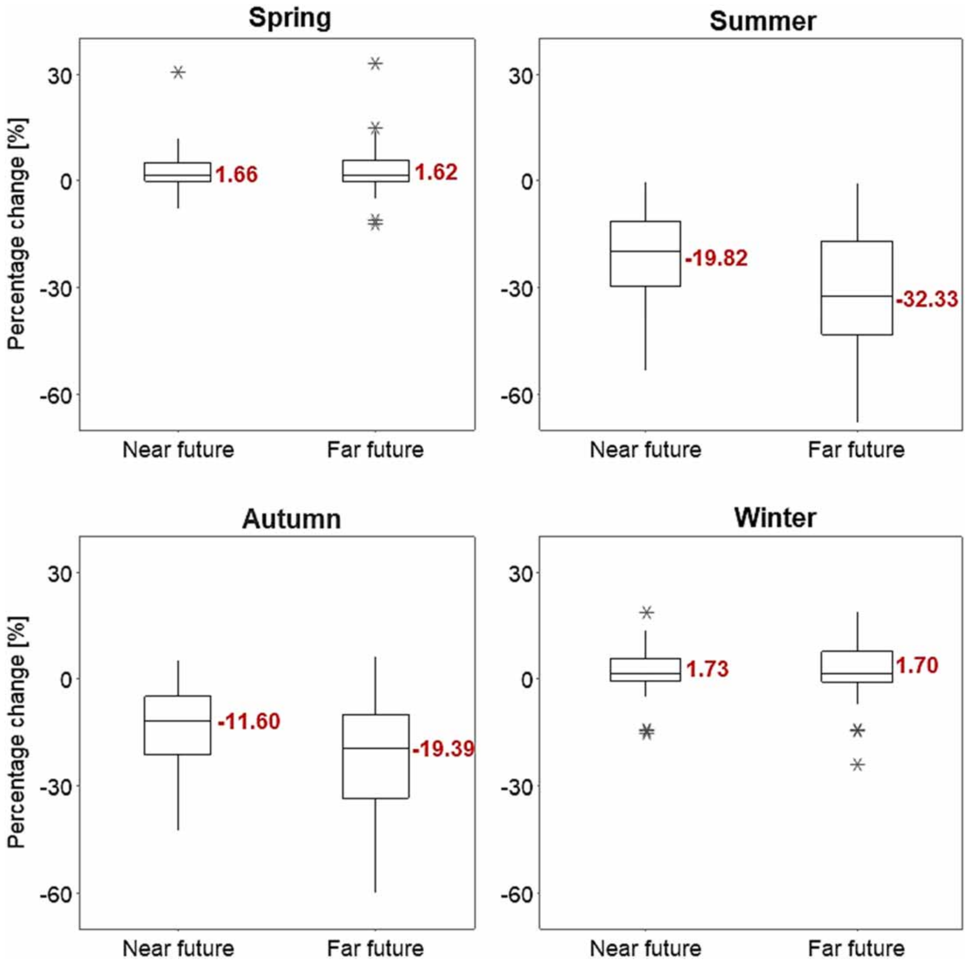

**Figure 5** | Percentage changes in seasonal available power for RoR schemes from the baseline (1980–2009) to the near future (2030–2059) and the far future (2050–2079). The value in red is the mean change (%) in available power.

vulnerability of seasonal water availability to climate-induced shifts. The OECD has highlighted the importance of designing, building, and operating infrastructure to anticipate and adapt to changing climate conditions, as well as retrofitting existing infrastructure to enhance climate resilience (OECD 2018). This policy perspective aligns with the challenges and opportunities presented by the study's findings, highlighting the need for a coordinated policy response to ensure that hydropower infrastructure is resilient to the impacts of climate change. Across GB, previous studies have indicated a decline in summer river flows, varied patterns in autumn, and both a decrease and increase in winter and spring flows (Werritty 2002; Christierson *et al.* 2012; Prudhomme *et al.* 2012; Kay 2021). Our study broadly aligns with these observations, indicating a projected decrease in summer and autumn flows and an increase in winter flows, along with mixed patterns in spring. This extends to the exploration of seasonal variations in power output, which is in accordance with the broader understanding that the seasonal dynamics of river flows significantly influence hydropower generation (Bocchiola *et al.* 2020; Casale *et al.* 2020). The findings of the study are in line with the priorities outlined in the UK CCRA and the Third NAP3, which emphasize the importance of understanding and addressing the impacts of climate change on critical infrastructure, including water resources and renewable energy.

Several studies (e.g., Carless & Whitehead 2013; Carvajal *et al.* 2017; Bocchiola *et al.* 2020; Casale *et al.* 2020) have highlighted the effects of climate change on hydropower potential. However, hydropower development is intricately linked to the topographical and hydrological features of the region in which it is constructed. The outcomes of regional or location-specific studies are often not directly comparable. Nonetheless, the results from the present study are in agreement with those of Carless & Whitehead (2013) and Dallison *et al.* (2021) that highlight future decreases in RoR potential

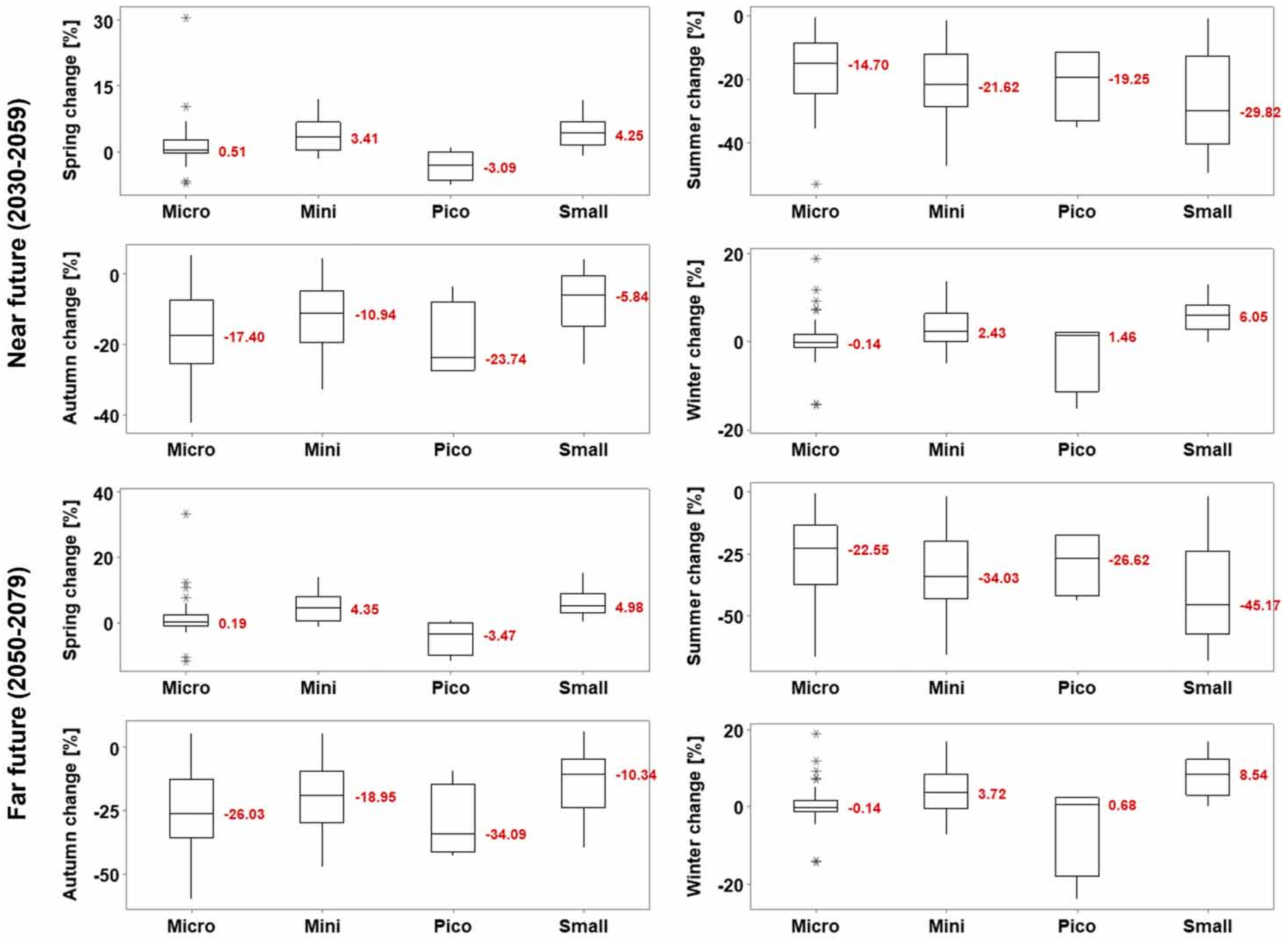

**Figure 6** | Boxplot of seasonal changes in available power in the near future (2030–2059) and the far future (2050–2079) from the baseline (1980–2009) for all the RoR schemes analysed, broken down by RoR type after (Golgojan *et al.* 2024). The value in red is the mean change (%) in available power.

**Table 4** | Seasonal changes in river flows at gauges near RoR stations and seasonal changes in available power at RoR schemes in the near future (2030–2059) and far future (2050–2079) from the baseline (1980–2009)

| | **Change in flows (%)** | | **Change in available power (%)]** | |
|---|---|---|---|---|
| **Season** | **Near future** | **Far future** | **Near future** | **Far future** |
| Spring | −3.13 | +6.87 | +1.66 | +1.62 |
| Summer | −26.34 | −37.06 | −19.82 | −32.33 |
| Autumn | −17.59 | −27.43 | −11.6 | −19.39 |
| Winter | +2.81 | +9.86 | +1.73 | +1.7 |

in summer and autumn and increases in winter and spring in Wales. Similar to Carvajal *et al.* (2017), Casale *et al.* (2020), Li *et al.* (2020), and Mutsindikwa *et al.* (2021), our study highlights that the river flow increases in winter are not entirely convertible to hydropower potential as these discharges exceed the maximum capacity of the turbines. The changing climate patterns lead to higher river discharges, which may seem beneficial for hydropower potential. However, our findings reveal a crucial limitation in harnessing this increased winter river flow for hydropower generation. The increase in river flows during these periods exceeds the maximum capacity of the turbines installed in many RoR hydropower locations. Consequently, the excess water cannot be efficiently converted into electricity, leading to untapped energy potential and rendering these periods less productive for hydropower operations. This discrepancy between river flow increases and the turbine capacity highlights the need for proactive measures to adapt hydropower infrastructure to changing climate conditions. Upgrading existing turbines to handle higher flows or designing new turbines capable of accommodating larger discharges may be essential steps to fully utilise the increased river flows during winter. The study's recognition of the influence of turbine technology on RoR systems has broader implications for the global hydropower industry, emphasising the importance of continually improving and adapting technologies to maximize efficiency and minimize environmental impacts. These insights are relevant not only for existing RoR locations but also for informing the design of future hydropower installations globally. It is also crucial to consider the broader environmental implications of altered river flow patterns. The increased water discharge during winter could result in heightened erosion and sediment transport downstream, impacting aquatic ecosystems and riverbank stability.

Conversely in the future, we show that environmental flows (assumed $Q_{95}$ in this study) will decrease significantly (by $-16.40\%$ in the near future and $-23.30\%$ in the far future). This has many policy implications, especially in the way $Q_{95}$ is determined for hydropower production. This analysis considers that environmental flows remain the same value in the future relative to the baseline period, but they could be amended to reflect the change in river flows. However, this change may come with negative effects on the water environment because different $Q_{95}$ flows may not be enough to assure river ecology (Higgins *et al.* 2011).

While this study contributes to the understanding of climate change's impact on RoR hydropower across GB, there were certain limitations. The scarcity of river flow gauges near potential RoR locations introduced uncertainties; however, this study considers the chosen potential RoR locations spread out uniformly over the study area and representative for all RoR types across GB. An additional uncontrolled factor was the use of an existing future flows database (Hannaford *et al.* 2022), which, although quality checked, introduced uncertainties to the analysis (i.e., only one climate change model – UKCP18 and emissions pathways – RCP8.5 was used). However, although the use of multiple climate models and emission scenarios is recommended (Smith *et al.* 2009; Shen *et al.* 2018; Kay *et al.* 2020; Kendon *et al.* 2021), our results show good agreement between simulated and gauged percentile flows.

Other sources of uncertainty may come from human activities, which can significantly affect hydrological systems. Land-use changes, such as urbanisation, deforestation, and agricultural practices, can alter runoff patterns, soil infiltration rates, and evapotranspiration, which in turn impact river flows (Eccles *et al.* 2019; Solanki *et al.* 2024). Water abstraction for agricultural, industrial, and domestic use also modifies flow regimes, particularly in regions with high water demand (Gosal *et al.* 2022).

Furthermore, the choice of a 40% capacity factor for RoR hydropower systems, while based on industry standards and previous studies (Sample *et al.* 2015; DUKES 2022), may not accurately represent the specific conditions of all RoR systems analysed. The capacity factor can vary depending on factors such as site-specific hydrology, plant design, and operational constraints. Future studies could explore the sensitivity of the results to different capacity factor assumptions or use site-specific data where available. Our analysis primarily focuses on the technical and environmental aspects of hydropower generation. However, socioeconomic factors, such as energy demand, policy changes, and market dynamics, can also influence the development and operation of hydropower systems.

Finally, to mitigate the negative impacts of climate change on hydropower generation, several adaptation strategies and policy recommendations can be considered:

- Improved water management: Implementing comprehensive water management strategies, including reservoir management, water conservation measures, and demand-side management, can optimise water resources for hydropower generation while minimising environmental impacts.
- Infrastructure upgrades: Investing in the upgrade and modernisation of hydropower infrastructure, including turbines and transmission systems, can improve efficiency, flexibility, and resilience to changing hydrological patterns and extreme weather events.
- Ecosystem-based approaches: Incorporating ecosystem-based approaches into hydropower planning and management, such as environmental flow requirements, habitat restoration, and fish passage facilities, can mitigate the adverse effects of hydropower development on aquatic ecosystems and biodiversity.

- Climate change adaptation policies: Formulating and implementing climate change adaptation policies and regulations that integrate climate considerations into hydropower planning, licensing, and operation processes can enhance the resilience of hydropower infrastructure and ensure sustainable energy generation in a changing climate.
- Stakeholder engagement and collaboration: Fostering collaboration and engagement among stakeholders, including government agencies, energy utilities, environmental organisations, and local communities, can facilitate the development of consensus-driven solutions and promote equitable and sustainable hydropower development.

By adopting a holistic approach that combines technological innovations, policy reforms, and stakeholder engagement, it is possible to mitigate the negative impacts of climate change on hydropower generation and foster a more resilient and sustainable energy future.

## 5. CONCLUSIONS

This is the first study to examine the possible effects of future river flow changes on RoR hydropower potential due to climate change across GB. We find that river flows (at gauges near potential RoR locations) are projected to decrease by −4.51% in the near future (2030–2059) and by −4.56% in the far future (2050–2079) compared to a 1980–2009 baseline period. While flows may decrease annually, in spring and winter, they may increase. These changes exhibit regional disparities with the southern regions likely to see year-round decreases, compared to northern parts that may experience increased river flows throughout all seasons, except summer. The RoR hydropower potential across GB in the future is closely related to changes in river flows. The corresponding results show that RoR hydropower potential is projected to decrease in the near and far future in both summer and autumn throughout GB, at a rate similar to the decreases in river flows. Some RoR locations in the southeast and east of GB are projected to have a decreased power output all year, with decreases as low as over −50%. Conversely, RoR hydropower potential modestly increases in spring and winter. Notably, increases in spring (approximately. +1.60%) and in winter (+1.70%) are smaller than decreases in summer (−19%) and autumn (−11%). As such, the results indicate a general decrease in the annual RoR hydropower potential across GB in the future. The projected decline in power output during the months of summer and autumn signifies potential challenges for meeting electricity demands during peak demand periods.

The key findings from this study highlight the need for adaptive water management strategies to mitigate the impacts of climate change on hydropower resources and have implications for the planning of new RoR schemes and adapting already operational schemes. Although river flows may increase in winter in parts of GB, turbines may not be able to take advantage of any increases. Therefore, unless RoR hydropower schemes are designed with climate change in mind at the planning stage, their power output will be limited. In addition, RoR schemes that were designed considering historical river flows can use the information from this study to better prepare for and adapt to possible future variations in river flows. The projected decline in power output during summer and autumn emphasises the urgency of proactive measures and adaptive strategies to ensure the sustainable and efficient utilisation of RoR hydropower resources considering changing conditions. This study transcends its specific geographic focus and holds relevance for global efforts in advancing sustainable energy and adapting to the challenges posed by climate change. The findings contribute valuable insights that can guide policymakers, energy planners, and researchers worldwide in developing strategies that balance energy needs, ecological sustainability, and climate resilience.

To develop a complete picture of how climate change affects RoR hydropower schemes, additional work is needed to minimise uncertainty in the future projections by considering multiple climate models, emissions pathways, and hydrological models. Furthermore, this study not only highlights possible future decreases in environmental flows but also emphasises the need for additional research to investigate the policy on environmental flows. Given the potential impact of climate change, it becomes necessary to explore specific risks to this type of hydropower, such as drought, which could further exacerbate the challenges related to environmental flows. Therefore, understanding the interactions between climate change, environmental flows, and drought becomes essential in developing effective strategies for sustainable water resource management and RoR hydropower generation.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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