UNDERSTANDING THE IMPACTS AND RISKS OF CLIMATE CHANGE ON RUN OF RIVER HYDROPOWER POTENTIAL IN GREAT BRITAIN

DECLARATION OF AUTHENTICITY AND AUTHOR'S RIGHTS

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date: 18 February 2025

STATEMENT OF CO-AUTHORSHIP

The following people and institutions contributed to this thesis:

Candidate Ana-Diana Golgojan, University of Strathclyde

Supervisor 1 Dr Christopher J. White, University of Strathclyde (Primary Supervisor)

Supervisor 2 Dr Douglas Bertram, University of Strathclyde (Second Supervisor)

Peer-reviewed publications featured in this thesis, including co-author contributions:

Paper 1 (presented as Chapter 3 in this thesis):

Citation: Golgojan, A.D., White, C.J., Bertram, D., 2024. An assessment of run of river hydropower potential in Great Britain. Proc. Inst. Civ. Eng. - Water Manag. 178, 42–61. https://doi.org/10.1680/JWAMA.23.00056

Status: Published. First submission 18 August 2023; revised submission 26 January 2024; accepted with minor revision 30 April 2024

Authors and contributions:

Ana-Diana Golgojan (90%): Conceptualisation; formal analysis; visualisation; writing – original draft preparation; writing – review & editing.

Christopher J. White (5%): Conceptualisation; writing – review & editing.

Douglas Bertram (5%): Conceptualisation; writing – review & editing.

Paper 2 (presented as Chapter 4 in this thesis):

Citation: Golgojan, A.-D., White, C.J. & Bertram, D. (2024). Golgojan, A.-D., White, C.J., Bertram, D., 2024. Future impacts of river flow on hydropower generation in

Great Britain. J. Water Clim. Chang. 15, 4840–4861. https://doi.org/10.2166/WCC.2024.355

Status: Published. First submission 01 May 2024; revised submission 19 July 2024; accepted with minor revision 01 August 2024

Authors and contributions:

> Ana-Diana Golgojan (90%): Formal analysis; visualization; writing – original draft preparation; writing – review & editing.
>
> Christopher J. White (5%): Conceptualisation; writing – review & editing.
>
> Douglas Bertram (5%): Conceptualisation; writing – review & editing.

Paper 3 (presented as Chapter 5 in this thesis):

Citation: Golgojan, A.-D., White, C.J. & Bertram, D. (2024). The effects of climate change on hydropower drought: A run of river case study, International Journal of Energy Research

Status: In review. First submission 10 May 2024; revised submission 11 October 2024

Authors and contributions:

> Ana-Diana Golgojan (90%): Formal analysis; visualization; writing – original draft preparation; writing – review & editing.
>
> Christopher J. White (5%): Conceptualisation; writing – review & editing.
>
> Douglas Bertram (5%): Conceptualisation; writing – review & editing.

Datasets generated and code written for this thesis:

Datasets:

- *Golgojan, A. (Creator), White, C. (Supervisor) (2 May 2023). An assessment of run of river hydropower potential in Great Britain. University of Strathclyde. Data_Repository(.zip). 10.15129/95db013c-d082-4aa9-a8ce-43b60568087d*
- *Golgojan, A. (Creator), White, C. (Supervisor), Bertram, D. (Supervisor) (6 Feb 2025). Data for "Future impacts of river flow on hydropower generation*

in Great Britain". University of Strathclyde. Data_repository(.zip). 10.15129/bc03010f-7ff7-4678-a510-2b2581a234ad

- *Golgojan, A. (Creator), White, C. (Supervisor), Bertram, D. (Supervisor) (11 Feb 2025). The effects of climate change on hydropower drought: A run of river case study. University of Strathclyde. Data_repository(.zip). 10.15129/ac1b30dd-2b2a-46b8-b902-648979f75dd5*

Code:

- *https://github.com/DianaGolgojan/Assessment-of-RoR-hydropower.git*
- *https://github.com/DianaGolgojan/Future-changes-to-RoR-potential.git*

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisors, Christopher White and Douglas Bertram, for their invaluable guidance, support, and encouragement throughout this journey. Their expertise, patience, and unwavering commitment have been instrumental in shaping this research and my academic growth.

My sincere appreciation goes to the staff and faculty at the University of Strathclyde, whose dedication to excellence in education and research has created a conducive environment for academic inquiry and intellectual exploration.

I am indebted to my colleagues and peers, especially Claire Kennedy, Josh Peters, Jack Roden, Jason Erikson and Adam Buchanan for their camaraderie, collaboration, and extracurricular activities, which have fostered a vibrant scholarly community and contributed to my personal and professional development.

Last but not least, I extend my heartfelt gratitude to my family for their unwavering love, encouragement, and understanding throughout this endeavour. Their steadfast support and sacrifices have been a source of strength and motivation, inspiring me to persevere in pursuit of my academic goals.

I would like to dedicate a special acknowledgment to my husband, Alexandru Golgojan, whose unwavering love, encouragement, and support have been the bedrock of my PhD journey. Their patience, understanding, and belief in me, even during the most challenging times, have been a constant source of strength and motivation.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CH4	Methane
CO_2	Carbon dioxide
COVID-19	Coronavirus 2019
CSP	Concentrated solar power
DEM	Digital elevation model
eFLaG	Enhanced Future Flows and Groundwater
FDC	Frequency duration curve
G2G	Grid to grid hydrological model
GB	Great Britain
GHG	Greenhouse gases
GIS	Geographical information systems
GRP	Glass reinforced plastic
GW	Gigawatt
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised cost of electricity
MW	Megawatt
NFRA	National River Flow Archive
NO_x	Nitrogen oxides

NPV Net present value

PV Photovoltaic

Q_5 Flow with an exceedance probability of 5%

Q_{10} Flow with an exceedance probability of 10%

Q_{50} Flow with an exceedance probability of 50%

Q_{70} Flow with an exceedance probability of 70%

Q_{95} Flow with an exceedance probability of 98% (also referred to in this thesis as environmental flow or compensation flow)

RCP4.5 Representative Concentration Pathway 4.5 (labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m2, respectively)

RCP8.5 Representative Concentration Pathway 8.5 (labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m2, respectively)

SO_2 Sulphur dioxide

TW Terawatt

UK United Kingdom

UKCEH United Kingdom Centre for Ecology & Hydrology

UKCP09 UK Climate projection 2009

UKCP18 UK Climate projection 2018

ABSTRACT

Climate change is a multifaceted global phenomenon that poses a significant threat to critical infrastructure water availability, human health, etc. as evidenced by increasing occurrences and severity of extreme weather events. A vital step in minimising the long-term effects of climate change is reducing carbon dioxide (CO_2) emissions. To this end, countries worldwide have committed to reaching net zero emissions in the future.

The UK has committed to decarbonising its electricity system by 2035. The Department for Energy Security and Net Zero accepted that hydropower is critical to delivering greater energy security and independence, economic growth, and the UK's net zero ambitions. While most large hydropower sites have been utilised in the UK, run of river (RoR) hydropower is a type of hydropower generation that has the potential to be further developed in the UK, to meet the country's ambitious net zero target. RoR systems work in the same way as large hydropower schemes, except they are not dependent on water storage but instead are reliant on the natural seasonality of river flows. The benefits of RoR systems include smaller initial investments, shorter planning and construction times, use of smaller areas for construction, less inundation (if any) compared to large hydropower, and the typical use of local labour and materials. Considering the RoR advantages over large hydropower and the Climate Change Committee's recommendation for fast renewables development, RoR hydropower could be developed to support the UK's net zero targets. Although hydropower is generally a well-developed and well-researched technology, the effects of climate change and the potential risks to RoR hydropower are not fully understood. Addressing this gap is crucial for informed decision-making, enabling effective adaptation strategies to be developed and ensuring the resilience of RoR hydropower in the face of evolving climatic conditions.

This thesis aims to improve the understanding of RoR hydropower potential and the effects and risks climate change has on this type of hydropower. This includes the mapping of RoR hydropower potential, the impacts of future river flow changes on

RoR hydropower and an assessment of the potential risks to RoR hydropower generation using Great Britain (due to lack of data for Northern Ireland) as a case study area. It develops a comprehensive methodology to assess the RoR hydropower potentials for various scheme sizes – pico, micro, mini, and small – across the study area. Notably, it evaluates the maximum hydrological and realisable potentials in addition to the financial and technical potentials considered in prior studies. The subsequent phase explores the impact of climate change on river flows and RoR hydropower potential in Great Britain, utilising the eFLaG future flows projections based on the latest UK climate data (UKCP18). The investigation extends further into how hydropower drought is defined and climate change implications on this phenomenon are explored, illustrated through virtual RoR schemes. This streamlined approach contributes valuable insights into RoR hydropower potentials and their susceptibility to climate-induced changes, providing a foundation for practical applications in planning and adapting hydropower schemes.

For the test region, this research identifies the total hydrological RoR hydropower potential to be 20 GW, technical potential to be 11 GW, financially viable potential to be between 320 MW to 420 MW, and the realisable potential to be between 290 MW to 320 MW. Most of the realisable schemes are found to be either mini or small (100 kW – 5 MW), situated in the west and north-west parts of Great Britain, with the largest realisable potential in the Taff Group catchment in Wales (20 MW). However, RoR hydropower potential throughout Great Britain is found to decrease in the near and far future in summer and autumn and increase in spring and winter. The increases in spring (~1.60 %) and in winter (~1.70 %) are smaller than the decreases in summer (~ -19 %) and autumn (~ -11%). Therefore, RoR hydropower plants are likely to see a decreased energy output in the future. Furthermore, the results show that hydropower drought is a phenomenon that affects RoR, with schemes experiencing summer hydropower drought events with the high frequency and severity. This analysis shows that on an annual scale, the duration of drought events is expected to increase by approximately two days across Great Britain, accompanied by a 13.5% rise in both the frequency and severity of hydropower droughts in the near future.

This thesis adds to the understanding of the RoR potential and offers a reliable estimate of the amount of RoR hydropower that can be produced alongside suitable RoR scheme locations to support next zero targets. Furthermore, the findings of this study have practical implications for the planning of new RoR schemes and adapting already operational schemes. The methodology developed here could be applied to other countries or regions with similar climatic regimes to Great Britain, such as Canada, New Zealand or France, to gain further knowledge of hydropower potential and risks. Using the same methodology over multiple regions could help create a consistent database containing RoR hydropower potential informing of potential renewable resources to help reach net zero targets.

CHAPTER 1 INTRODUCTION

1.1 Background and motivation

There is “irrefutable evidence” that the global climate is changing due to human activities (IPCC, 2021). In order to limit the effects of climate change, governments worldwide have adopted climate legislation to limit their emissions. In the UK, the Government adopted its Climate Change Act in 2008 (UK Government, 2019), which requires the UK to meet a legally binding target of 100% emission reduction by 2050 from 1990 levels. The biggest greenhouse gas emitter worldwide is the energy sector (Ritchie et al., 2020). Although, in the UK the biggest emitter is the transport sector (Department for Energy Security and Net Zero, 2024) an ambitious target of decarbonising the UK energy system by 2035 has been set (Department for Business Energy & Industrial Strategy, 2021).

Currently, over 40% of the UK’s electricity comes from renewable sources (Department for Energy Security and Net Zero, 2023a). Hydroelectricity produces 5,000 GWh of energy per year (British Hydro Association, 2022a), which accounts for approximately 2% of the national capacity (Department for Business Energy and Industrial Strategy, 2022). However, hydropower is a reliable and well-researched technology, with hydropower assets having the potential to deliver beyond the 2050 net zero target (International Hydropower Association, 2022a). Although the UK Government strategy focuses on delivering net zero and decarbonising the electricity grid mainly through wind energy (HM Government, 2021), the path to net zero is fraught with delivery risks and time challenges. To broad opportunities and supply resilience, all renewable technologies should be progressed. However, most of the large hydropower sites have been already utilised in the UK (International Hydropower Association, 2022b), so further development is likely to be limited. Nevertheless, there is renewed interest in hydropower in the UK, especially pumped storage hydropower. The Coire Glas scheme in the Scottish Highlands for example will, if installed, increase its current capacity to 1.5 GW and become a pumped hydro facility, to help improve UK energy security (BBC News, 2023).

Run of river (RoR) hydropower is a type of hydropower that could be further developed in the UK (Sammartano et al., 2019). RoR systems, which typically divert water from a river to a turbine then release it back into the river downstream, work in the same way as impoundment systems, except they do not store water (Mosier et al., 2016). Instead, RoR schemes are dependent on the natural seasonality of river flows. The benefits of RoR hydropower include smaller initial costs, shorter planning and construction times, use of smaller area, and less inundation (if any) compared to large hydropower projects (Rojanamon et al., 2009). However, changes in hydrological variables (temperature, precipitation, evaporation, etc.) in a warming climate are likely to affect hydropower production, especially RoR schemes which lack the storage capacity to buffer seasonal changes. In the summer months, electricity production could potentially decrease due to lack of precipitation and lower flows (Sample et al., 2015). In the winter months, even if the flows increase, the installed penstocks and turbines might not be able to take advantage of the higher flows (Sample et al., 2015). With renewed interest in hydropower generation (BBC News, 2023) and investment opportunities, this type of renewable source could become a part of the transition to net zero, alongside other renewable electricity sources, such as wind and solar.

RoR hydropower has been recognised as a dependable and cost-effective renewable technology for generating clean electricity (Crootof et al., 2021). A RoR hydropower scheme lacks storage (i.e., without a reservoir) and functions by directing water from a river through a weir intake. Subsequently, the water flows through a series of pipes and penstocks, ultimately driving a turbine that generates electricity. The lack of storage, however, makes RoR hydropower dependent on river flows. Until now, there have been a few major country wide studies trying to determine the potential for RoR hydropower in the UK. However, most of them have focused on either Scotland or England and Wales separately, with the latest UK-wide study undertaken over 30 years ago and the last major study in Scotland completed 10 years ago. Separately, various studies (e.g., Kay, 2021; Prudhomme et al., 2012; Watts et al., 2015) have investigated the effects of climate change on river flows across the UK. The potential influence of climate change on river flows, including seasonality and low environmental flows (Q_{95}), has been the subject of extensive research, providing valuable insights into the impacts of temperature and rainfall pattern changes on river flow. For example, Gudmundsson et al. (2021) analysed the trends in mean and extreme river flow attributed to climate change, highlighting the expected effects of anthropogenic climate change on global river flow. Additionally, research specific to Great Britain (GB) has been conducted to assess the effects of climate change, particularly global warming, on temperature, rainfall, and river flows (Kay et al., 2021a). However, a notable gap in the literature remains regarding how these changes may impact hydropower systems in the UK, in particular RoR. Existing research has predominantly focused on broad assessments of river flow alterations, overlooking the nuanced implications for hydropower generation, especially within the RoR context. Furthermore, climate change poses other risks to RoR hydropower, such as increased effects of drought and floods (J. Opperman et al., 2022). Despite their significance to RoR hydropower generation, these specific implications have not to date been thoroughly examined.

1.2 Aim of the thesis and guiding research questions

The aim of this research is to improve the understanding of RoR hydropower potential, and the possible effects climate change will have on this type of hydropower using GB as a case study. The high level objectives of this thesis – posed as five research questions (RQs) (Table 1-1) – include a detailed mapping of RoR hydropower potential, an exploration of how future changes in river flows may impact RoR hydropower and hydro electricity production, and a comprehensive assessment of drought risk to RoR hydropower generation. By mapping RoR hydropower potential, this research seeks to provide a nuanced understanding of the geographic areas with the highest capacity for harnessing this renewable electricity source. Furthermore, by examining the effects of projected changes in river flows on RoR hydropower, the research aims to unravel the intricacies of possible future climate-induced impacts. Assessing potential risks to RoR hydropower generation involves identifying vulnerabilities and uncertainties that may arise in the evolving climate scenario, contributing valuable insights for resilient infrastructure planning. This work not only contributes to the specific understanding of RoR hydropower potential and climate change impacts in GB but also provides a template for global assessments. It is intended that the outcomes and methodologies of this study may guide policymakers, researchers, and energy practitioners in multiple regions toward sustainable hydropower development amid a changing climate.

Table 1-1: Guiding research questions used in this thesis

RQ1	How can the potential for RoR hydropower be determined using the latest available data and technologies?	Addressed in Chapters 2 and 3
RQ2	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 in Chapter 4
RQ3	What are the effects of climate change on RoR hydropower schemes, including power and energy output?	Addressed in Chapter 4
RQ4	Is there a necessity to establish a distinct and standardised definition for ‘hydropower drought’ to comprehensively assess and address the specific impacts of drought on hydropower generation?	Addressed in Chapter 5
RQ5	To what extent does climate change influence the risks associated with hydropower generation, including the emergence of the condition referred to as ‘hydropower drought’?	Addressed in Chapter 5

1.3 Thesis structure

The thesis is divided into seven chapters, comprising a background review (Chapter 2), the main analysis and results are presented in Chapters 3, 4 and 5 which are written as peer-reviewed journal articles (as stated in the Statement of Co-Authorship) and therefore contain their own independent abstract, introduction, discussion, conclusions and acknowledgment sections, followed by a discussion (Chapter 6) and ending with conclusions (Chapter 7). The focus and contents of each chapter are as follows:

Chapter 2 provides an overview of how climate changes may influence water resources, leading to changes in hydropower production. It also explains why hydropower can be an important part of the UK’s electricity system and how it compares to other renewable generation types. Past hydropower assessments and the need for a novel one using the latest datasets and not skewed towards financial potential is highlighted, followed by an overview of possible future changes to RoR hydropower due to climate change and gaps in ways to measure them using GB as an example. Finally, it explains the need for defining hydropower drought and determining climate change effects on hydropower drought. By weaving together findings from various studies, this background review provides a holistic understanding of the challenges posed by shifting climatic patterns and human activities to water resources.

Chapter 3 creates a methodology to assess the hydrological, technical, financially viable and realisable potential for RoR in GB (Northern Ireland is excluded from this analysis due to lack of data for that region). This assessment is the most recent and most complete RoR hydropower assessment for GB. This chapter highlights the influence of financial viability on the RoR potential and the results show possible suitable locations for RoR schemes in areas without run of river development.

Chapter 4 determines the effects of climate change on river flows and RoR potential in GB. Using a novel future flow dataset (Hannaford et al., 2022) this chapter analyses possible changes in river flows (including annual, seasonal and low flows) in the near (2030-2059) and far future (2050-2079) from the baseline (1980-2009). It also explores how the changes in river flows may affect RoR hydropower potential in the future. The results presented in this chapter show that, in the future, run of river hydropower potential may decrease.

Chapter 5 looks at risks to hydropower production, mainly drought. It defines, for the first time, hydropower drought as a period of minimum of five consecutive days where the available power is below a certain level. Most previous studies focus on the risks of hydrological drought, which refers to reduced water availability in rivers and reservoirs due to prolonged dry periods, and its impact on hydropower production, rather than the risk of hydropower drought - a more focused term that refers to periods when hydropower schemes are unable to generate sufficient electricity.. This study fills this gap by using the novel definition for hydropower drought and four run of river (RoR) to determine how climate change affects hydropower drought characteristics (duration, frequency, severity). The chapter concludes with a comprehensive set of results, highlighting the changes in hydropower drought characteristics between the baseline and future periods. The findings contribute insights into the potential impacts of climate change on hydropower systems, informing adaptive strategies for sustainable hydropower management.

Chapter 6 further discusses the broad findings presented in Chapters 3, 4 and 5 in the context of the original research questions and proposes directions for future research.

Finally, **Chapter 7** concludes the thesis, restating the aims and results and answers the research questions posed in the Introduction.

CHAPTER 2 BACKGROUND REVIEW

2.1 Water resources and climate change

The nexus between climate change and water resources is evident, manifesting through shifts in precipitation patterns, modifications to hydrological cycles, and a surge in extreme weather events (Seneviratne et al., 2023). Recent research (Abbass et al., 2022) portrays a landscape of substantial alterations in hydrological systems attributable to climate change. A notable intensification of the global water cycle, accentuating the propensity for heightened rainfall events alongside extended periods of drought is observed (Bhaga et al., 2020; Ebi et al., 2021). The ramifications of these alterations are palpable in the escalating occurrences of extreme weather events such as floods and hurricanes, amplifying the vulnerability of water security (Mosley, 2015). Kemp et al. (2022) examines the escalating frequency of extreme weather events, unravelling their cascading repercussions on the resilience of water infrastructure and supply systems. These transformations usher in challenges concerning both the quantity and quality of available water resources. Beyond the immediate implications for water availability, climate change reverberates through ecosystems and biodiversity. Capon et al. (2021) examine the pervasive disruptions in aquatic ecosystems arising from alterations in water temperature, shifts in flow regimes, and transformations in habitat availability. Their research underscores the intricate ecological ramifications that necessitate holistic considerations in water resource management strategies. In tandem with climatic influences, anthropogenic factors emerge as pivotal contributors to the stressors imposed on water resources. Caretta et al. (2022) accentuate the substantial role played by human activities in exacerbating both water scarcity and pollution. This intersection of climate-induced changes and human-induced stressors amplifies the complexity of challenges faced in sustaining water resources.

These challenges for water resources can be observed worldwide (Tabari, 2020). Countries in Africa and Asia are particularly vulnerable to climate change impacts on water resources. Changes in rainfall patterns and increased temperatures exacerbate water scarcity issues, affecting agriculture, sanitation, and overall water security

(Trisos et al., 2022). In North and South America, climate change influences water resources differently across regions. While some areas face prolonged droughts, others experience increased rainfall and flooding (Seneviratne et al., 2023). In Europe, warming temperatures impact water resources through changes in snowmelt timing, altered river flows, and shifts in aquatic ecosystems (Lobanova et al., 2018), while the Arctic's rapid warming has implications for global sea levels and ocean circulation patterns (Rantanen et al., 2022).

The United Kingdom (UK), renowned for its historical abundance of consistent rainfall, is grappling with a transformative era of uncertainties in its water resources, primarily attributable to the effects of climate change (Climate Change Committee, 2021). This intricate interplay of climatic variables, as delineated by recent studies (Lane et al., 2022), encompassing alterations in precipitation patterns and the escalation of temperatures, poses challenges to the traditionally dependable water supply systems within the nation. Evidenced by shifts in the temporal and spatial characteristics of rainfall events and the manifestation of prolonged dry spells, the UK is contending with an augmented variability in water availability (Watts et al., 2015). Recent attribution studies underscore the severity of these challenges, citing instances of extreme weather events, including intense floods and heatwaves, which have become increasingly frequent and are indicative of the changing climate landscape in the UK (Ciavarella and Mccarthy, 2020; Vautard et al., 2020).

Climate changes in the UK are manifesting through alterations in precipitation patterns and temperatures, resulting in changes in river flows and hydrological dynamics. Based on future projections of river flows (Murphy et al., 2009), it is expected that there will be a decrease in spring and summer flows, a varying pattern in autumn, and slight increases in winter flows over the UK in the future. These changes may fluctuate by as much as ± 20%, but overall, annual flows are not expected to change significantly throughout the country (Watts et al., 2015). These changes are spatially and temporarily variable, with areas, that might see a flow reduction visible all year, especially in eastern and southern Scotland. A summary of these projected changes can be found in Table 2-1.

Table 2-1: Summary of future flow changes from peer reviewed literature. Adapted from: Boca et al. (2022)

Flow type	**Study region**	**Range of changes**	**Ref.**
Annual	Scotland	Annual run-off for the four Scottish catchments measured (Braemar, Edinburgh, Stornoway, and Dumfries) is predicted to increase by 8.9-11.6%, with the predicted increase in to be between 5-15%, locally exceeding 27%.	Werritty (2002)
	UK	There is relatively large uncertainty in projections of mean annual flow with most catchments exhibiting changes with a non-null probability ranging from -10% to +10%.	Christierson et al. (2012)
Winter	GB	Flow in Scotland show a small increase or decrease, although this is still mainly within 20% with changes in the east reaching up to 40%.	Prudhomme et al. (2012)
	GB	Maps of seasonal mean flow changes suggest increases in the north/west but possible decreases in the south/east (median change 9% and range −42% to 51% for the far-future).	Kay (2021)
	UK	Results in terms of central estimates (50^{th} percent quartile) show a marked seasonal cycle with a small increase in flows (from November to March) can be noted over the western part of the UK.	Christierson et al. (2012)
	Scotland	The changes in winter are in the range of ±20%.	Watts et al. (2015)
Spring	GB	Decreases of up to 40% in flows.	Prudhomme et al. (2012)
	Scotland	Changes in flows are typically negative but with some small positive values in the west (median −6%, range −29% to 15%).	Kay (2021)
Summer	GB	Scenarios predominantly show decreases in runoff through the UK, but range from +20% to -80%. The largest percentage decreases are mainly in the north and west of the UK although the range in these areas between scenarios can be large (0 to 80%).	Prudhomme et al. (2012)
	GB	Summer flows show large decreases across the country (median −45%, range −66% to −5%)	Kay (2021)
	UK	Results in terms of central estimates (50th percent quartile) show a marked seasonal cycle, with large reductions in summer flows. Except for the western part of the UK, in all other catchments a decrease in river flows is visible all year round.	Christierson et al. (2012)
Autumn	GB	There is a mixed pattern with a full range of percentage changes (+60 to 80%) across the UK. Most scenarios indicate decreases in flows, especially in the south and east (up to 80%), whilst in the west and north, changes can be small.	Prudhomme et al. (2012)
	GB	Changes in autumn flows are also mostly negative, particularly in the south/east (median −29%, range −59% to 22%).	Kay (2021)

2.2 Hydropower

Hydropower derives electricity from the movement of water, establishing a direct connection between hydropower generation and water resources. This relationship is fundamental to the operation and efficiency of hydropower systems. The availability and predictability of water sources are paramount for the consistent and reliable operation of hydropower plants. Seasonal variations, changes in precipitation patterns, and alterations in river flows directly impact the potential for electricity generation.

Worldwide, hydropower is the most used renewable generation type with 1,330 gigawatts (GW) installed as of 2020, comprising approximatively 16% of the total renewable electricity worldwide in 2019 (International Hydropower Association, 2022c). In the UK, hydroelectricity produces 5000 GWh of energy per year (British Hydro Association, 2022a), which accounts for approximately 2% of the national capacity (Department for Business Energy and Industrial Strategy, 2022). Out of the total installed capacity of approx. 4.6 GW in the UK, almost 500 MW is made up of run of river hydropower (Kennedy et al., 2023). However, hydroelectricity is important for the integration of other variable renewable generation sources (e.g., wind, solar) (International Hydropower Association, 2022b).

Hydropower can be a reliable, versatile and low-cost source of renewable electricity generation. With appropriate water management, hydropower with an impounding reservoir can function as a complementary resource to variable renewable sources such as wind and solar (Siri et al., 2020). Due to its rapid response capabilities, operational flexibility and energy storage potential, it can meet demand when intermittent sources are unavailable (Tarroja et al., 2019). Hydropower plants typically operate with higher capacity factors than wind farms, and in some circumstances may be more socially and environmentally acceptable (Sample et al., 2015). Pumped storage hydropower, operating like a rechargeable battery, absorbs energy when supply exceeds demand and returns energy when demanded (Jurasz et al., 2018).

2.2.1 Hydropower types

There are different types of hydropower: large hydropower, pumped storage, small hydropower, run of river, tidal and wave energy hydropower. This thesis focuses on onshore hydropower, so in the following sections only large (including pumped storage) and small hydropower are discussed.

According to British Hydro Association (2022b) large hydropower is any plant with a capacity greater than 5 MW. However, there are multiple capacity levels for large hydropower worldwide: in the US, The Department of Energy defines large hydropower as having a capacity above 30 MW; in India above 15 MW; and in China above 25 MW. Capacity is not the only criteria to assess the size of a hydropower plant. For example, size or impoundment volume are also classification conditions.

Pumped hydropower storage is another type of large hydropower which uses the force of gravity to generate electricity using water that has been previously pumped from a lower source to an upper reservoir. The water is pumped to the higher reservoir at times of low demand and low electricity prices. At times of high demand - and higher prices - the water is then released to drive a turbine in a powerhouse and supply electricity to the grid (International Hydropower Association, 2023).

Hydropower is considered small hydropower if it has a capacity of less than 5 MW (British Hydro Association, 2022b). Small hydropower is usually considered to be run of river plants, which do not usually have an artificial lake built behind a dam. Although run of river (RoR) is usually considered to be small hydropower, they are also subclassified by size in pico, micro, mini and small (British Hydro Association, 2022b), as explained in Table 2-2. As RoR hydropower schemes often serve local communities, they contribute to a decentralised electricity grid, reducing reliance on large-scale grid connectivity and associated costs (Karapici et al., 2024). In regions where RoR can meet localised electricity needs without extensive grid infrastructure it could enhance resilience and self-sufficiency (Venus et al., 2020). However, the extent to which RoR hydropower is prioritised as a political strategy depends on national energy policies, financial incentives, and regional grid stability (Burke and Stephens, 2018).

Table 2-2: Classification of small hydropower. After British Hydro Association (2022b).

Small hydropower type	**Installed power**
Pico	<5 kW
Micro	5-100 kW
Mini	100 kW – 1 MW
Small	1 – 5 MW

RoR hydropower systems employ turbines to convert the kinetic energy of flowing water into electricity, typically without the need for large reservoirs. Below are five common turbine types used in RoR hydropower systems, each suited to different operating conditions and site characteristics:

- Francis Turbine: A reaction turbine suitable for medium to high heads and a wide range of flows, efficient for large-scale applications.
- Kaplan Turbine: A reaction turbine ideal for low heads and high flows, with adjustable blades for optimised performance under varying conditions.
- Pelton Turbine: An impulse turbine designed for high-head, low-flow scenarios, often used in mountainous areas.
- Cross-Flow Turbine: A versatile option for low to medium heads, particularly effective for small-scale installations.
- Archimedean Screw: A low-head, environmentally friendly turbine, excellent for sensitive areas and small-scale community projects.

2.3 Hydropower and sustainability

Sustainability is a key consideration in the development of renewable generation systems, encompassing three interconnected pillars: environmental, societal, and economic. These pillars, often referred to as "people, planet, and profit," are critical in assessing the long-term viability of any hydropower project (Correia, 2018). The environmental pillar focuses on the ecological impacts of hydropower, such as effects on river ecosystems, greenhouse gas emissions over the life cycle, and the project's overall contribution to reducing carbon emissions. The societal pillar covers the social aspects of sustainability, including the acceptability of hydropower projects within local communities, potential impacts on livelihoods, and how hydropower can contribute to broader societal goals, such as improving energy access. Finally, the economic pillar relates to the financial sustainability of hydropower projects, including the costs of development, operation, and maintenance, and how these projects contribute to energy security and overall economic resilience.

The sustainability of hydropower is examined in the following section by discussing the environmental impacts and life cycle emissions (environmental pillar – Sections 2.3.1 and 2.3.2), social acceptability (societal pillar – Section 2.3.5), project costs (economic pillar – Section 2.3.4), and energy security (which spans all three pillars – Section 2.3.3).

2.3.1 Environmental impact

Many of the renewable generation sources have a range of environmental impacts related to habitat change, which depend on site characteristics and the implementation of the technology (Intergovernmental Panel on Climate Change, 2014). Potential hydropower environmental impacts include the discontinuation of river flows and obstruction of fish passage (Abbasi and Abbasi, 2011; Agostinho et al., 2002; Lenzen, 2010; Neachell, 2014). This contrasts with onshore wind where distinctive environmental impacts are mechanical and aerodynamic noise that can affect sleep and cause headaches (Leung and Yang, 2012). Bioenergy generation presents a risk to the biodiversity of crops (Firbank, 2008), and solar PV panels can pose a health risk from their manufacture, use and disposal (Tsoutsos et al., 2005).

The largest environmental impact of large hydropower plants is the flooding of large areas in order to accumulate a massive volume of water behind the dam (Lenzen, 2010). Another problem arising from the construction of dams is thermal pollution, which is the change in temperature of lakes, rivers or oceans by man-made structures (A. Bobat, 2015). This is because the natural river flow is interrupted by the dam, fish can’t migrate upstream to lay their eggs, thus affecting their population. In order to mitigate this negative effect, fish ladders have been added to dam structures but with little efficiency (Agostinho et al., 2002).

The environmental impacts of small hydro, such as RoR, are lesser than those of large hydropower sites. The greatest problem is the discontinuation of flow; if the minimal flow is not assured or there are cascading small hydropower plants, downstream of the plant can be affected, so it is necessary to assure a minimal flow downstream (Pang et al., 2015). Small hydro and run of river sites use very little land (Pang et al., 2015) making their impact smaller than those of large hydropower schemes.

Assessing environmental impacts for each renewable generation source, incorporating all stages of its lifecycle per kWh produced, shows hydropower to have a low environmental impact, with RoR hydropower having the lowest overall environmental impact (Kouloumpis et al., 2015) of all renewable electricity types. This is consistent with other studies (Atilgan and Azapagic, 2016; Siddiqui and Dincer, 2017) which show that the overall environmental impacts of hydropower are the lowest compared to other renewable energy sources.

2.3.2 CO_2 emissions

CO_2 emissions per kWh produced have been assessed as carbon dioxide represents the most harmful emission. Other emissions, such as SO_2 (Sulphur Dioxide), NO_x (Nitrogen Oxides) or CH_4 (Methane), are in lower quantities compared to CO_2 (Ritchie et al., 2020). CO_2 lifecycle emission estimates from Amponsah et al. (2014); Edenhofer et al. (2011); Moomaw et al. (2011); Turconi et al. (2013) are shown in Figure 2-1, based on the 50th percentile values of emissions (the 50th percentile offers the most reasonable estimate given the wide range of site-specific CO_2 releases). One of the smallest emissions of CO_2 come from hydropower. However, Edenhofer et al. (2011) argue that hydropower reservoirs emit a considerable amount of methane but in most tropical areas, as CH_4 emissions are temperature dependent. Nonetheless, in most sites in temperate and colder climates, such as Europe, those emissions are small (Moomaw et al., 2011).

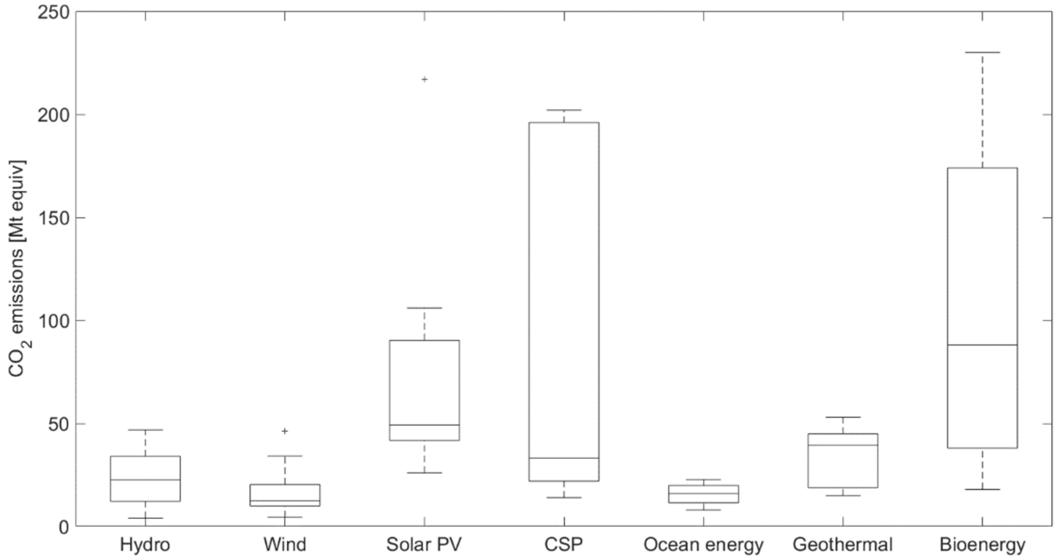

Figure 2-1: Box plot of median lifecycle CO_2 emissions from renewable generation sources. Data taken from (Amponsah et al., 2014; Edenhofer et al., 2011; Moomaw et al., 2011; Turconi et al., 2013)*. Each box represents the interquartile range (from 25th percentile to 75th percentile) and the line inside the box signifies the median value. The whiskers extend towards the maximum and minimum values and the points outside those are outliers. The smallest median lifecycle emissions come from wind energy. Solar PV refers to solar photovoltaic; CSP refers to concentrated solar power; Ocean energy refers to wave and tidal energy sources.*

2.3.3 Energy security

Although the environmental benefits of renewables are widely understood, their contribution to energy security, especially in the longer term (since their "fuel" is non-depleting), is not as well recognised (Ölz et al., 2007). For example, in the UK, energy security policy ensures customers can access the energy they need at prices that are not excessively volatile (Department of Energy and Climate Change, 2010), which means energy supply must meet energy demand. If a sudden increase in demand appears, supply from dispatchable renewable generation sources such as stored hydro, biomass or geothermal can assure the UK's electricity reserve. For the power grid to function, electricity transmission needs an operational frequency of 50 Hz, with fluctuations as small as 1% being able to damage equipment and infrastructure (Drax, 2018). UK frequency management is already provided by large hydropower (including pumped storage), bioenergy and partially by wind and solar energy. In addition to frequency management, the transition between a power plant turning off and another coming online needs to be managed smoothly to ensure grid inertia. The ability of a power plant to start without any additional electricity is termed black start and this can only be achieved by spinning hydropower, bioenergy, and geothermal energy source turbines; the other renewable technologies cannot provide that service without additional energy input first.

The UK's grid energy market already has a high proportion of wind and solar energy sources, energy storage will therefore play a critical role in further variable renewable energy penetration into the power grid (Zafirakis, 2010). The need for additional UK energy storage was further highlighted during the first COVID-19 lockdown, when wind farms were forced to shut down due to decreased demand. Pumped storage is already the cheapest energy storage technology in the world in terms of cost per installed kilowatt-hour of capacity (Green Tech Media, 2020). This provides an opportunity for increased investment in mature pumped storage hydropower which can act as a rechargeable battery. This is reflected in the planned construction of the Coire Glas pumped storage scheme in Scotland (BBC News, 2023).

Considering all renewable sources, large hydropower and bioenergy are best suited to provide grid energy security. Large hydropower is an ideal complement to variable renewables like wind and solar due to its flexibility and energy storage services. Large hydropower can also provide ancillary services, such as dispatchability, energy storage, frequency management, grid inertia and black start ability of other renewable types, providing additional energy security to the power grid. For bioenergy, however, fuel supply chains were interrupted during COVID-19 lockdowns (International Energy Agency, 2020) decreasing biofuel's potential somewhat. Nonetheless, a combination of renewable generation sources can provide a robust and resilient energy supply system.

2.3.4 Affordability

Large hydropower and hydropower plants in general are characterised by a high initial installation cost, but low operational and maintenance costs and no fuel cost. Small hydropower plants have a lower initial cost, but a higher price per installed kW due to the economies of scale. Initial cost is estimated to be between 500.22-3751.65 £/kW (International Renewable Energy Agency, 2021) in the last 10 years with the average cost in 2021 of 1667.4 £/kWh for small hydropower plants. The operational and maintenance (O&M) cost is approximatively 2% of the initial cost/kW/year. For large hydropower the LCOE (levelised cost of electricity) in 2021 was £0.040/kWh worldwide, lower than newly commissioned fossil fuel plants (International Renewable Energy Agency, 2021).

Another aspect to consider is the power plant's capacity factor which is the ratio between actual electricity output over the maximum possible electricity output if the plant were running 24/7. The bigger the capacity factor, the more electricity that installation is producing. Usually, capacity factors are measured per year. Between 2010 and 2021, the global weighted average capacity factor of newly commissioned hydropower projects (both large and small) of all sizes increased from 44% to 45% (International Renewable Energy Agency, 2021).

To assess affordability of renewable technology, four costs are usually examined: initial capital cost, fuel costs (valid only for bioenergy), operational and maintenance costs (O&M) and the levelised cost of electricity (LCOE). LCOE is the average cost for electricity generation over a power plant's lifetime, representing the mean revenue needed to recover the initial, operational, maintenance and fuel costs. Figure 2-2 shows that even though hydropower has higher initial capital cost and moderate O&M costs, it had the lowest LCOE in 2021, making it an affordable renewable source and a possible part of the UK's net zero portfolio However, a caveat of the using past costs to assess affordability is that they may change in the future. It is also important to note that although CSP (concentrated solar power) was presented in Figure 2-2, it is less effective in regions with lower solar irradiance, such as the UK (Calderón et al., 2021).

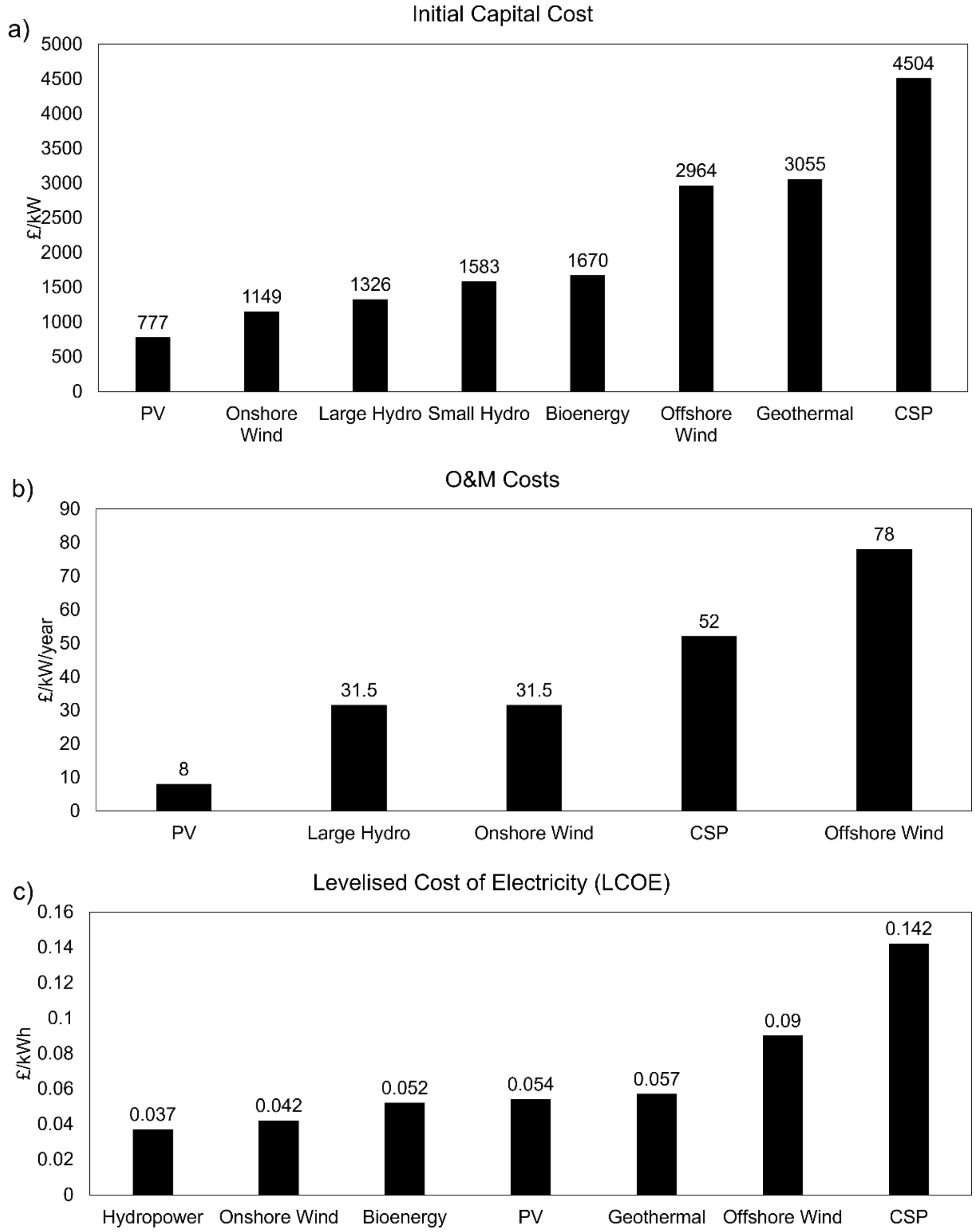

Figure 2-2: a) Initial cost of electricity from renewable generation sources in increasing order (left to right); b) Operation and maintenance cost for renewable generation sources in increasing order (left to right); and c) Levelised cost of electricity (LCOE) for renewable generation sources in increasing order (left to right). Since data was not available for all renewable sources, only the available information was presented. All prices are estimates for 2021 taken from International Renewable Energy Agency

(2021) *and converted from USD to £ using the current exchange rate.. PV refers to photovoltaic solar power; CSP refers to concentrated solar power.*

2.3.5 Social acceptance

No matter how affordable, environmentally friendly, carbon neutral or secure a renewable generation source is, it must be acceptable. Public attitudes towards social acceptance can be influenced by a range of factors, including: awareness of climate change, knowledge of the renewable technology, fairness of the decision-making process, overall evaluation of costs, risks and benefits of the technology, local context and trust in decision makers and other relevant stakeholders (Hofman et al., 2014). While most elements that influence public attitudes are difficult to quantify, technology risks and benefits can be evaluated based on the safety record of each generation source. Social acceptance risks of renewable sources were reviewed by comparing the safety of each generation type considering accidents and air pollution. Based on the yearly UK electricity production (285.16 TWh in 2019), it would take more than 11 years for one death to occur from hydropower related accident (0.024 deaths/kWh), up to five years for solar PV (0.019 deaths/kWh), only six months for wind (0.035 deaths/kWh) and a death would occur every four days for biomass (4.63 deaths/kWh, including air pollution) (Sovacool et al., 2016).

2.4 Hydropower assessments

Considering the rising concern for fossil fuel emissions, including more renewable generation sources in the electricity mix is important. However, renewable generation sources, such as hydropower and climate change are closely related: hydropower mitigates the effects of climate change by decreasing the GHG emissions and climate change affects hydropower generation by altering the hydrological cycle (Mutsindikwa et al., 2021). Hydropower schemes with a reservoir have the capacity to cope with climate variability due to the ability to store water. On the other hand, hydropower plants which do not have an impoundment, like run of river RoR, are more vulnerable to climate change (Michels-Brito et al., 2021). To assess the effects and risks climate change has on RoR hydropower potential (RQ 1), firstly, the potential must be assessed.

The assessment of RoR hydropower potential in a region is usually determined by analysing the geography and hydrology. Conventionally, assessments have been carried out by performing labour intensive analysis of maps to identify areas with high annual precipitation which could be suitable to produce hydroelectricity and steep slopes to provide sufficient head. The term ‘head’, also known as ‘hydrological head’ refers to the height difference between the water source (such as a river or reservoir) and the point where the water flows through a turbine in a hydropower system. This height difference creates potential energy, which is converted into kinetic energy as the water moves downhill. The greater the hydrological head, the more energy is available to generate electricity, as the water has more gravitational force acting on it. After the initial desk study, the potential sites would be further investigated and visited. However, developments in the availability of geospatial or remote sensing data have enabled an automated, less labour intensive and higher resolution hydropower resource assessment which permits a more complex analysis, including financial, environmental impact, sustainability, and social impact data.

Locating a feasible RoR hydropower scheme involves many unknowns, which increase the level of complexity of such a task. The lack of direct observations of head and flows challenges a realistic assessment, especially at national scale (Pasha et al., 2014). However, rapid development of geospatial datasets for topography, river network and flow characteristics is making the assessment of hydropower locations more accessible.

RoR hydropower potential at a global scale has been assessed using different methods and different types of potential (gross, technical, economical, exploitable, etc.). Gross potential represents the theoretical maximum power that could be generated from available water flows and elevation, assuming ideal conditions with no technical, environmental, or economic constraints. From this, technical potential narrows the scope to what could realistically be harnessed using existing technology, while still disregarding economic or environmental limitations. Economic potential further refines this by identifying sites where power generation is financially viable, factoring in costs, discount rates, and market conditions. Finally, exploitable potential considers all limitations, including environmental and regulatory restrictions, to identify the power generation that is both technically and economically feasible and also permissible under current policies.

Hoes et al. (2017) and van Vliet et al. (2016) used a systematic approach to determine the gross RoR hydropower potential across the world. Hoes et al. (2017) calculated the potential per capita in the UK at less than 3300 kWh/year/person. Zhou et al. (2015) determined the global hydropower potential using streamflows from 1970-2000 and assessed the theoretical, technical, economic and exploitable potential. Although their study presents a more complete methodology, some of their assumptions and limitations include the consideration for the use of only modern equipment for the technical and economic assessments which may not be realistic worldwide and the inclusion of smaller hydropower sites which may not be feasible, leading to a higher hydropower potential compared to other studies. They estimate that the UK has an exploitable potential of 9 TWh per year (~315 kWh/year/person). While these large-scale studies cover a large surface, their results are less relevant at country or sub-regional level because their inputs are usually at a coarse resolution and do not capture local streamflows and terrain elevations.

Various studies (e.g., Bergström and Malmros, 2005; Dhaubanjar et al., 2021) have used Geographical Information Systems (GIS), merit-based matrices and other tools to assess RoR hydropower potential in several regions of the world. Some interesting methods include the consideration of social impacts of RoR hydropower development (Rojanamon et al., 2009) or determining the sustainable RoR hydropower potential (Dhaubanjar et al., 2021). Merit-based approached (Pasha et al., 2014) consider flow, head and flooded area with different weightings to determine the best locations for RoR hydropower. While these studies have very detailed methodologies, they have been developed for smaller regions and their methods are mostly only applicable to that region. The exception is Mosier et al. (2016) study which has worldwide applicability, but for small regions, not larger areas, such as countries.

There have been four major studies (Duncan, 2012; Forrest, 2008; Salford Civil Engineering, 1989; The Department of Energy & Climate Change, 2010) with published methodologies carried out in various regions of the UK in the last 35 years, which claimed different numbers for the UK's technically and financially feasible RoR hydropower potential. The methodologies, assumptions and limitation of these studies are explained in detail in Chapter 3. The limitations of previous studies and lack of an UK-wide (or GB-wide) study using the latest available data and a high resolution dataset suggest the need for an updated assessment of the RoR hydropower potential in the UK (or GB). Additionally, integrating the strengths of the previous studies' methods into a single, consistent methodology can support the identification of a sensible hydropower potential, not skewed towards specific sizes or dominated by financial considerations.

2.5 Hydropower and climate change

Global observations (Jackson and Gunda, 2021; Pokhrel et al., 2018) indicate significant changes in the potential of RoR hydropower, reflecting the dynamic interplay between water availability and climatic shifts. The evolving landscape of precipitation patterns, alterations in river flows, and the frequency of extreme weather events contribute to variations in the feasibility and efficiency of RoR hydropower systems, which depend on a consistent and predictable flow of water. The observed shifts in river flows can affect the overall electricity output and reliability of RoR hydropower installations (Casale et al., 2020; Duratorre et al., 2020). Recent research (Carvajal et al., 2017; Casale et al., 2020) contributes valuable insights into the complex interactions between climate-induced hydrological variations and the performance of run-of-river hydropower schemes. These observed changes emphasise the need for a comprehensive understanding of the evolving conditions impacting RoR hydropower potential. Furthermore, climate change introduces additional risks to hydropower, such as droughts and floods (Opperman et al., 2022). Understanding these impacts and risks is crucial for effective planning and operation of run-of-river hydropower systems.

Carless and Whitehead (2013) and Dallison et al. (2021) studied the potential impacts of climate change on RoR hydropower generation at various locations in Wales. They determined changes in monthly electricity output and changes in annual trends in number of days with the minimum abstraction volume required to start and the maximum permitted abstraction volume achieved for the future periods from the baseline. Another study in Europe (Duratorre et al., 2020) determined the changes in projected mean monthly volumes of energy, discharge and snow melt in the future from the baseline in the Italian Alps.

While there are various studies looking at how these changes affect RoR hydropower at catchment or smaller scale (e.g., Bocchiola et al., 2020; Carless and Whitehead, 2013; Carvajal et al., 2017; Casale et al., 2020), there is a gap in the literature of studies at a regional/country level, especially in the UK. Furthermore, most studies (e.g., Bocchiola et al., 2020; Casale et al., 2020; Duratorre et al., 2020) determine changes in annual generation, without considering seasonal changes. A comprehensive review of previous studies looking at the impact of climate change on RoR hydropower is presented in Chapter 4.

2.5.1 Risks for hydropower production

Extreme weather events, including floods and droughts, have become more frequent and intense (Seneviratne et al., 2023), introducing additional challenges to RoR hydropower projects. Floods can lead to excess sedimentation and physical damage to infrastructure, while droughts reduce the available water for electricity generation, both compromising the overall efficiency and sustainability RoR systems. For example, RoR is identified in Scotland as a vulnerable sector to water scarcity (Visser-Quinn et al., 2021).

The most common risks related to RoR operation are related to periods of low flows or droughts. In RoR hydropower, lower than average precipitation, river flow or snowmelt can immediately reduce the outflow through turbines and thus decreases hydropower output. Drought risks pose a critical challenge to hydropower production, as water scarcity directly impacts the availability and reliability of water resources for electricity generation. Despite the significant consequences of droughts on hydropower (J. Opperman et al., 2022), there is currently no standardised definition for "hydropower drought," indicating a noteworthy gap in the existing literature. This absence of a clear conceptualisation hinders comprehensive assessments of how drought specifically affects hydropower generation. Furthermore, the interaction between hydropower drought and climate change remains a relatively unexplored area in research. While various studies (Gudmundsson et al., 2021; Kay et al., 2021b) have investigated the impacts of climate change on overall river flows and hydrological systems, there is a notable dearth of research focusing on how climate-induced changes specifically influence hydropower drought events. The absence of studies addressing this underscore the need of research in this domain, as climate change continues to exacerbate the frequency and severity of droughts globally.

2.6 Summary

The intricate relationship between climate change and water resources is evident globally, marked by shifts in precipitation patterns, alterations to hydrological cycles, and an increase in extreme weather events. Recent research (Tabari, 2020) highlights changes in hydrological systems attributable to climate change, intensifying the global water cycle and resulting in heightened rainfall events and extended periods of drought.

Hydropower, as a renewable generation source, relies on harnessing the movement of water, establishing a crucial link between hydropower and water resources. This association is vital for the operational efficiency of hydropower systems, where the predictability and availability of water sources are paramount. The relationship between hydropower and climate change involves a two-way interaction: hydropower mitigates climate change effects by reducing greenhouse gas emissions, while climate change impacts hydropower generation through alterations in the hydrological cycle. Reservoir-based hydropower schemes can handle climate variability by storing water, whereas RoR plants without impoundments are more vulnerable to climate change. Assessing the potential of RoR hydropower is crucial for understanding its viability and susceptibility to climate change, providing essential insights for sustainable planning and resource management. Large-scale global assessments have been carried out, but their results may not be relevant at the country or sub-regional level due to their coarse resolution. In the UK, for example, several studies with different methodologies have been carried out, but an updated assessment using the latest available data is needed for informed decision-making.

Future changes to RoR hydropower potential are anticipated to be influenced by ongoing climate shifts, marked by alterations in precipitation patterns, river flows, and an increase in extreme weather events. Global observations (Jackson and Gunda, 2021; Pokhrel et al., 2018) suggest that the dynamic interplay between water availability and climatic variations will continue to impact the feasibility and efficiency of RoR hydropower systems. However, there is a lack of specific, detailed studies on the UK that comprehensively investigate and provide a nuanced understanding of how ongoing climate shifts will influence future changes RoR hydropower potential.

Finally, this Chapter highlights drought risks associated with RoR hydropower generation and the need for a hydropower drought definition assessing how drought specifically affects RoR hydropower generation. The lack of a clear definition hinders exploration of the interaction between hydropower drought and climate change, highlighting a noteworthy gap in the existing literature and underscoring the need for focused research in this domain as climate change intensifies the frequency and severity of droughts globally (Haile et al., 2020). The following chapters will therefore aim at filling these gaps, with a focus on understanding where and how much the RoR potential is in the UK (Chapter 3) and how climate change is likely to affect this potential (Chapter 4). Furthermore, Chapter 5 proposes a novel definition for hydropower drought and determines the climate change impacts on hydropower drought. Each chapter also includes a detailed background review in the introduction section to highlight the existing literature relevant for the respective chapter.

CHAPTER 3 AN ASSESSMENT OF RUN OF RIVER HYDROPOWER POTENTIAL IN GREAT BRITAIN

3.1 Preface

This chapter (excluding this preface) has been published in the Proceedings of the ICE – Water Management journal. Numberings of chapters and figures have been adapted for consistency of the overall thesis, and the references have been compiled at the end of the thesis.

Corresponding publication: Golgojan, A.D., White, C.J., Bertram, D., 2024. An assessment of run of river hydropower potential in Great Britain. Proc. Inst. Civ. Eng. - Water Manag. 178, 42–61

Corresponding DOI: https://doi.org/10.1680/jwama.23.00056

Corresponding dataset: Golgojan, A. (Creator), White, C. (Supervisor) (2 May 2023). An assessment of run of river hydropower potential in Great Britain. University of Strathclyde. Data_Repository(.zip).DOI: 10.15129/95db013c-d082-4aa9-a8ce-43b60568087d

Corresponding code: https://github.com/DianaGolgojan/Assessment-of-RoR-hydropower.git.

This chapter directly addresses the following research question (posed in Chapter 1.2 – Table 1-1):

RQ 1. How can the potential for RoR hydropower be determined using the latest available data and technologies?

The aim of this chapter is mapping potential RoR hydropower locations across GB using the latest available data, creating a comprehensive dataset of hydrological, technical, financially viable and realisable RoR hydropower potential. The findings presented here serve as a crucial foundation for the subsequent analyses conducted in Chapters 4 and 5, where an exploration of the impacts of climate change on RoR hydropower schemes will be undertaken.

The methodology in this chapter was implemented using MATLAB, with custom code developed for each stage of the analysis. First, new code was written to calculate the maximum power output for each river section, defined as the hydrological potential. Next, additional code was developed to incorporate technical constraints, such as available pipe diameters and potential turbine configurations, refining the analysis to determine the technical potential. Subsequently, code was implemented to calculate the cost and net present value (NPV) for each technically viable scheme, identifying the financial feasibility of each option. Finally, the realisable potential was determined by overlaying financially viable schemes onto a map of environmentally protected areas, excluding schemes located within protected zones from the final analysis. The later was performed using ArcGIS software. All the newly developed code can be found here: https://github.com/DianaGolgojan/Assessment-of-RoR-hydropower.git .

3.2 Abstract

In the UK, hydropower produces 1.65 GW of energy, only 2% of the national capacity. With most large-scale storage-based hydropower potential sites already utilised in the UK, further development is minimal due to financial, environmental and construction time concerns. However, run of river (RoR) is a type of hydropower that has the potential to be further developed. While there are studies that estimate different ranges of RoR hydropower potential, the last UK-wide study was undertaken in 1989, which makes it outdated. In this study, we create a methodological framework to assess the potential of RoR hydropower in GB. This study determines the hydrological, technical, financial and realisable potentials for pico, micro, mini and small RoR hydropower. The results show that the total hydrological potential is 20 GW, technical potential is 11 GW, financially viable potential is between 320 MW to 420 MW, the realisable potential is between 290 MW to 320 MW. Most of the realisable schemes are either mini or small, situated in the west and north-west parts of GB. This study adds to the understanding of the RoR potential in GB and offers a

reliable estimate of RoR hydropower that can be produced alongside suitable RoR scheme locations.

Keywords chosen from ICE Publishing list:

Hydrology & water resource, Renewable energy

3.3 Introduction

Hydropower is the most used renewable energy type globally with 1,330 gigawatts (GW) installed as of 2020, comprising approximatively 16% of the total renewable electricity worldwide in 2019 (International Hydropower Association, 2022c). In the UK, installed hydropower capacity is 1.65 GW of energy (British Hydro Association, 2022a), which accounts for approximately 2% of the national capacity (Department for Business Energy and Industrial Strategy, 2022). However, hydropower with impoundment is an ideal complement to variable renewables like wind and solar due to its flexibility and energy storage services. Hydropower with impoundment can also provide ancillary services, such as dispatchability, energy storage, frequency management, grid inertia and black start ability of other renewable types, providing additional energy security to the UK's power grid (International Hydropower Association, 2022b). For example, pumped hydro storage like the Coire Glas scheme (SSE Renewables, 2023) could smooth the transition from oil, gas and coal to intermittent sources of energy like wind and solar.

The UK has committed to decarbonising its electricity system by 2035 (Department for Business Energy & Industrial Strategy, 2021). Department for Energy Security and Net Zero (2023) accepted that hydropower would be critical to delivering greater energy security and independence, economic growth, and the UK's net zero ambitions. However, the CCC (2023) recognises that the current pace of delivery and deployment of renewable generation and infrastructure may not be enough to meet the 2035 target. They recommend easing the planning and regulatory regimes, so that energy infrastructure can be built at the necessary speed. Large hydropower or pumped hydro storage schemes, like Coire Glas, take a long time (5-6 years) to build, mainly because of the complicated and extensive civil works (BBC News, 2023).

Additionally, large hydropower schemes usually require flooding of a large areas in order to accumulate massive volumes of water behind a dam (Lenzen, 2010), which can cause negative environmental impacts (Agostinho et al., 2002; Alaeddin Bobat, 2015; Chaudhari and Pokhrel, 2022). Furthermore, most of the large hydropower developments in the UK have already been constructed (Sample et al., 2015).

Another type of hydropower that has a lesser environmental impact and a shorter construction time compared to large hydropower or pumped storage hydro is small hydropower. The environmental impacts of small hydro are lesser than those of large hydropower sites, but it cannot be used to store energy and it cannot complement other variable renewable sources as well as impoundment hydropower. Common impacts include water depletion, water quality degradation, loss of connectivity, habitat degradation, and changes to biota communities (Kuriqi et al., 2021). The greatest impact is the discontinuation of flow; if the minimal flow is not assured or there are cascading small hydropower plants, downstream of the scheme can be affected, so it is necessary to assure a minimal flow downstream (Pang et al., 2015),also known as environmental flow. Furthermore, (Kuriqi et al., 2019) demonstrate a pronounced reliance of small hydropower generation on the prescribed environmental flow releases.

Small hydropower is usually considered to be run of river (RoR) schemes. They divert water from a river to a turbine and then release it back into the river downstream. RoR systems work in the same way as large hydropower schemes, except they lack the ability to store water and are therefore dependent on the natural seasonality of flow (Mosier et al., 2016). RoR systems can be classified by installed capacity in pico (less than 5 kW), micro (between 5 kW and 100 kW), mini (between 100 kW and 1MW), and lastly, small (between 1 MW and 5 MW) (British Hydro Association, 2022b). The benefits of RoR systems include smaller initial investments, shorter planning and construction times, less inundated area (if any) compared to large hydropower, and the use of local labour and materials (Rojanamon et al., 2009). Considering its advantages over large hydropower and the CCC’s recommendation for fast renewables development, RoR hydropower could be developed in the UK to meet the net zero target as part of a portfolio of different renewable generation sources.

Selecting the location and assessing the feasibility of a RoR scheme is a complex task. Historically, the lack of direct observations of head and flows meant obtaining a realistic assessment of hydropower potential was challenging, especially at the national scale (Pasha et al., 2014). However, recent developments in the availability of geospatial and remote sensing data (e.g., Copernicus (2016) could enable high-resolution hydropower resource assessments than have previously not been possible. Such assessments offer the possibility of increasingly complex hydropower analyses, incorporating assessments of financial feasibility, environmental impact, sustainability, and social impacts.

Hydropower potential at a global scale has been assessed using different methods and different types of potential (gross, technical, economical, exploitable, etc.). Hoes et al. (2017) and (Zhou et al., 2015) used a systematic approach to determine the gross hydropower potential across the world. Hoes et al. (2017) calculated the theoretical potential per capita in the UK at less than 3300 kWh/year/person. Zhou et al. (2015) determined the global hydropower potential using streamflows from 1970-2000 and assessed the theoretical, technical, economic and exploitable potential. Although their study presents a complete methodology, some of their assumptions and limitations include the consideration for the use of only modern equipment for the technical and economic assessments which may not be realistic worldwide and the inclusion of smaller hydropower sites which may not be feasible, leading to a higher hydropower potential compared to other studies. They estimate that the UK has an exploitable potential of 9 TWh per year (~138 kWh/year/person). While these global-scale studies cover a large surface, their results are less relevant at country or sub-regional level because their inputs are usually at a coarse resolution and do not capture local streamflows and terrain elevations.

On a smaller scale, various studies (e.g., Garegnani et al., 2018; Pasha et al., 2014; Sammartano et al., 2019) have used Geographical Information Systems (GIS), merit-based matrices and other tools to assess hydropower potential in several regions of the world. Merit-based approaches (Pasha et al., 2014) consider flow, head and flooded area with different weightings to determine the best locations for run of river hydropower. Sammartano et al. (2019), Garegnani et al. (2018) and Zaidi and Khan

(2018) developed a GIS-based procedure to determine potential locations for run of river schemes in various locations (the Taw at Umberleigh river basin in southwest England, the Gesso and Vermenagna valleys in the Alps, Kunhar River in Pakistan) showing the versatility of using GIS-based approaches. However, the selection algorithm employed by Zaidi and Khan (2018) is not rooted in an optimisation framework, which may limit the accuracy of the estimated maximum hydropower potential. Although these studies present detailed methodologies, they are tailored for small regions and catchments and do not address the context of country-wide assessments.

There have been few studies in the last 35 years that have estimated the RoR hydropower capacity of the UK for the remaining financially and technically feasible water resource. The earliest – and still, to date, the only known UK-wide study – is Salford Civil Engineering (1989).This study estimated the RoR hydropower potential to be 322.3 MW in the 25 kW to 5 MW range in the UK. This study used a general approach of regression equations, evapotranspiration maps and annual average rainfall estimates to calculate the mean annual flow for England and Wales. For Scotland and Northern Ireland, a desk study approach was used. While providing an indicative RoR estimate for the UK, this approach meant the results have not been validated. The Department of Energy & Climate Change (2010) updated the 1989 study by considering current (for 2010) financial and technical constraints for England and Wales. The study identifying 1692 sites with a RoR potential of between 146,280 and 248,400 kW, which is a notable increase from the 36.3 MW from the Salford Civil Engineering study. In a separate study, Forrest (2008) used a GIS approach to interrogate flow and elevation data at points along a river network in Scotland using a Digital Elevation Model (DEM). The approached analysed a range of factors that affected energy production and found the most sensitive factors to be discount rate and electricity sales revenue. This study found 36,252 technically feasible sites with a RoR hydropower potential of 2.6 GW. From these, 1,019 schemes (657 MW) were also deemed to be financially feasible considering an 8% discount rate. However, key details such as the development of flow duration curves (FDCs from each gauging station are assumed to have been scaled based upon catchment area and to provide estimates of flow at points on the river network), limits the usability of this study. More recently, Duncan (2012) identified financially viable schemes across Scotland considering the feed-in-tariff and different discount rates. The scope and usability of this study is now limited as it only considered schemes that were financially viable without calculating the hydrological, technical, and realisable potential, and considered a feed-in-tariff that is no longer used (Ofgem, 2019).

The limitations and age of previous studies, the renewed interest in renewables development in the UK and lack of a UK-wide study using the latest available data highlight the need for an updated assessment of the RoR hydropower potential in the UK. Integrating the various approaches from the previous studies into a single, consistent methodology can be used to support the identification of a sensible hydropower potential. In this study, we create a methodological framework to determine the RoR hydropower potentials for pico, micro, mini and small schemes across Great Britain (GB). Northern Ireland is omitted due to a lack of river flow data. The study's main objectives are validating simulated flow data against observed river flows, generating points along the river network containing information about flow, elevation, etc., and calculating hydropower potential across various RoR sizes, classified by hydrological, technical, financial viability, and realisable potentials.

For the first time, the maximum hydrological and realisable potentials (Figure 3-1) for RoR hydropower are assessed in addition to the financial and technical potentials that previous studies have evaluated for GB, providing a holistic view of the hydropower landscape. This inclusive approach ensures that the assessment is not solely reliant on economic factors but also considers environmental and social implications, thus presenting a more balanced perspective on the feasibility and sustainability of RoR hydropower projects. Moreover, this research addresses a crucial gap in the existing literature by providing a comprehensive and up-to-date picture of the size and spatial distribution of RoR hydropower potential in GB. The significance of this study lies not only in its role in addressing the current gaps in knowledge but also in its practical implications for supporting the sustainable development of small hydropower to meet the UK's net-zero targets through practical and feasible policy recommendations.

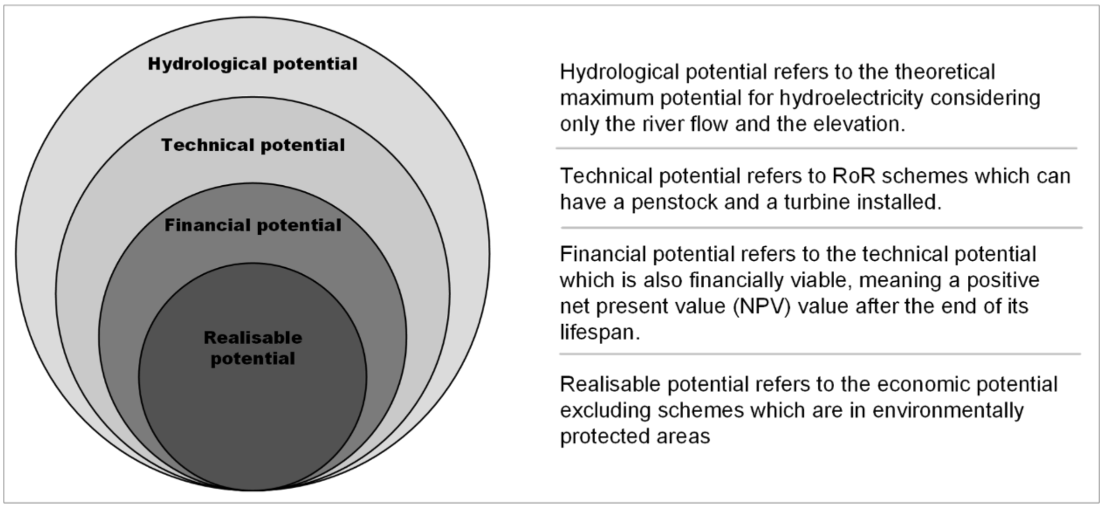

Figure 3-1: Hydropower potential classes details. The hierarchical relationship within the hydropower potential categories is structured such that hydrological potential encompasses technical potential, technical potential encompasses financial potential, and financial potential encompasses realisable potential.

3.4 Methods

In this original research paper, a methodological framework containing the workflow steps was created to determine the RoR hydropower potential (Figure 3-2), offering a comprehensive evaluation that extends beyond conventional technical and financial considerations. An overview of the key steps taken in the methodology is presented below:

1. Validation of Simulated Flows:
    - Simulated flows for gauged catchments in Great Britain were obtained from the UK Centre for Ecology and Hydrology's MaRIUS project, using the G2G hydrological model.
    - The simulated flows were validated against observed flows at 1498 gauged locations across GB, using the National River Flow Archive dataset.
    - The coefficient of determination (R^2) was calculated for various flow percentiles and flow statistics to assess the accuracy of the simulated flows.
2. Generating Analysis Points:

- Input data, including a Digital Elevation Model (DEM), a vectorized river network of GB, and monthly flow data, were processed in ArcGIS.
- A Python script generated points along the river network at 25 m intervals, capturing information such as river segment ID, percentile flow, coordinates, and elevation.

3. Hydropower Potential Calculation:
    - The study analysed the maximum available potential run-of-river hydropower resource in GB, categorising it into pico, micro, mini, and small RoR hydro.
    - Hydrological potential was calculated by considering the available power at each river segment, factoring in flow, head, and turbine efficiency.
    - Technical potential was refined by considering factors like penstock diameter, turbine type, and other technical limitations.
    - Financial potential was assessed by calculating the costs and net present value of each technically viable RoR scheme.
    - Realisable Potential: Schemes located in environmentally protected areas identified from Natura 2000 maps were excluded from the realisable potential, considering environmental constraints.

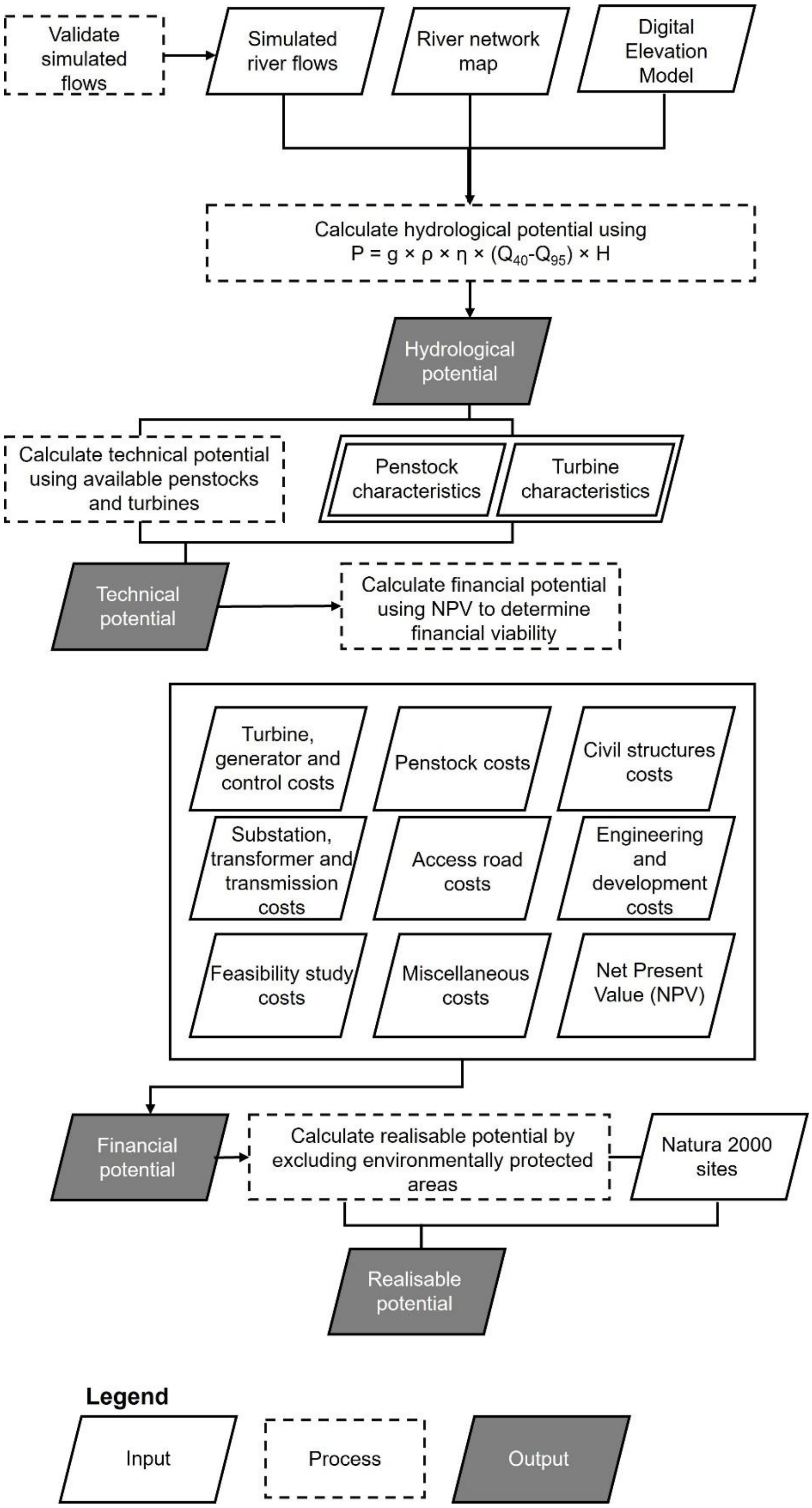

Figure 3-2: Methodological framework for the analysis

3.4.1 Flow dataset validation

Simulated flows for gauged catchments in GB (excluding Isle of Wight, Anglesey, Kintyre Group, Inner Hebrides, Outer Hebrides, Orkney, and Shetland due to lack of river flow data) from 1891 to 2015 were obtained from the UK Centre for Ecology and Hydrology (UKCEH) MaRIUS (Managing the Risks, Impacts and Uncertainties of drought and water Scarcity) project (Bell et al., 2018), that used the G2G hydrological model. The G2G is a hydrological model that operates on a national scale for Great Britain. It uses a 1 x 1 km grid that aligns with the national grid, with a time-step of 15 minutes. The model is parameterised using digital datasets, such as soil types and land-cover. It takes into account the impact of urban and suburban land-cover on runoff and downstream flows. Studies (e.g., Bell et al., 2009; Formetta et al., 2018) have shown that G2G performs well for various catchments across Britain, particularly those with natural flow regimes, as it doesn't include artificial influences like abstractions and discharges on river flows. These were validated using the National River Flow Archive (NFRA) observed flow dataset consisting of 1498 gauged locations spread uniformly (exept for the Scottish Highlands) across GB (NRFA, 2023). The coefficient of determination (R^2) was used to determine how well the simulated flows predict the gauged flows. Bell et al. (2018) recommended that the comparison between simulated and observed flows should be made using statistics over lengthy periods of time, rather than time series. Therefore, R^2 was calculated for the percentile flows ($Q_{5\%}$, $Q_{10\%}$, $Q_{50\%}$, $Q_{70\%}$ and $Q_{95\%}$), minimum, mean and maximum flows at all gauges.

3.4.2 Point generation

The input data (Figure 3-3) used were a DEM of the UK at a 25 m resolution (Copernicus, 2016), a vectorized river network GB (Ordnance Survey, 2022), monthly flow data from the MaRIUS dataset (Bell et al., 2018) for GB ranging from 1891 to 2015. Monthly flow data was statistically processed into percentile flows from Q_1 to Q_{95} in increments of 5 (Q_1 having an exceeding probability of once in 100 years, etc.). Once the mentioned data was loaded in ArcGIS, a Python script generated points with unique IDs along the river segments spaced at 25 m (the same resolution as the

DEM). Each point was assigned a unique ID and the following information: the river segment ID (from Ordnance Survey (2022), percentile flow (Q_1 to Q_{95}), coordinates (easting and northing) and elevation. However, since the area considered for this analysis is large (209,331 km^2), it was necessary to divide it into smaller catchments to be able to compute the results. The hydrometric areas from the National River Flow Archive (2014) were then used to divide GB into catchments (Figure 3-3-D). A table with the names, areas of each hydrometric area can be found in Table S1. All input data used in this study can be found at https://doi.org/10.15129/95db013c-d082-4aa9-a8ce-43b60568087d.

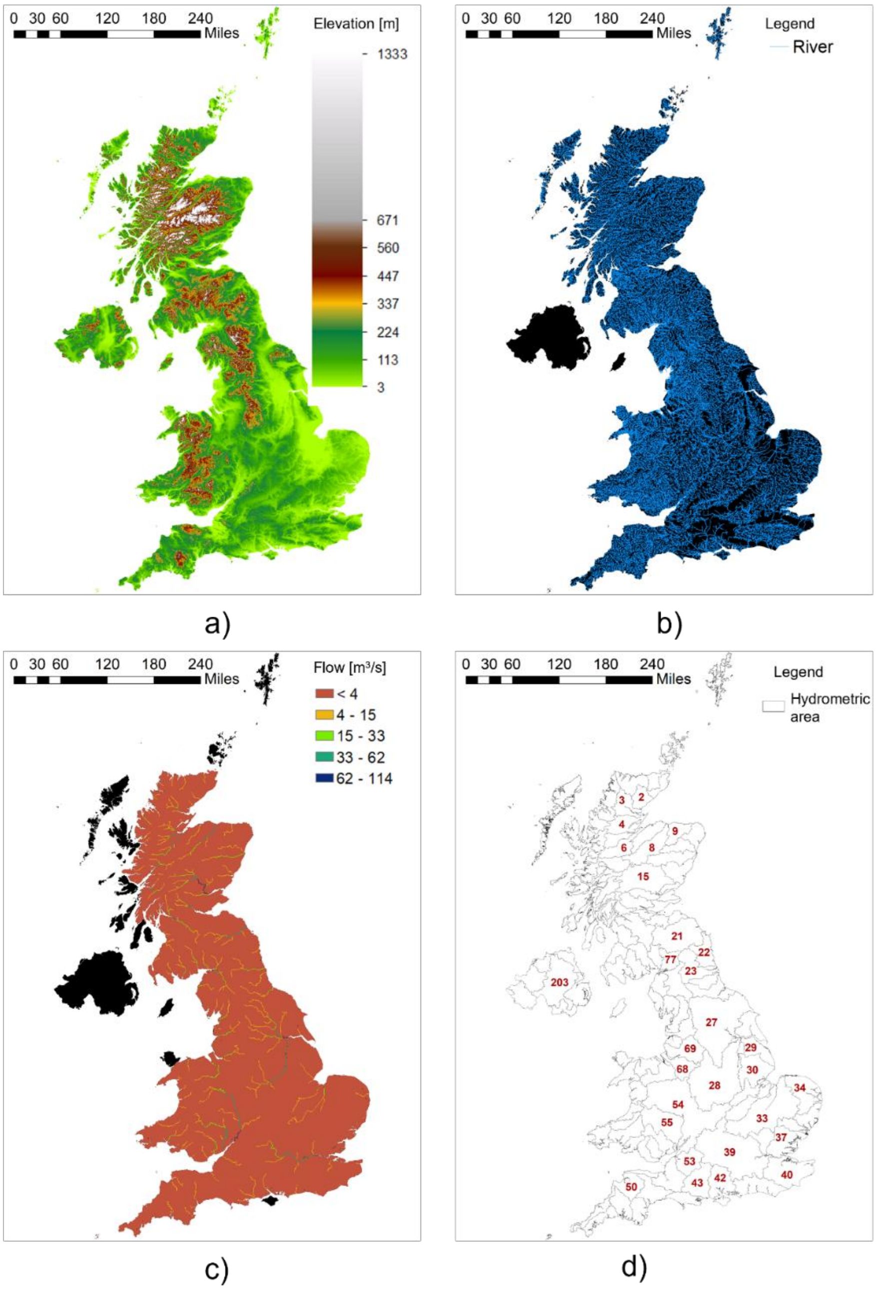

Figure 3-3: Inputs used for the analysis: a) is the Digital Elevation Model (Copernicus, 2016)*; b) is the river network for the UK, excluding Northern Ireland* (Ordnance Survey, 2022) *- "© Crown Copyright and Database Right [08/20/2022]. Ordnance Survey (Educational Service Provider Licence Number 100025252); c) is a representation of the monthly flows dataset excluding Northern Ireland and islands* (Bell et al., 2018)*, and d) is a representation of the hydrometric areas from National River Flow Archive (2014). For d) only some of the hydrometric area numbers are represented.*

3.4.3 Hydropower potential calculations

This study analysed the maximum available potential RoR hydropower resource in GB. The total potential was split between pico, micro, mini and small RoR hydro and between the hydrological, technical, financial and realisable potential (Figure 3-1).

Hydrological potential

Figure 3-4 shows the methods used to calculate hydrological potential. The available power was calculated considering the first upstream point on a river segment to be the intake (Step 1) and passed through all the downstream points (Step 2), which were considered powerhouses, to calculate available power. After the algorithm went through all the possible powerhouse locations for the first point, it considered the second downstream point as the intake and proceeded to calculate available power considering the next downstream points as powerhouses (Step 3). This was done until the most downstream point of that river segment was reached. After this step was performed on all the river segments and all possible available power combinations were calculated, the algorithm chose the intake and powerhouse locations on each river segment which generated the largest amount of power (Step 4). Only one RoR scheme was considered for each river segment for computational ease and to ensure that the schemes are independent (not cascading schemes). Another assumption made was that penstocks followed the river segment; therefore, they are not a straight line from intake to powerhouse like the sketch from the Figure 3-4.

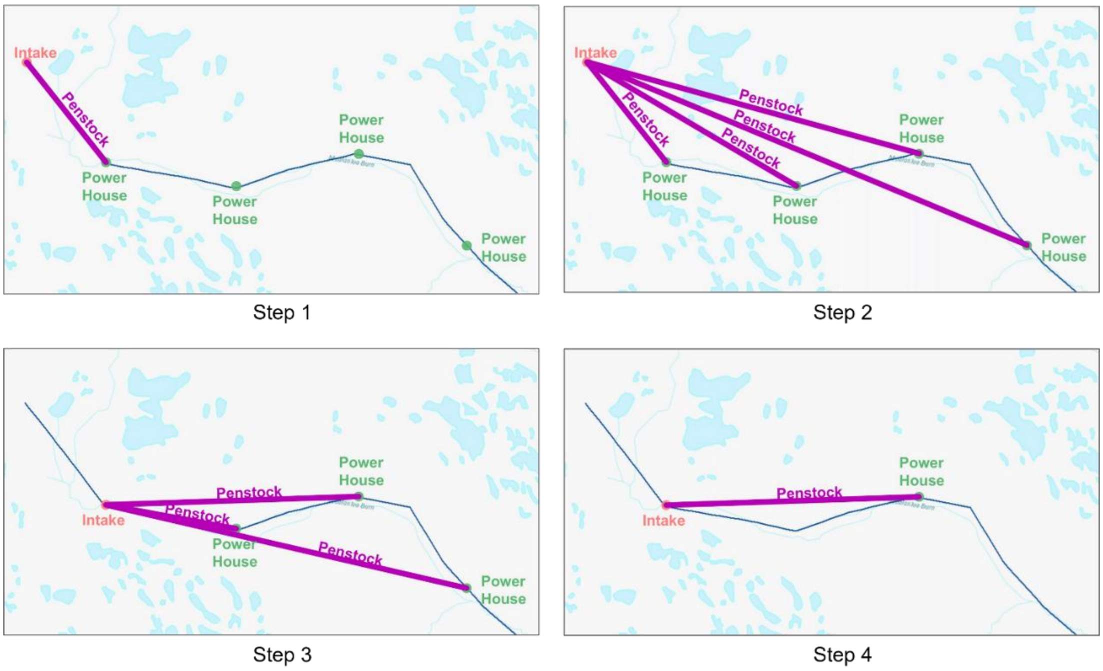

Figure 3-4: Steps used for the run of river locations search.

The power was calculated using the following formula provided in Eq. 3-1:

$$P = \frac{g \cdot \rho \cdot \eta \cdot (Q_{40} - Q_{95}) \cdot H}{1000} \qquad \textit{Eq. (3-1)}$$

where P is the available power in kW; g is the acceleration due to gravity and is equal to 9.81 m/s^2; ρ is the water density and is equal to 1000 kg/m^3; η is the turbine efficiency and is considered to be 0.85, which is an average efficiency value (Kabalci et al., 2021); Q_{40} is the flow with the exceedance probability of 40%; Q_{95} is the flow with the exceedance probability of 95% and is considered to be the minimum flow which needs to be available downstream of the intake and H is the available head between the intake and the powerhouse in m. Q_{40} and Q_{95} are both measured in m^3/s.

Technical potential

After the hydrological potential locations were chosen, the next phase was to refine the search considering the technical limitations.

Penstock diameter

For this analysis only glass reinforced plastic (GRP) pipes were considered since those are most commonly used for small hydropower projects (Duncan, 2012). These pipes come in a variety of diameters, from 100 mm to 4 m, and pressure classes, from PN6 (resistant to pressures of up to six bars) to PN32 (resistant to pressures of up to 32 bars). The choice of optimal penstock diameter has been achieved by trialling different penstock diameters for a given design flow (Q_{40}-Q_{95}) to determine the optimal diameter.

The GRP penstocks only come in sizes from 100 mm to 4 m. If there are RoR schemes which would require a diameter greater than 4 m, the flow was decreased at that location to try to find a suitable diameter. If even with the smallest flow the pipe diameter was still greater than 4 m, than that location was not considered since there are not any penstocks suited for it. In the case of an initial diameter smaller than 100mm, the diameter was chosen to be 100 mm. If the total head was greater than 320 m (correspondent to approximately 32 bars), that RoR scheme location was not considered for this analysis because the penstock pressure would be too large. A possible solution to high heads is to reinforce the last part of the penstock (where the pressure would be greater than 32 bars) with steel interior, however this option was not considered for this analysis.

Turbine type

Five turbine types were considered for this project: Pelton, Francis, Kaplan, Archimedean Screw and Cross-flow. Considering the flow and the head available at the RoR locations a turbine type was assigned for each location. If a location did not have a suitable turbine, the flow was modified to match the conditions of one the five turbine types, otherwise that location was not considered for this analysis. The design criteria for each turbine is presented in the Table 3-2. Detailed equations on the choice of penstock diameter and turbine efficiency are presented in the Appendices (Appendix 1.1).

Table 3-1: Turbine selection criteria.

Type	Criteria
Pelton	Flow ≤ 2 m^3/s and Net Head ≥ 100 m OR Flow ≤ 0.5 m^3/s and 50 m ≤ Net Head ≤ 100 m
Francis	2 m^3/s ≤ Flow ≤ 0.5 m^3/s and 100 m ≤ Net Head ≤ 300 m OR 0.5 m^3/s ≤ Flow ≤ 20 m^3/s and 20 m ≤ Net Head ≤ 100 m
Kaplan	20 m^3/s ≤ Flow ≤ 50 m^3/s and 3 m ≤ Net Head ≤ 50 m OR 0.5 m^3/s ≤ Flow ≤ 20 m^3/s and 3 m ≤ Net Head ≤ 20 m OR Flow ≤0.5 m^3/s and 3 m ≤ Net Head ≤ 50 m
Archimedean Screw	1 m^3/s ≤ Flow ≤ 20 m^3/s and 1.5 m ≤ Net Head ≤ 5 m and L ≤ 25 m[(*)]
Crossflow	0.1 m^3/s ≤ Flow ≤ 5 m^3/s and 2 m ≤ Net Head ≤ 40 m

[(*)]The length for the Archimedean Screw turbine is chosen to be less than 25 m because the distance between river points is 25 m, which means that schemes where the Archimedean Screw turbine could be installed are next to each other.

Financial potential

The costs and net present value (NPV) of each technically viable RoR scheme were calculated. There are fourteen costs which were added up to measure the initial total cost (turbine, generator and control costs, penstock costs, civil structures costs, substation and transmission costs, transmission costs, access road costs, engineering costs, development costs, feasibility study costs and miscellaneous costs). The costing methodology was based upon the work of Duncan (2012) and the RETScreen (RETScreen, 2022) software developed for North American Hydro projects. This approach was used since empirical cost functions are not available for GB.

Assumptions and limitations

The RETScreen software used pricing base on the Canadian dollar so a conversion factor for sterling pound was used based on the exchange rate for the present year C_{ex} = 0.58. Since the exchange rate was made for the current year, prices inflation was not considered. Additionally, a map of the national power grid is not available, so the distance for the transmission lines is considered 1 km for all schemes. The cost of Cross-flow turbine was taken as the cost of the Pelton turbine. The cost for the Archimedean Screw turbine was considered to be 22% less than the Pelton turbine (YoosefDoost and Lubitz, 2020). Cumulative NPV (net present value) was calculated considering the lifespan of the RoR scheme to be 25 years (or 35 years) and the yearly discount rate is set to 4% to determine if a scheme is financially viable. Verán-Leigh and Vázquez-Rowe (2019) argue that RoR schemes could have a lifespan of up to 50 years. However, electromechanical equipment can have a lower lifespan (40 years for Pelton turbines, 25 years for Francis turbines, 30 years for generators, and 30 years for transformers (Flury and Frischknecht, 2012). The lower lifespan of these prompted the selection of a conservative lifespan for the RoR schemes. The yearly operational and maintenance cost is set to be 3% of the initial total cost. Typical values range from 1% to 4% (International Renewable Energy Agency, 2021).

After a preliminary financial analysis, all pico and micro RoR schemes had a negative NPV after a lifespan of 25 years. This prompted the design of a colour system: green RoR schemes have a positive NPV and are financially viable considering a life span of up to 25 years and amber RoR schemes have a positive NPV considering a longer time span of up to 35 years. Additionally, for pico and micro schemes, since they are more likely to serve small communities or farms and local industries, the transmission line cost is considered zero, meaning they are not connected to the national grid. A detailed methodology for the financial potential can be found in the Appendices (Appendix 1.2).

Net present value

The yearly income from selling electricity was calculated considering a capacity factor of 40% and a wholesale energy price of 45 £/MWh (accurate for 2020 according to Business Electricity Prices (2021) using the following formula:

$$Income_{yearly} = P_d \cdot (365 \cdot 24) \cdot 0.4 \cdot 45 \qquad \textit{Eq. (3-2)}$$

Where P_d is the installed power in MW, 365 represents the days in a year, 24 represents the hours in a day and 0.4 is the capacity factor (40%).

Realisable potential

After computing the financially viable potential, the realisable potential was calculated next. This was determined by excluding schemes in environmentally protected locations taken from the Natura 2000 maps (European Environment Agency, 2022). Although the UK has exited the European Union which manages these sites, the UK Government has decided to continue to protect these areas (Rapleys, 2021), so they are still suitable to exclude schemes which may not be able to be built due to environmental concerns[1].

3.5 Results

The flow dataset (Bell et al., 2018) was validated against the gauged river flows from the National River Flow Archive (National River Flow Archive, 2014). Table 3-2 shows the R^2 value for percentile flows for all gauges. The simulated flows perform better for higher and mean flows (Q_{50}, Q_{10}, Q_1) than for small and minimum flows. However, the simulated dataset is good to use in the analysis with most R^2 values above 0.5 (Shen et al., 2018). Looking at the spatial distribution, R^2 values are mostly over 0.7, with a few locations with a value below 0.3 (Figure 3-5showing that the simulated flows are predicted accurately by the dataset used in this study (Bell et al., 2018).

---

[1] In the UK, effective planning and siting are crucial for balancing development with environmental conservation. Natural parks and Sites of Special Scientific Interest (SSIs) play a significant role in this process. These protected areas are designated to preserve the country's biodiversity, landscapes, and geological features (GOV UK, 2024) . Natural parks, such as the Lake District and the Peak District, provide not only recreational opportunities but also essential ecosystem services, including water purification and carbon sequestration (GOV UK, 2013).

SSIs, on the other hand, are critical for safeguarding specific habitats and species that are of scientific interest. They ensure that any development or land use changes within these areas are carefully managed to prevent ecological damage (GOV UK, 2016)The integration of these protected sites into hydropower planning helps maintain ecological integrity while accommodating sustainable development. This approach is further supported by policies and regulations from both UK-wide and devolved administrations, ensuring a cohesive strategy for environmental protection across the country.

Table 3-2: R^2 values for the percentile flows, minimum, maximum and mean flows considering all gauges from the National River Flow Archive

Flows	**R^2**
Q_{95}	0.56
Q_{70}	0.67
Q_{50}	0.70
Q_{10}	0.71
Q_5	0.71
Min	0.28
Max	0.56
Mean	0.71

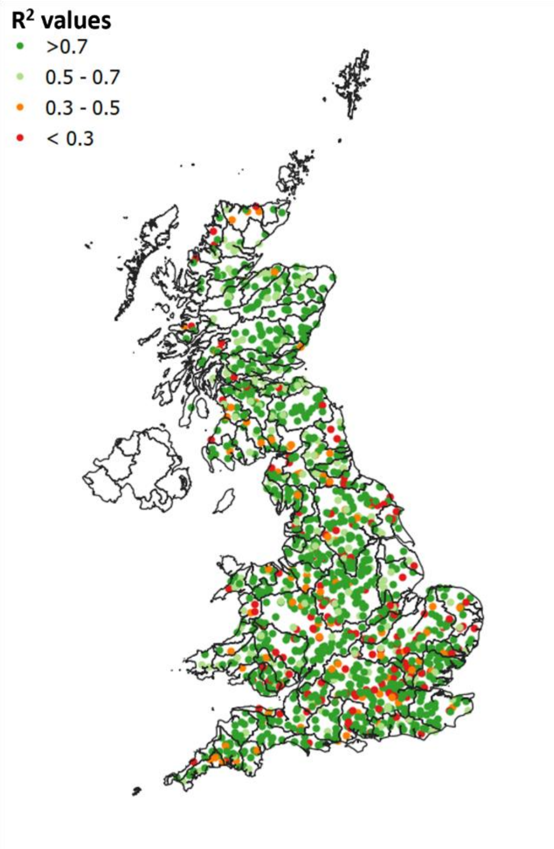

Figure 3-5: R^2 values at each NRFA gauge. R^2 was calculated based on the percentile (Q5, Q10, Q50, Q70 and Q95) and min, mean and max flow values at each gauge, comparing the simulated and observed flows.

The total GB-wide (excluding islands) hydrological potential is assessed to be ~20 GW, with the total technical potential ~11 GW. The total financial potential, however, is much smaller – estimated to be between 390 and 420 MW, with the total realisable potential between 290 and 320 MW (Figure 3-6). The large drop in potential from the technical potential to financial potential is likely due to the assumptions and limitations of the financial criteria used in this analysis (i.e. the lifespan of 25 years (for green schemes) or 35 years (for amber schemes), the lack of information on the national power grid, which prompted the selection of a fixed transmission line length and not considering the benefits of selling renewable energy to the grid). Additionally, the present study considered a fixed wholesale electricity price of £45/MWh and that the RoR scheme will produce electricity 40 % of the time in a year (the capacity factor selected was 0.4). These numbers may differ as the RoR scheme may sell electricity at higher prices during peak times and the capacity factor may change from year to year depending on river flow availability. However, increasing the wholesale electricity price (from £45/MWh to £70/MWh according to the latest figures from (Business Electricity Prices, 2021) did not lead to an substantial increase in financial potential, suggesting that price does not play an important role in determining the financial feasibility of RoR schemes.

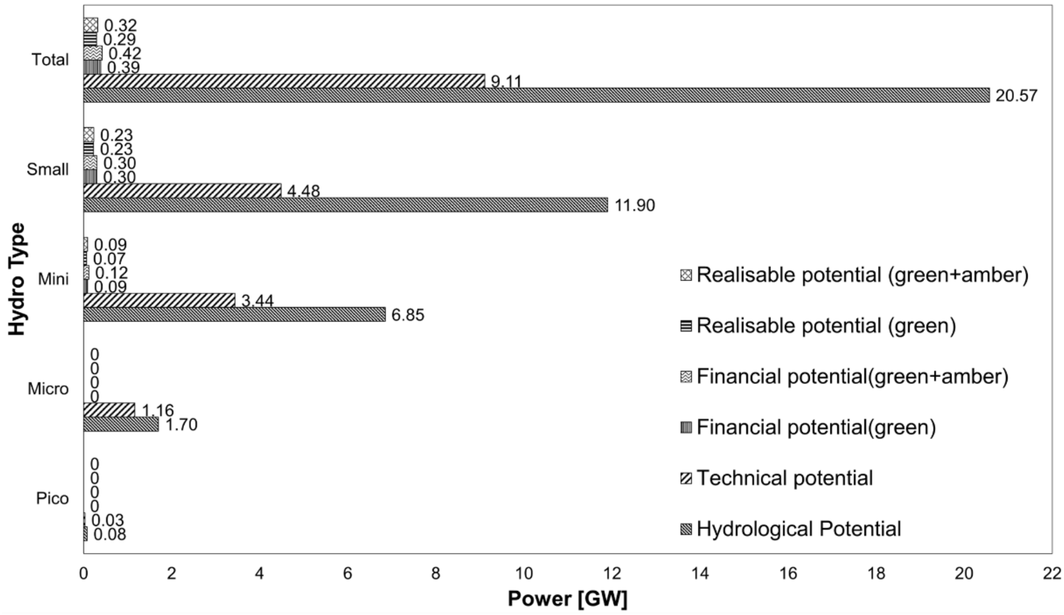

Figure 3-6: GB-wide run of river hydropower potential split between the pico (< 5 kW), micro (5 kW – 100 kW), mini (100 kW – 1MW), small (1 MW – 5 MW) and total potential. Financial potential (green) and realisable potential (green) represent schemes which have a positive net present value (NPV) before 25 years of operation and financial potential (green+amber) and realisable potential (green+amber) represent schemes which have a positive NPV after 25 but before 35 years of operation.

While sizable hydrological and technical potential is evident for pico and micro schemes (1.78 GW of hydrological and 1.19 GW of technical potential, respectively for both pico and micro schemes), the financial and realisable potential from these types of schemes is null. This is due to their smaller installed capacity (less than 100 kW) which, using this study's financial criteria (see Methods), does not produce and sell enough electricity to cover both the initial costs and the annual operation and maintenance costs. Two thirds of the hydrological potential for pico and micro schemes is technically viable. This suggests most of the pico and micro hydrological potential could be achieved with today's technology. On the other hand, only 42 % of the mini and small hydrological potential is technically viable.

3.5.1 Hydrological potential

The spatial distribution of RoR hydrological potential across the four hydropower types (pico, micro, mini and small) is uniform for pico schemes, while the micro, mini and small schemes are mostly located in the west of GB (Figure 3-7). The largest clusters of RoR schemes are in the Taff Group, Mid-Glamorgan Group and Glaslyn Group catchments in Wales and at the intersection between the Ouse, Mersey and Irwell and Ribble catchments in England. Micro RoR schemes are similarly spread throughout the country, with clusters in Wales and a cluster in England, in the Tyne, Wear, Tees Group, Wyre and Lune, Kent Group, Esk Group, Derwent Group, and Eden catchments. Mini and small RoR schemes, however, are mostly located in the western side of the study area. Clusters are found in the Scottish Highlands for both mini and small RoR schemes in the Loch Linnhe Group, Lochy, Beauly and Ness catchments. The Tay catchment in Scotland has the largest total hydrological potential at 1,250 MW (6 % of the total hydrological potential). This is perhaps expected due to the catchment size (5,093.17 km^2 – the largest in Scotland), the mountainous terrain and high annual precipitation (Met Office, 2014).

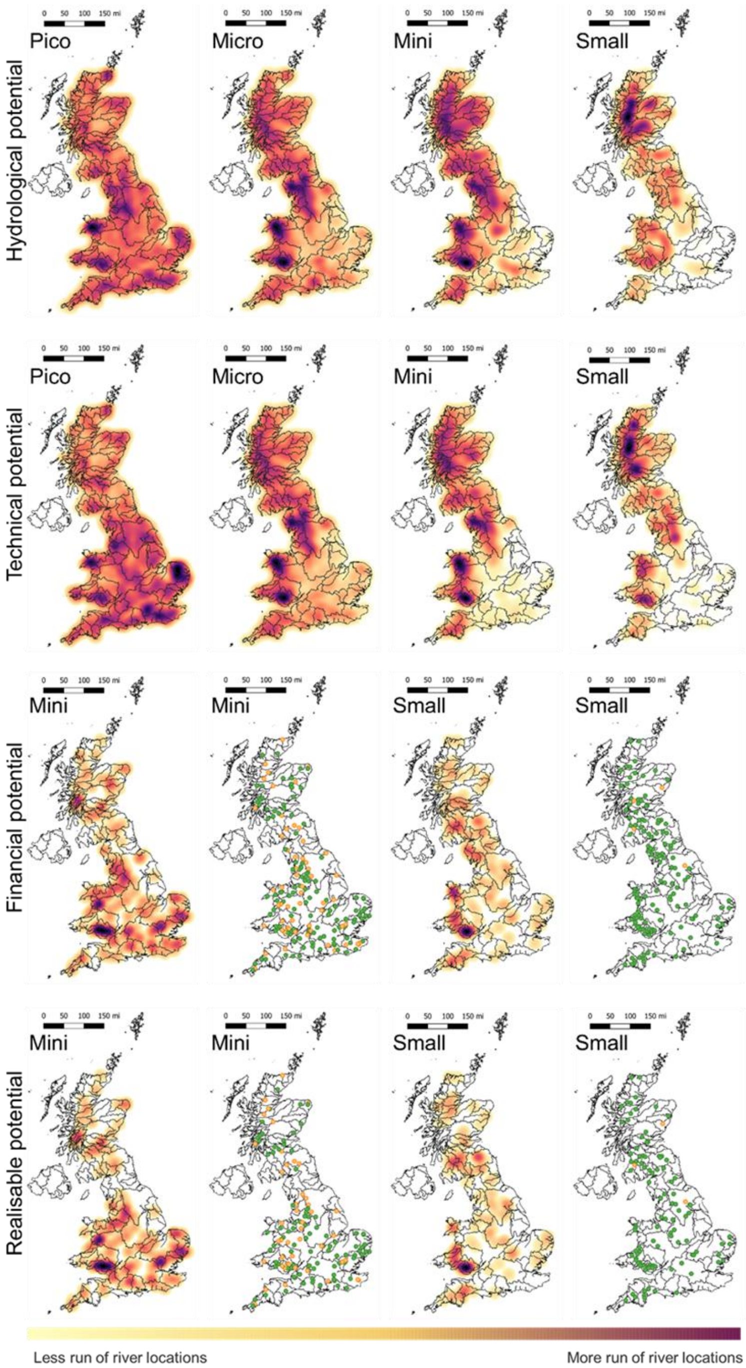

Figure 3-7: Maps of pico (< 5 kW), micro (5 kW-100 kW), mini (100 kW – 1MW), small (1 MW – 5 MW) hydrological, technical, financial and realisable RoR hydropower potential. The green dots represent locations which have a positive NPV before 25 years and amber dots represent locations with a positive NPV between 25 and 35 years.

3.5.2 Technical potential

Most of the technical potential is in the western part of the study area, with clusters showing the largest technically viable potential to be in the same locations as the largest hydrological potential. The technically viable pico schemes are situated in south-eastern England (Norfolk Rivers Group, East Suffolk Rivers, Thames and Sussex Rivers Group catchments). Other clusters are located in the west of the study area in the Glaslyn Group and Douglas Group catchments. Technically viable micro RoR schemes are situated in the same locations as the hydrologically viable micro schemes. The mini and small RoR technically viable potential is in the west and north part of the country. The largest total technically viable potential is in the Ouse Catchment in Yorkshire (the second largest catchment in England) with a total potential of 476 MW (5 % of the total technical potential).

3.5.3 Financial potential

Clusters of mini RoR schemes are identified in the west and south of the study area, with the largest ones in the Dify Group, Taff Group, Mid-Glamorgan Group and Loughor Group catchments in Wales. Small RoR schemes are situated in the west and southwest of the country, with the largest cluster in the Taff Group catchment in Wales. The largest financially viable potential is found in the Taff Group catchment, with a total potential of 21 MW (4.9 % of the total financially viable potential).

Most of the small RoR plants have a positive net present value (NPV) before 25 years of operation (green schemes), with a few having a positive NPV after 25 years but before 35 years of operation (amber schemes). Conversely, half of the viable mini RoR schemes are green schemes, while the other half are amber schemes. This is because small RoR schemes reach a positive NPV earlier in their lifetime (11 years for small RoR and 22 years for mini RoR schemes on average). This leads to a higher NPV at the end of their lifetime compared to mini RoR plants. The median initial cost of a financially viable mini RoR scheme is £0.92M, while the median initial cost for a financially viable small RoR is £1.80M. However, the median NPV of a mini RoR scheme is £0.12M, whereas the median NPV of a small RoR scheme is £1.33M.

These results suggest that small RoR schemes are more financially viable, with the highest NPVs, compared to mini RoR schemes.

In the case of mini RoR schemes, the most profitable schemes have a combination of flows of 0.75 m^3/s with head of 100 m and flows between 0.25 – 1 m^3/s with heads between 175 – 300 m. For small RoR plants, locations with flows between 2 – 4.5 m^3/s and heads between 75 to 200 m are the most profitable considering the financial criteria used in this analysis (Figure 3-8). The cut-off installed power above which RoR schemes become financially viable is approximately 312 kW for mini RoR, respectively 1001 kW for small RoR (as seen in Figure 3-8).

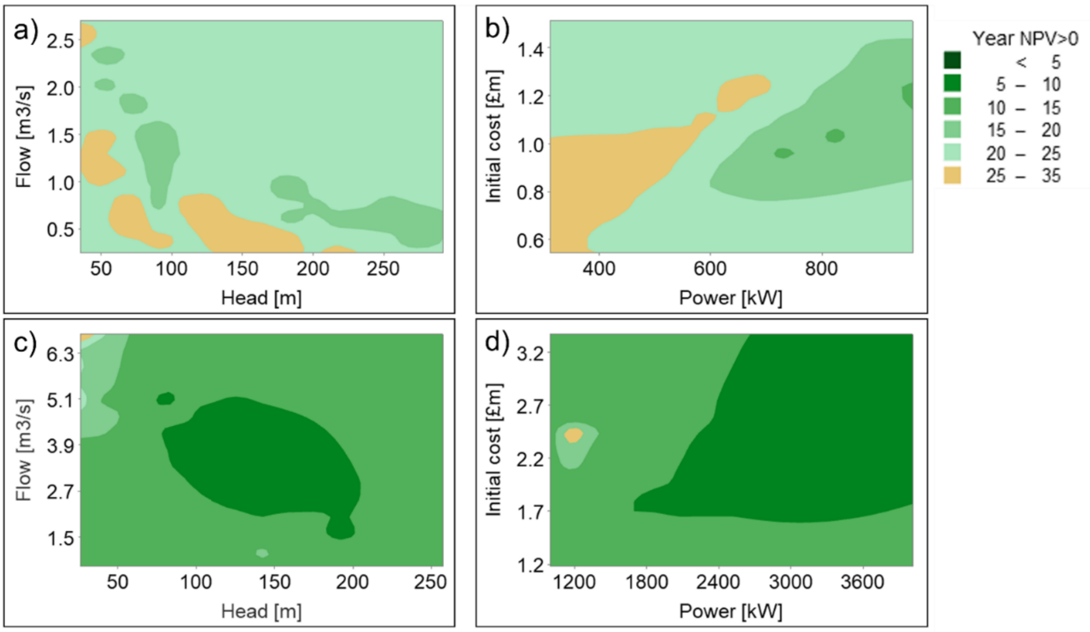

Figure 3-8: Contour plots of the dependence between the year the NPV becomes positive and the flow, head, initial cost and installed power of financially viable mini and small RoR plants. a) and c) show the relationship between NPV, flow and head for a) financially viable mini RoR schemes and c) financially viable small RoR schemes; b) and d) show the relationship between NPV, initial cost and installed power for b) financially viable mini RoR schemes and d) financially viable small RoR schemes. The amber colour represents schemes that reach a positive NPV after 25 years of operation, but before 35 years (corresponding to the amber schemes from Figure 3-7). The green areas represent schemes that reach a positive NPV before 25 years of operation (corresponding to the green schemes from Figure 3-7). The darker the green colour, the sooner a scheme reaches positive NPV and the more profitable it is.

Regarding the initial costs (Figure S1 5), for mini RoR the largest cost is the turbine (~18 % of the total initial cost on average), followed by the civil structures (~17 % of the total initial cost on average). The largest initial cost for small RoR plants is the civil structures (~ 25 % of the total initial cost on average), followed by the turbine (~19 % of the total initial cost on average). For both mini and small RoR plants, the penstock cost is the most unpredictable, with a standard deviation of 4.67 % for small RoR, respectively 9.23 % for mini RoR.

3.5.4 Realisable potential

The realisable potential is similarly spread across GB as the financially viable potential. The largest clusters are in the same regions as the financial potential clusters, and the largest realisable potential is located in the Taff Group catchment with a total potential of 20 *MW* (6.5 % of the total realisable potential).

3.6 Discussion

The methodology presented in this study aligns with recent international studies on hydropower potential, including significant works by Zaidi and Khan (2018), Sammartano et al. (2019), and Garegnani et al. (2018). For example, in this study, potential hydropower values were calculated using the Q_{40} flows and geospatial data techniques like GIS and remote sensing, similar with the methods used in Zaidi and Khan (2018). The hydrological, technical, financial and realisable potentials characteristics are similar to those in Garegnani et al. (2018) and Sammartano et al. (2019). This contextualises our research within the broader global landscape of hydropower assessment and strengthens the overall body of knowledge in the RoR hydropower assessment domain.

Examining global studies (Hoes et al., 2017; Zhou et al., 2015), their assessment of the UK's gross hydropower potential yielded figures of less than 3300 kWh/year/person, with an exploitable potential estimated at approximately 138 kWh/year/person. Considering the population of Great Britain (excluding islands) at approximately 60 million individuals, the hydrological potential findings from the present study are in accordance with prior research at approximately 3000 kWh/year/person. However, the determined realisable potential values are marginally lower than the exploitable potential (comparable with the realisable potential in our study). reported by (Zhou et al., 2015), standing at approximatively 47 kWh/year/person. This discrepancy is likely attributed to methodological variations, primarily in the selection of the design flow: our analysis adopted Q_{40} as the design flow to ensure a flow sufficient for at least 40% of the year, whereas (Zhou et al., 2015). opted for a higher design flow of Q_{30}, consequently increasing their hydropower potential results. Another reason for this discrepancy in results may be the inclusion of smaller hydropower sites, which may not be feasible in their study.

Previous studies in GB have largely based their criteria for selecting and assessing suitable locations for RoR hydropower on technical and financial viability (e.g., DECC, 2010; Duncan, 2012; Forrest, 2008; Salford Civil Engineering, 1989). However, the present study has developed and demonstrated a framework that assess the hydrological and realisable RoR potential alongside financial and technical potentials. The method presented provides, for the first time, a clearer and up to date picture of the size and location of the RoR hydropower potential across GB. Furthermore, this study has raised important questions about the implications of the financial viability criteria. Our study only considered the monetary value of selling electricity to the grid, ignoring the other benefits of producing renewable energy: avoided emissions, green jobs created, improved health benefits, etc. Not considering the financial value of these benefits has most likely led to an under estimation of the financial potential.

The results are broadly consistent with the findings of the Salford Civil Engineering report (1989), which determined the RoR hydropower financial potential to be 322.3 MW for the UK, although the Salford study did not consider any financial constraints for Scotland and Northern Ireland. For Scotland, the estimated financial potential is 120 MW, less than Duncan (2012) (204 MW – 898 MW, depending on the discount rates) and Forrest (2008) (657 MW). However, the methods used in Duncan (2012) considered the feed-in-tariff that is no longer used and prioritised the financial viability rather than harnessing the most available hydropower. Forrest (2008) determined the potential for a different range of RoR sizes than those used in our analysis. For

England and Wales, our estimated financial potential is between 277 - 310 MW, similar to the estimate from the The Department of Energy & Climate Change (2010).

When comparing our total financial and realisable potential results to the already installed RoR capacity in GB (Kennedy et al., 2023), the results are similar (Figure 3-9). However, the spatial distribution of RoR schemes in this study is different than the already installed ones. For example, most of the installed RoR schemes are in the Scottish Highlands, but our study discovered potential RoR locations in Wales and England (Figure 3-7).

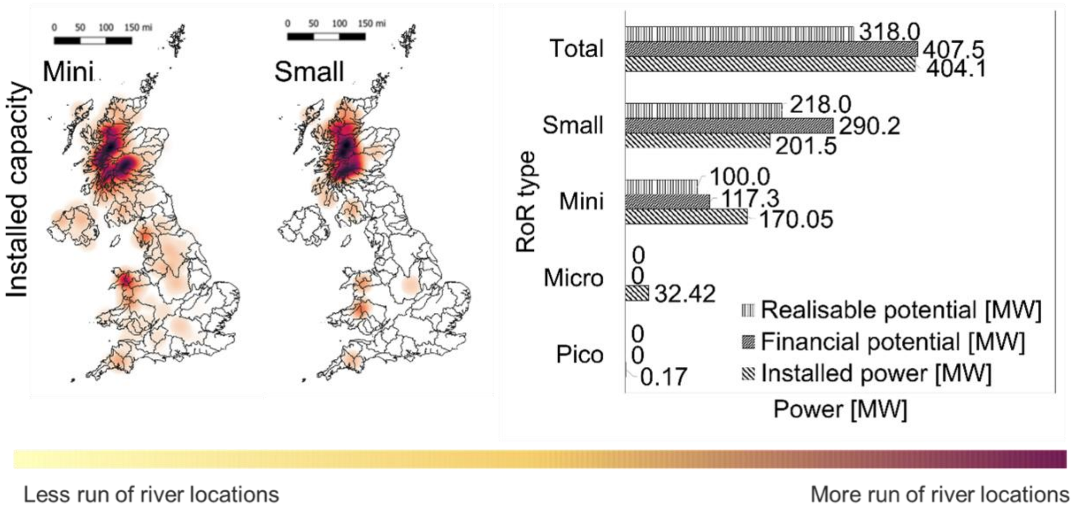

Figure 3-9: Comparison between the potential for RoR and the installed power in the UK. Data from Kennedy et al. (2023)

Based on this study's results, the following practical policy recommendations can be proposed:

1. Financial incentives for small RoR Schemes: Recognising the financial viability of small RoR schemes, policymakers could consider implementing targeted financial incentives to encourage their development. These incentives could include subsidies, tax credits, or grants for initial construction costs, especially for schemes with optimal flow conditions (e.g., flows between 2 – 4.5 m^3/s and heads between 75 to 200 m), where financial viability is higher.

2. Streamlining approval processes: Given the smaller initial investments and shorter planning and construction times associated with RoR schemes compared to large hydropower schemes, regulatory bodies could streamline approval processes to expedite project development. Expediting approvals can contribute to the faster deployment of RoR projects, aligning with the urgency of meeting renewable energy targets.
3. Local community engagement: Given the advantages of RoR schemes, such as smaller inundated areas and the use of local labour and materials, policymakers could actively promote community engagement in hydropower projects. Establishing community-based partnerships can enhance acceptance, address local concerns, and ensure sustainable development practices in line with environmental and social considerations.
4. Strategic focus on technically and financially viable regions: Policymakers could strategically focus on regions with high technical and financial potential for RoR schemes, particularly in the western part of the study area. Infrastructure and grid development initiatives can be targeted in these regions to harness the available hydropower potential efficiently.
5. Research and development for pico and micro schemes: While financial and realisable potential for pico and micro schemes may currently be limited, policymakers should encourage research and development efforts to enhance the feasibility of these smaller-scale projects. Funding for pilot projects and studies focused on overcoming the challenges associated with pico and micro schemes could pave the way for future expansion.

By incorporating these policy recommendations, policymakers can create an enabling environment for the sustainable development of RoR hydropower projects in GB, contributing significantly to the nation's renewable energy goals and environmental objectives.

While robust, this method may be improved by considering the cost of connecting to the national grid based on the spatial distribution of available substations, which was not available for this analysis. This limitation affects the financial and realisable potential results that could be made more accurate by considering the actual cost of the transmission lines (see Appendix 1). However, this only affects the viability of mini and small schemes because pico and micro schemes were considered too small to be connected to the grid in this analysis. In addition, while the primary function of this study was to determine the maximum hydropower potential across GB, the methods and tools used could also be adapted to quickly determine suitable locations for turbines.

3.7 Conclusions

The study created a comprehensive framework to determine the potential for RoR hydropower in GB (excluding islands), identified the total hydrological potential to be 20 GW, technical potential to be 11 GW, financially viable potential to be between 320 MW to 420 MW, and the realisable potential to be between 290 MW to 320 MW. Most of the realisable schemes were found to be either mini or small (100 kW – 5 MW) situated in the west and north-west parts of GB, with the largest realisable potential in the Taff Group catchment in Wales (20 MW).

This study is one of the first attempts to thoroughly examine the RoR hydropower potential across GB and the first to do so in the context of the drive to Net Zero. The analysis of RoR potential undertaken here has extended our knowledge of the size and location of hydrologically, technically, financial and realisable potential in GB and about the impact of the financial criteria chosen. However, this study was limited by the absence of a map of the national grid to allow for accurate transmission line pricing, lack of updated data on penstock and turbine prices, lack of flow and river network data for the Isle of Wight, Anglesey, Kintyre Group, Inner Hebrides, Outer Hebrides, Orkney, and Shetland, and the use of a monthly flow time series, rather than a daily or even hourly flow time series. Despite its limitations, the study certainly adds to our understanding of the RoR potential in GB and offers a reliable estimate of the amount of hydropower that can be produced and favourable RoR scheme locations. Furthermore, the findings presented in this study offer valuable insights that extend beyond regional boundaries. Industries involved in hydropower development can benefit from the novel methodological framework proposed here, which can be applied to different regions. This adaptability makes the research relevant and transferable, offering a valuable resource for regions to evaluate their own hydropower potential and make informed decisions regarding renewable energy development.

A natural progression of this work would be to analyse the effects of climate change on RoR hydropower potential, considering the proposed lifespan of the more than 25 years of the schemes identified in this study. Climate change poses significant challenges to hydropower systems globally, impacting both their performance and sustainability (Marshall and Chen, 2018). Changes in precipitation patterns, increased frequency of extreme weather events, and altered hydrological cycles are affecting river flow dynamics, ultimately influencing hydropower generation (Seneviratne et al., 2023). Based on future projections, in Great Britain, a reduction in river flows during spring and summer is expected, with a marginal increase in winter flows, and varied projections for autumn flows (e.g., Christierson et al., 2012; Kay, 2021; Prudhomme et al., 2012). These envisaged alterations in the hydrological regime across Great Britain are expected to alter hydropower production, particularly affecting RoR schemes without energy storage capabilities for accommodating seasonal variations. For example, in Scotland, mean annual flow is projected to vary between +/- 5% in the future (2050s) (UK Centre for Ecology & Hydrology, 2023) suggesting that hydropower potential in that area could vary from the 120 MW determined in this study to 114 - 126 MW. A comprehensive study that incorporates up-to-date climate projections, for example the dataset from (Hannaford et al., 2022) 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 may be useful.

3.8 Acknowledgments

We gratefully acknowledge the reviewers of our manuscript for providing valuable and constructive feedback. We extend our heartfelt thanks to our families and friends for their unwavering encouragement and understanding during the completion of this research.

Chapter 4 FUTURE CHANGES ON RUN OF RIVER HYDROPOWER IN GREAT BRITAIN

4.1 Preface

This chapter (excluding this preface) was published in the Journal of Water and Climate Change. Numberings of chapters and figures have been adapted for consistency of the overall thesis, and the references have been compiled at the end of the thesis.

Corresponding publication: Golgojan, A.-D., White, C.J., Bertram, D., 2024. Future impacts of river flow on hydropower generation in Great Britain. J. Water Clim. Chang. 15, 4840–4861.

Corresponding DOI: https://doi.org/10.2166/WCC.2024.355

Corresponding dataset: Golgojan, A. (Creator), White, C. (Supervisor), Bertram, D. (Supervisor) (6 Feb 2025). Data for "Future impacts of river flow on hydropower generation in Great Britain". University of Strathclyde. Data_repository(.zip). DOI: 10.15129/bc03010f-7ff7-4678-a510-2b2581a234ad

Corresponding code: https://github.com/DianaGolgojan/Future-changes-to-RoR-potential.git

This chapter directly addresses the following research questions (posed in Chapter 1.2 – Table 1-1):

RQ 2. *How are temperature and rainfall pattern changes influencing river flows, both now and in the future, including seasonality and low environmental flows (Q95)?*

RQ 3. *What are the effects of climate change on RoR hydropower schemes, including power and energy output?*

This chapter explores the impacts of climate change on run of river (RoR) hydropower potential, emphasising the broader relevance of the findings. It integrates the Enhanced Future Flows and Groundwater (eFLaG) dataset (Hannaford et al., 2022), which provides nationally consistent hydrological projections based on the latest UKCP18 climate projections, with an existing database of RoR potential locations from the previous Chapter 3. The goal is to elucidate the complex interplay between anticipated climate-induced modifications in river flows and their resulting effects on RoR hydropower potential in Great Britain. The results from this chapter are significant for the development of new RoR systems and the modification of existing ones. Despite potential rise in river flows during winter in some regions of Great Britain, turbines might not be capable of utilising these increases. Consequently, if RoR hydropower systems are not planned with consideration for climate change, their energy production could be restricted. These insights contribute to discussions on renewable energy transitions, climate resilience in energy infrastructure and water resource management in a changing climate.

The methodology in this chapter was implemented using MATLAB software. New code was written to extract flow time series from the eFLaG dataset and calculate the available daily power for the baseline and the future periods. All the newly developed code can be found here: https://github.com/DianaGolgojan/Future-changes-to-RoR-potential.git.

4.2 Abstract

Climate change is likely to alter Great Britain's water resource availability for hydropower generation. These changes affect hydropower production due to uncertainty around the timing and magnitude of water availability, particularly run of river (RoR) schemes that lack the necessary storage capacity to buffer seasonal flow variability. This study examines the likely future changes on RoR hydropower potential at locations across Great Britain using the eFLaG dataset of future flow projections. Results show annual river flows are projected to increase in winter and spring but reduce in summer and autumn. These changes have an impact on RoR hydropower potential with projected decrease in the near (2030-2059) and far future (2050-2079) for both summer (-19 %, -32 %) and autumn (-11%, -19%) throughout Great Britain. Therefore, results indicate a general decrease in the annual RoR hydropower potential in Great Britain. This study underscores the importance of incorporating

climate change considerations in the planning and operation of RoR hydropower schemes to ensure sustainable energy generation in Great Britain. 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 river flows during winter. However, this should be done with consideration of the technical limitations and of the opportunities for optimisations for system generation.

Keywords:

Climate change, Run of river hydropower

4.3 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., 2022a). 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 (IPCC, 2021; King et al., 2023; Watts et al., 2015). Based on future projections, it is expected that river flows will decrease in spring and summer flows, contrasted with a slight increase in winter flows, with a mixed picture for autumn flows (Christierson et al., 2012; Kay, 2021; Prudhomme et al., 2012; Watts et al., 2015; Werritty, 2002). 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 and 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 and 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 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 and Whitehead (2013) used the UKCP09 climate projections, which are now outdated. Although the climate projections used in 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 upon 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 one 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, respectively 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 are power duration curves (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 (Climate Change Committee, 2021) emphasizes the impact of climate change on water availability and, consequently, energy supply that is dependent on water. The 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 and 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 and 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 UK are incorporated with an existing database of RoR potential locations (Golgojan et al., 2024a) 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 4.4 presents the methodology used to validate simulated future flows and to determine the changes in river flows and hydropower potential; Section 4.5 presents the key findings of this study; Section 4.6 discusses the implications of the results and compares them to previous studies; and, lastly, Section 4.7 concludes the findings of this study and possible implications for RoR developers and operators across GB.

The main objectives of this study are:

1. To assess the potential impacts of climate change on river flow patterns across Great Britain.
2. To evaluate how these changes in river flow could affect the hydropower potential of run of river (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)

4.4 Methods

The Enhanced Future Flows and Groundwater (eFLaG) future flows dataset (Hannaford et al., 2022) and an existing database of RoR potential locations (Golgojan et al., 2024a) was used to determine the effects of climate change on river flows and in run of river (RoR) hydropower potential across GB. eFLaG are nationally consistent hydrological (river flow, groundwater level and groundwater recharge) projections for the UK, based on the latest UK Climate Projections (UKCP18; Lowe et al. (2019) considering a high emission scenario RCP8.5. The eFLaG dataset utilises the UKCP18 dataset and applies a bias correction to its 'Regional' 12km projections.

These projections are then used as input for four river flow models (GRJ4, GRJ6, 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 UK, 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 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 Probability Distributed Model (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 non-linear 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 initialization 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 maximizing the modified Kling-Gupta efficiency.

Lastly, 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 initialization from observed rainfall and 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 (GCM) and regional climate models (HadGEM3-GC3.05 and HadREM3-GA705) with perturbed parameters. This results in 12 high-resolution (12km) climate projections that are consistent spatially across the UK. The projections cover the time period of December 1980 to 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 (R2efficiency), 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 Q95, Low-flow volume and Absolute percent error in the mean annual minimum on a 30day moving average). A full description of the metrics used can be found in Table 2 in 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 realization 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 (Parry et al., 2024).

4.4.1 Data

Alongside the eFLaG dataset presented above, a dataset of RoR hydropower schemes was used. (Golgojan et al., 2024a)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., 2024a) 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.

Selection of run of river locations

In the present study, we use the RoR locations identified in Golgojan et al. (2024a) that are in proximity to eFLaG gauges. The potential RoR schemes from Golgojan et al. (2024a)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. (2024a) were used for this study because they provide all the information needed to carry out the analysis.

Firstly, maps from Golgojan et al. (2024a) 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, etc.). 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 ± 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 4-1 shows the geographical location of the RoR schemes and nearby eFLaG gauges.

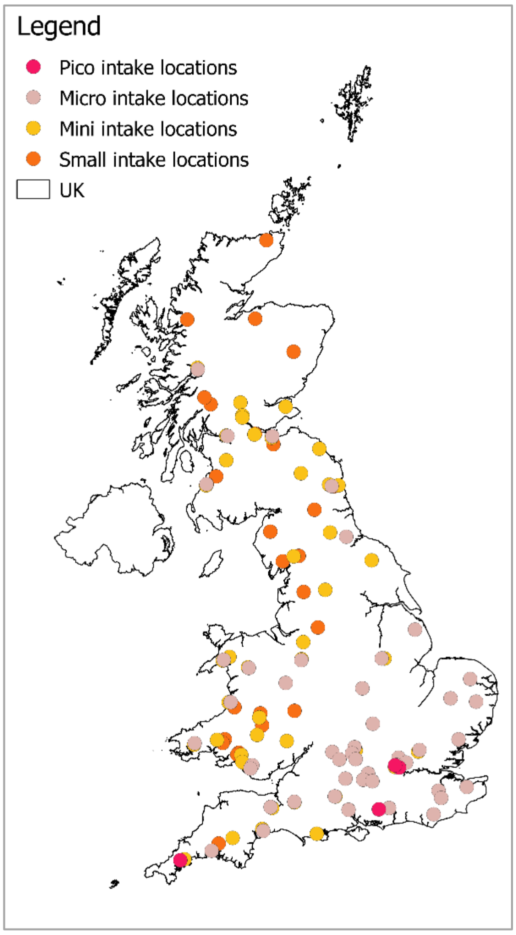

Figure 4-1: The location of potential run of river schemes intakes. Classified by size in pico, micro, mini and small run of river (see Golgojan et al. (2024a).

4.4.2 Validating the simulated future flows

Although the simulated flows from the eFLaG dataset were previously validated using various metrics (see 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 (NFRA) 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 Hannaford et al. (2022).

The coefficient of determination (R^2) was used to determine how well the simulated flows predict the gauged flows since this was not used prior 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 and Torrie, 1962). Bell et al. (2018) recommend 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}, Q_{60}) and low or environmental (Q_{95}) simulated eFLaG flows were compared to the observed corresponding exceedance flows from the National River Flow Archive (NRFA, 2021) at all the eFLaG stations for the four hydrological models: G2G, GR4J/GR6J and PDM (see 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.

4.4.3 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%, respectively 95% (Golgojan et al., 2024a), 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 environmental flow, so it's essential to assess any changes in this flow for RoR operation.

4.4.4 Changes in future run of river hydropower potential

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 and 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 w 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:

$$P_{daily\_baseline} = \frac{g \cdot \rho \cdot \eta \cdot Q_{baseline} \cdot H}{1000} \qquad \text{Eq. (4-1)}$$

where, $P_{daily\_baseline}$ is the available power in kW; g is the acceleration due to gravity and is equal to 9.81 m/s^2; ρ is the water density and is equal to 1000 kg/m^3; η is the turbine efficiency, $Q_{baseline}$ 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 to in Eq. 4-1 was the design flow (maximum flow captured at the RoR intake). The turbine efficiency, η, differs based on the turbine type and its efficiency curve (Dellinger et al., 2016; Pereira et al., 2021; Sinagra et al., 2014). For the near (2030-2059) and far future (2050-2079), the available power was calculated using the predicted future flows from the eFLaG dataset (Eq. 4-2)

$$P_{daily\_future} = \frac{g \cdot \rho \cdot \eta \cdot Q_{future} \cdot H}{1000} \quad \text{Eq. (4-2)}$$

where, P_{daily_future} is the available power in kW and Q_{future} is the average daily flow in the future (average from all the RCMs).

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

$$E_{daily\_baseline} = P_{daily\_baseline} \cdot 24\ hr \quad \text{Eq. (4-3)}$$

$$E_{daily\_future} = P_{daily\_future} \cdot 24\ hr \quad \text{Eq. (4-4)}$$

where, $E_{daily\_baseline}$ and E_{daily_future} are the daily energy produced for the baseline and the future in kWh.

The monthly power and energy for the baseline (Eq. 4-5 and 4-7) and the future (Eq. 4-6 and 4-8) was calculated using the following formula:

$$P_{monthly\_baseline} = \frac{\sum_1^n P_{daily\_baseline}}{n} \qquad \text{Eq. (4-5)}$$

$$P_{monthly\_future} = \frac{\sum_1^n P_{daily\_future}}{n} \qquad \text{Eq. (4-6)}$$

$$E_{monthly\_baseline} = \sum_1^n E_{daily\_baseline} \qquad \text{Eq. (4-7)}$$

$$E_{monthly\_future} = \sum_1^n E_{daily\_future} \qquad \text{Eq. (4-8)}$$

where, $P_{monthly\_baseline}$, $P_{monthly\_future}$, $E_{monthly\_baseline}$ and $E_{monthly\_future}$ 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 (Eq. 4-9 and 4-11) and the future (Eq. 4-10 and 4-12) were calculated using the following formulas:

$$P_{annual\_baseline} = \frac{\sum_1^m P_{monthly\_baseline}}{m} \qquad \text{Eq. (4-9)}$$

$$P_{annual\_future} = \frac{\sum_1^m P_{monthly\_future}}{m} \qquad \text{Eq. (4-10)}$$

$$E_{annual\_baseline} = \sum_1^m E_{monthly\_baseline} \qquad \text{Eq. (4-11)}$$

$$E_{annual\_future} = \sum_{1}^{m} E_{monthly\_future} \qquad \text{Eq. (4-12)}$$

where, $P_{annual\_baseline}$, P_{annual_future}, $E_{annual\_baseline}$ and E_{annual_future} are the mean annual power and 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.

4.5 Results

4.5.1 Simulated flows validation

All hydrological models evaluated in this study are found to demonstrate high accuracy in predicting simulated flows, particularly with respect to percentile flows. Table 4-1 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 Q95 flow, R^2 is less than 0.7, which is considered the upper limit for a good R^2 value (Moore et al., 2013).

Table 4-1: 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 4-2 presents a graphical representation of the simulated versus observed percentile flows for gauge 2001 as an example. 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 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, G2G is less able to simulate 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 like 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.

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

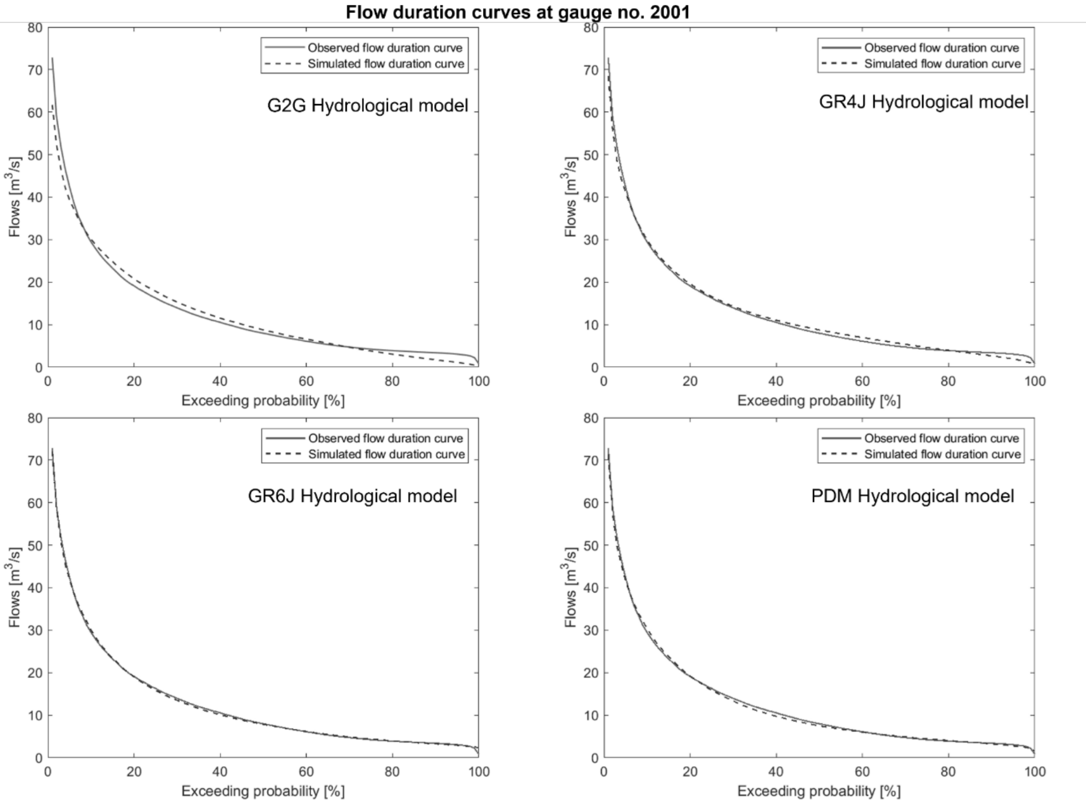

Figure 4-2: Simulated and observed flow duration curves at gauge no. 2001

4.5.2 Future changes to 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 4-3).

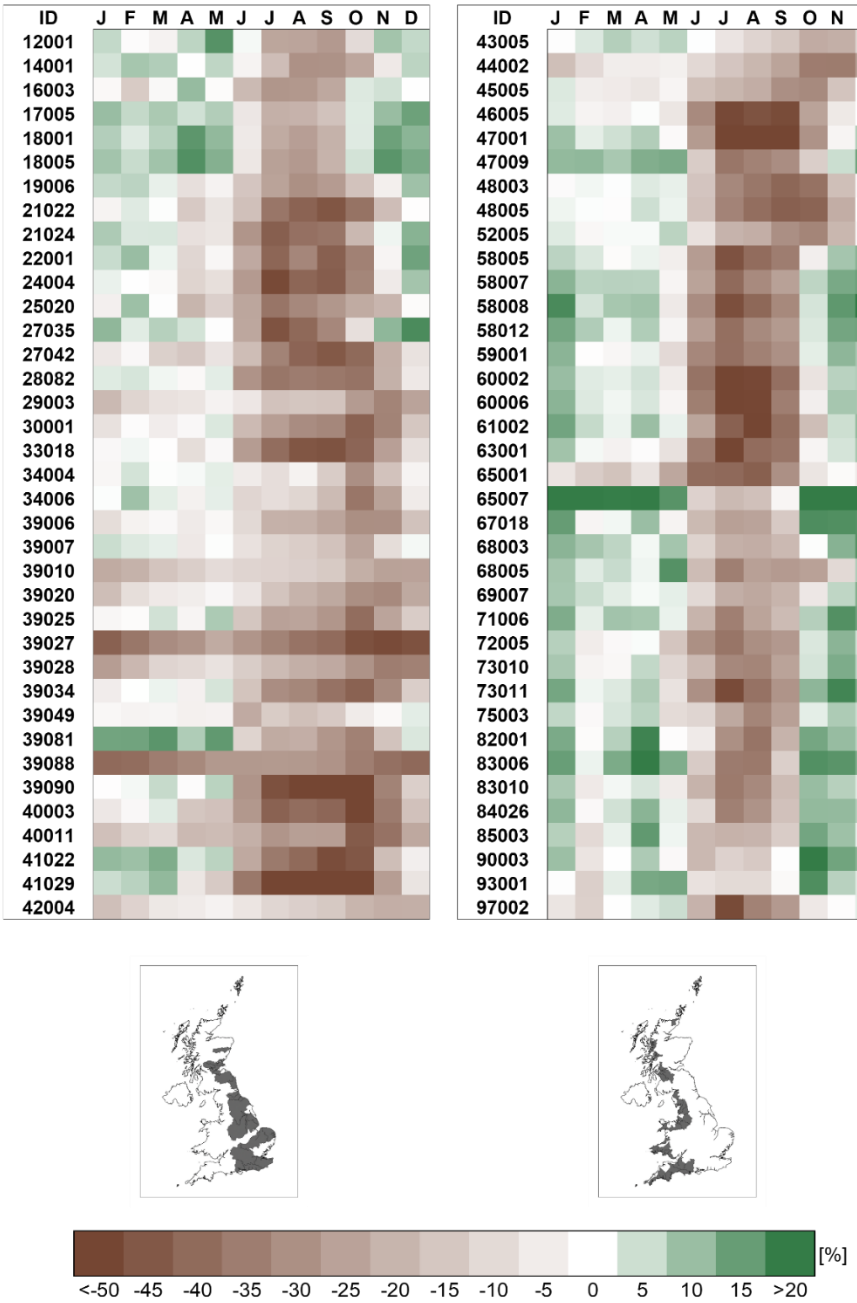

Figure 4-3: Monthly percentage changes in river flows at the gauging station near RoR schemes. The baseline flows are the flows simulated using the GR6J hydrological model for the period 1980-2009. The near future flows are the mean for all the RCM simulated flows for the period 2030-2059. The maps below show the catchments where the gauges are in each column. The legend refers to percentage change in mean monthly flows in the future from the baseline.

The design flow (considered Q_{40} in this analysis) decreases by -2.6 % in the near future, respectively -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 4-2). 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; +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.

Table 4-2: 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

Metric	Change from the baseline	
	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

4.5.3 Future changes to run of river hydropower potential

Results show that most of the RoR locations analysed (presented in Figure 4-1have a reduced power and energy output in the near and far future (Table 4-3). 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 and Lubitz, 2020). Nevertheless, seasonally, most RoR locations may see an increase in available power in the near and far future in winter (Figure 4-4). The exception are locations in the southern and south-easter 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 4-5), while summer and autumn shows 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 4-4). In 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 south east.

Table 4-3: 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

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 [%]
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
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

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 [%]
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	1087.13	1098.92	1099.38	1.08	1.13
2509	1326.01	1354.77	1328.94	2.17	0.22

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 [%]
5831	832.20	854.86	869.88	2.72	4.53
8564	762.76	742.39	724.78	-2.67	-4.98
9988	1604.53	1522.05	1510.45	-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	2831.22	2825.12	2814.03	-0.22	-0.61
18896	5316.39	5020.60	4813.32	-5.56	-9.46
18944	897.38	873.78	845.25	-2.63	-5.81
20693	1297.00	1313.19	1265.97	1.25	-2.39
22277	1397.25	1302.14	1228.24	-6.81	-12.10
25548	1885.71	1961.06	1958.68	4.00	3.87
27404	2378.79	2290.19	2238.49	-3.72	-5.90
30466	1146.18	1051.15	989.03	-8.29	-13.71
33633	1421.29	1398.71	1363.28	-1.59	-4.08
34822	5570.15	4991.19	4661.17	-10.39	-16.32
44301	1464.71	1340.68	1261.17	-8.47	-13.90
59684	1343.32	1291.19	1256.46	-3.88	-6.47

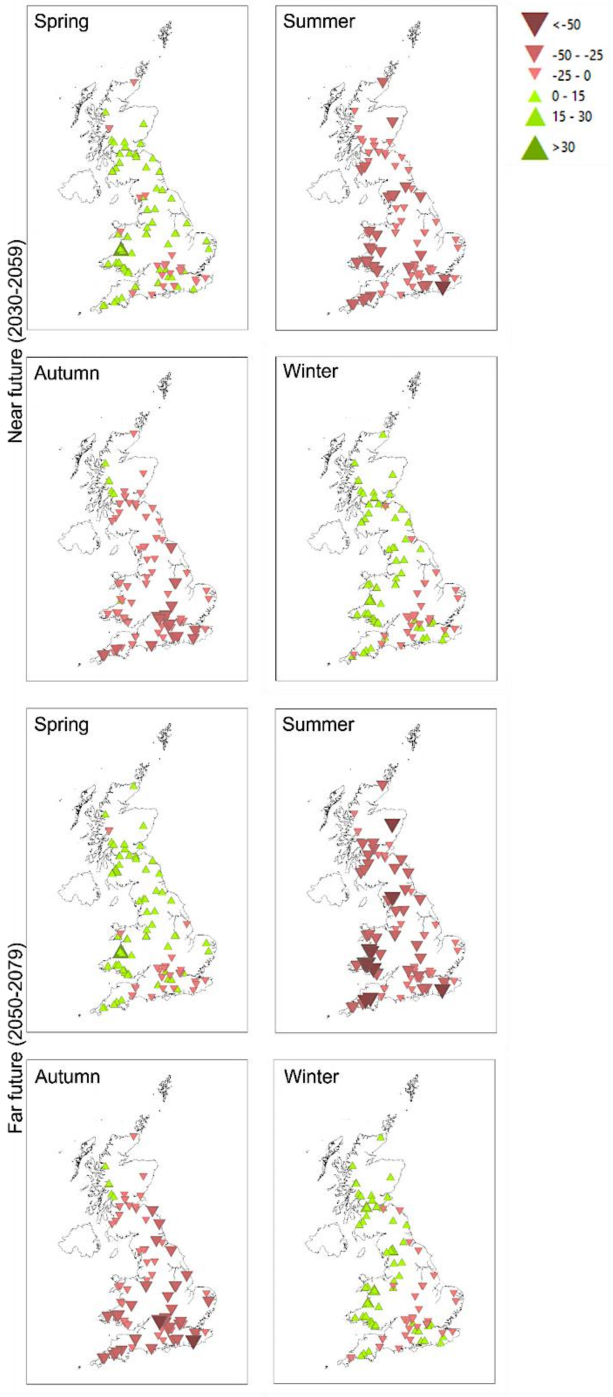

Figure 4-4: Percentage changes in seasonal available power for the RoR schemes selected in the near future (2030-2059) and far future (2050-2079) from the baseline (1980-2009).

RoR systems can be classified by installed capacity in pico (less than 5 kW), micro (between 5 kW and 100 kW), mini (between 100 kW and 1MW), and lastly, small (between 1 MW and 5 MW). Looking at each type of RoR hydropower (micro, mini, pico and small) (see Golgojan et al. (2024a), the seasonal changes differ based on RoR scheme size (Figure 4-6). 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, 6.05 % in the near future) in winter compared to the baseline.

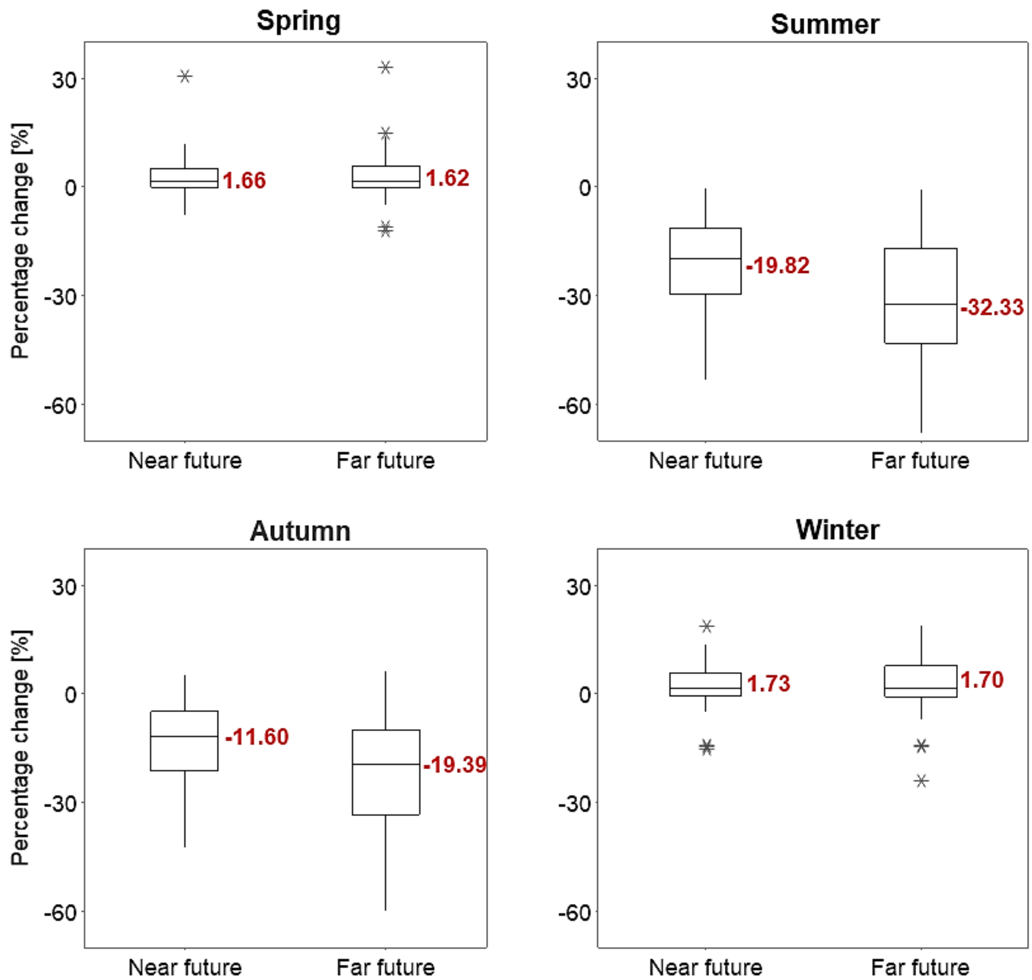

Figure 4-5: Percentage changes in seasonal available power for RoR schemes from the baseline (1980-2009) to the near future (2030-2059) and the far future (2050-2079). The value in red is the mean change in available power.

Comparing future seasonal changes in flows with the seasonal changes in RoR hydropower power output shows a clear relationship (Table 4-4). 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 to May) (Figure 4-3). 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.

Table 4-4: 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

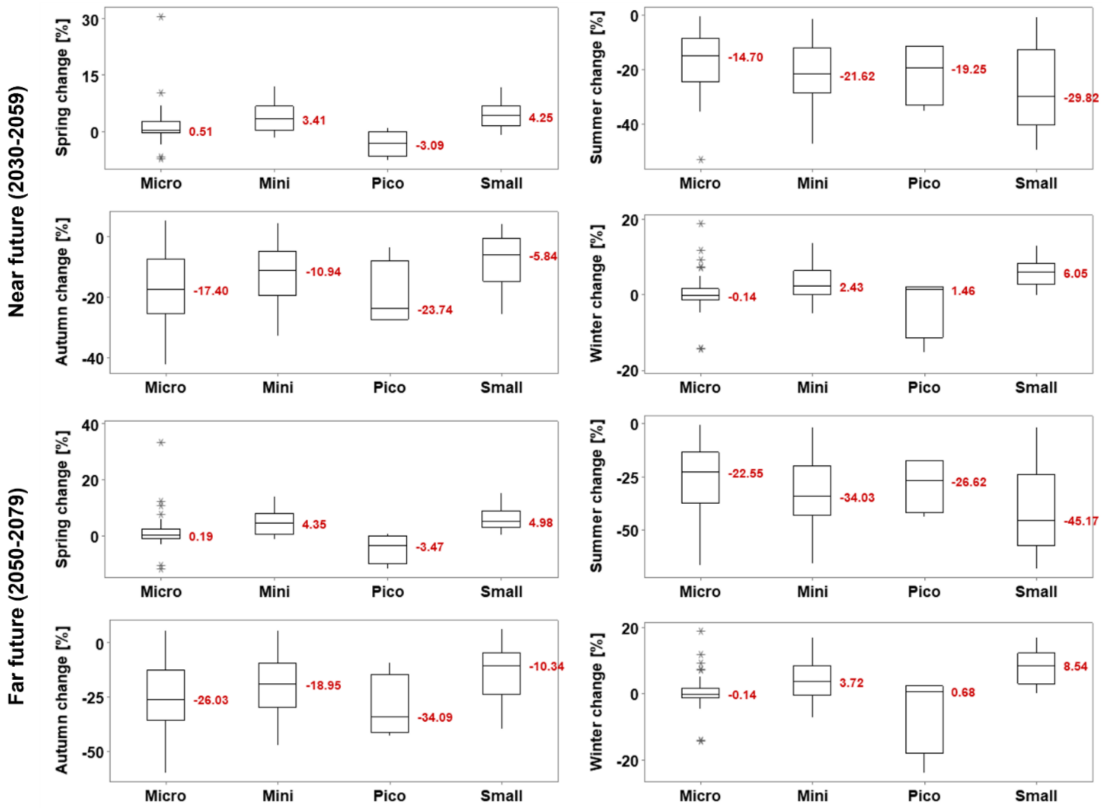

Figure 4-6: Boxplot of seasonal changes in available power in the near future (2030-2059) and the far future (2050-2079) from the baseline (1980-2009) for all the RoR schemes analysed, broken down by RoR type after Golgojan et al. (2024a)*.*

4.6 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 (Ali et al., 2019; Van Vliet et al., 2013), emphasising the vulnerability of seasonal water availability to climate-induced shifts. The Organization for Economic Cooperation and Development (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 (Christierson et al., 2012; Kay, 2021; Prudhomme et al., 2012; Werritty, 2002). 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 Climate Change Risk Assessment (CCRA) and the Third National Adaptation Programme (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., Bocchiola et al., 2020; Carless and Whitehead, 2013; Carvajal et al., 2017; 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 and Whitehead (2013) and Dallison et al. (2021) that highlight future decreases in RoR potential 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; 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, emphasizing 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 (-16.40 % in the near future and by -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 and emissions pathways was used). However, although the use of multiple climate models and emission scenarios is recommended (Kay et al., 2020; Kendon et al., 2021; Shen et al., 2018; Smith et al., 2009), 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 run of river (RoR) hydropower systems, while based on industry standards and previous studies (DUKES, 2022; Sample et al., 2015), 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 organizations 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.

4.7 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 river flows may increase. These changes exhibit regional disparities, however, 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. Understanding 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 south-east and east of GB are projected to a have a decreased power output all season, with decreases as low as over -50%. Conversely, RoR hydropower potential modestly increases in spring and winter. Notably, the increases in spring (approx. +1.60 %) and in winter (+1.70 %) are smaller than the 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. Additionally, 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.

CHAPTER 5 THE EFFECTS OF CLIMATE CHANGE ON HYDROPOWER DROUGHT: A RUN OF RIVER CASE STUDY

5.1 Preface

This chapter (excluding this preface) was submitted to the International Journal of Energy Research on 10 May 2024. Numberings of chapters and figures have been adapted for consistency of the overall thesis, and the references have been compiled at the end of the thesis.

Corresponding dataset: Golgojan, A. (Creator), White, C. (Supervisor), Bertram, D. (Supervisor) (11 Feb 2025). The effects of climate change on hydropower drought: A run of river case study. University of Strathclyde. Data_repository(.zip). DOI:10.15129/ac1b30dd-2b2a-46b8-b902-648979f75dd5

This chapter directly addresses the research question (posed in Chapter 1.2 - Table 1-1

RQ 4. *Is there a necessity to establish a distinct and standardised definition for 'hydropower drought' to comprehensively assess and address the specific impacts of drought on hydropower generation?*

RQ 5. *To what extent does climate change influence the risks associated with hydropower generation, including the emergence of the condition referred to as 'hydropower drought'?*

The aim of this chapter is to create a novel definition for hydropower drought, focusing on assessing the potential effects of climate change on hydropower drought characteristics utilising data from specified case study locations. The primary objectives are to analyse the duration, frequency, and severity of hydropower drought events during both a 30-year baseline period (1980-2009) and a future period (2030-2059). The investigation employs a dataset derived from the eFLaG dataset (Hannaford et al., 2022), covering daily river flows to determine hydropower drought events and uses four run of river (RoR) locations from Chapter 3 as case studies. The findings presented in this chapter contribute valuable insights into the potential impacts of climate change on hydropower systems, informing adaptive strategies for sustainable hydropower management.

5.2 Abstract

Climate change is amplifying the occurrence, severity, and duration of droughts in some areas, highlighting the connection between these phenomena. While drought impacts on various sectors have been studied extensively, the distribution of research focus across different sectors, including agriculture and energy, varies. Hydropower is increasingly impacted by droughts, which are exacerbated by climate change. This study determines the observed frequency, duration and severity of drought events relating to hydropower generation and how it may change in the future, using the UK as a case study. Historically, the UK has experienced several severe drought events, notably in 1975-1976, 1995-1997, and 2010-2012. More recently, the summer of 2022 underscored the country's ongoing vulnerability to drought conditions. To achieve this, we create a novel definition for 'hydropower drought' focused on run of River (RoR) hydropower schemes (that are vulnerable to drought due to direct reliance on streamflow) using four hypothetical schemes selected across the UK. Our analysis, based on daily power production data and river flows from the eFLaG dataset revealed that all four RoR hydropower schemes studied experienced hydropower drought events. These events were characterized by periods when power output fell below a defined threshold due to reduced river flows. Specifically, our findings indicate that the summer season consistently exhibited the highest frequency and severity of hydropower drought events compared to other seasons.to project. Analysis shows on an annual scale the duration of drought events is expected to increase by approximately two days, accompanied by a 13.5% rise in both frequency and severity of future hydropower droughts by in the future (2030-2059) relative to a 1980-2009 baseline period at the case study locations in the UK. While this study offers insights into optimizing hydropower generation under varying hydrological conditions, it is important to note that the findings are based on a limited scope, focusing on four hypothetical schemes. Therefore, while the results provide a useful starting point, they may not be universally applicable. Further research is needed to validate and extend these findings to a broader range of scenarios and conditions. Even though the results

are specific to the RoR schemes used in this study, a rise in drought duration, frequency and severity due to climate change has been observed across the world. The methods used here can be applied to analyse drought vulnerability of hydropower facilities in other regions, informing climate adaptation planning.

5.3 Introduction

Drought is a widespread climatic phenomenon, evident across diverse climate regimes globally (Balting et al., 2021). Unlike other climatological or hydrological hazards that are confined to specific areas, such as floodplains or coastal regions, droughts often exhibit extensive hazard footprints (World Health Organization, 2023). Droughts are a widely studied hazard (e.g., Allan et al., 2020; Freire-González et al., 2017; Hyland and Russ, 2019), with focus often being placed on the agricultural sector due to its vulnerability to long-term climatic events. Reduced crop production is the primary consequence of drought, which can have significant economic and health implications (Dolan et al., 2021).

However, other industries, including renewable energy generation and transportation, are also impacted by extreme climate events (He et al., 2019; Perera et al., 2015). Furthermore, impacts are often interconnected. For example, drought-induced agricultural losses can affect transportation and manufacturing industries that rely on agricultural products. Similarly, energy production challenges can have cascading effects on water treatment, manufacturing, and urban infrastructure (Byers et al., 2020). Wan et al. (2021) and Wang et al. (2020) show that prolonged dry spells can lead to decreased water levels in reservoirs, which in turn can limit the amount of electricity that can be generated. This has significant implications for energy production and can affect the overall stability of power grids in affected areas, which has been witnessed across Europe. The Po River in Italy, for example, was affected by record low water levels in 2022 due to the absence of rainfall and snowfall in the mountains (Montanari et al., 2023). This event was part of a long-term trend of more frequent and severe drought in the area. The drought that hit northern Italy in 2022 was unprecedented in more than two centuries. The flow of the Po River fell to one-tenth of its usual rate, and water levels were two meters below normal. This saw significant impacts on hydropower generation, with the stored energy value of Italian reservoirs 22% lower than the average for the preceding seven years (Schroders, 2022). In the same year, there was a decrease of 44% in the amount of electricity being produced in Spain, mirroring a similar trend to what was happening in other places (e.g., Norway) (BBC, 2022). Electricity from hydropower dropped by 20% overall in 2022 due to drought, providing evidence that hydropower is becoming increasingly affected by periods of low precipitation leading to water scarcity and droughts, with climate change exacerbating these vulnerabilities (e.g., Opperman et al., 2022; Oxford Policy Management, 2019; Reuters, 2021).

Climate change refers to a significant change in weather or its variability over a long period. This change could be in the average of temperature, rainfall, humidity, weather patterns, wind, etc. (YoosefDoost et al., 2018). Drought is a complex natural phenomenon that is characterized by a prolonged period of abnormally low rainfall, leading to a shortage of water (Hasan et al., 2019). It can have wide-ranging impacts on water security, agriculture, energy, and human health. Unlike most natural hazards, droughts can develop anywhere, evolve rapidly within a month or slowly over a season, and span months to decades without a clear beginning or end (Sugg et al., 2020). Droughts and climate change are intricately connected, with climate change amplifying the occurrence and severity of droughts, particularly in semi-arid areas that are already grappling with substantial water scarcity (Cook et al., 2018). As weather patterns become more unpredictable, there is growing uncertainty about the frequency and severity of drought events. The twentieth century has seen an increase in the extent and duration of more severe droughts, primarily attributed to rising temperatures and reduced precipitation (IPCC, 2021). Worldwide, long-term droughts may become three times more common from the mid-twentieth century to the end of the twenty-first (Sheffield and Wood, 2008). Studies, such as those conducted by Watts et al. (2015) and Gosling (2014), have investigated the link between climate change and drought in the UK, concluding that summer droughts are projected to increase over most of the UK. However, the specific impact of extreme events like droughts on hydropower generation due to climate change remains uncertain (Golgojan et al., 2024b).

Hydropower, a renewable energy source, generates electricity from the movement of water, directly linking its efficiency to water resources. The consistent and reliable operation of hydropower plants heavily depends on the availability and predictability of water sources, which are influenced by seasonal variations, precipitation patterns, and river flows. Hydropower can be categorized into large hydropower, pumped storage, small hydropower, and run of river.

Large hydropower, defined as having a capacity greater than 5 MW according to the British Hydro Association (2022b), varies internationally: the US Department of Energy defines it as above 30 MW, India as above 15 MW, and China as above 25 MW. Besides capacity, factors like size and impoundment volume also classify hydropower plants. Pumped storage hydropower, a type of large hydropower, generates electricity using gravity by releasing water from an upper reservoir, previously pumped from a lower source during low demand and low electricity prices, to drive a turbine during high demand (International Hydropower Association, 2023).

Small hydropower is defined as having a capacity of less than 5 MW (British Hydro Association, 2022b) and typically includes run-of-river plants without artificial lakes behind dams. These are subclassified by size into pico, micro, mini, and small hydropower. Hydropower is a reliable, versatile, and low-cost source of clean renewable energy (YoosefDoost and Lubitz, 2020). It complements variable renewable sources like wind and solar through responsible water management, offering rapid response times, flexibility, and energy storage services, thus meeting demand when intermittent sources are unavailable (Tarroja et al., 2019). Hydropower plants generally have higher capacity factors than wind farms and can be more socially and environmentally acceptable in certain contexts (Sample et al., 2015). Pumped storage hydropower acts like a green, rechargeable battery, storing excess energy when supply exceeds demand and returning energy when needed (Jurasz et al., 2018).

Run of river (RoR) hydropower generation – a type of hydropower that relies on streamflow without a reservoir or impoundment – is particularly susceptible to lower than average precipitation or snowmelt, which can immediately reduce the outflow through turbines, reducing energy generation (Raynaud et al., 2018). The direct relationship between river flow and hydropower output makes RoR hydropower more vulnerable to droughts than conventional impoundment hydropower (Golgojan et al., 2024b). Reservoir-based hydropower schemes have the benefit of storing water during rainy periods and utilising it during droughts, which is not possible with RoR schemes. This research therefore focuses on RoR schemes to demonstrate their vulnerability to droughts and climate change, as they are particularly sensitive to changes in river flows and drought conditions (e.g., Carless and Whitehead, 2013; Mohor et al., 2015).

Drought conditions directly affect hydropower generation by reducing water availability. Wan et al. (2021) analysed the impact of streamflow drought on hydroelectricity production across multiple regions and found that electricity production by hydropower is negatively affected during drought periods, with the severity of impact varying by location and drought intensity. In the western United States, a region heavily reliant on hydropower, an analysis of drought impacts on hydroelectric generation was conducted, which examined over two decades of data from more than 600 hydroelectric plants across 11 states, provided insights into the resilience of the western hydropower fleet to extreme drought conditions (Turner et al., 2022b). Qiu et al. (2023) explored how climate-driven changes in drought could disrupt electricity systems that depend heavily on hydropower, finding that reduced hydropower generation during drought periods could potentially increase reliance on fossil fuel generation, leading to higher emissions and impacts on air quality.

Furthermore, climate change is expected to exacerbate the challenges posed by drought to hydropower generation. Qiu et al. (2023) emphasized the need for ongoing research to understand how evolving climate conditions will impact western hydropower in the future. Similarly, Wang et al. (2020) projected that under the SSP585 scenario (a high emissions pathway), the risk of extreme energy droughts could increase by 88%±1.2% compared to historical levels. These studies highlight the need for adaptive management strategies and further research to enhance the resilience of hydropower systems in the face of changing climate conditions and increasing drought risks.

Based on the previous literature, there are gaps regarding a specific definition for hydropower drought. While the concept is discussed in various studies, a standardised definition is not explicitly presented, with the focus being more on the impacts and consequences of drought on hydropower generation rather than defining the concept of hydropower drought itself.

To determine the impacts of drought on RoR schemes, it becomes imperative to formulate a tailored definition specific to the context of hydropower. Current definitions for drought (e.g., agricultural, hydrological or meteorological drought; Kchouk et al., 2021) lack the specificity and context required to quantify the challenges posed by droughts in the context of hydropower generation. Drought definitions generally fall into two broad categories: conceptual and operational (Wilhite and Glantz, 1985). Conceptual definitions, akin to dictionary entries, establish the conceptual boundaries of drought, providing a generic understanding of the phenomenon. For instance, the Encyclopaedia of Climate and Weather (Schneider et al., 2011) characterises drought as *"an extended period—a season, a year, or several years—of deficient rainfall relative to the statistical multi-year mean for a region"*. While valuable for descriptive purposes, conceptual definitions lack the detail needed to detect the onset of drought. In contrast, operational definitions aim to precisely identify the characteristics and thresholds that delineate the onset, continuation, and conclusion of drought episodes, including their severity (McEwen et al., 2021). Operational definitions serve as the cornerstone of effective early warning systems, enabling proactive responses to emerging drought conditions (Wilhite and Svoboda, 2000). Furthermore, they facilitate analyses of drought frequency, severity, and duration within a given historical period. Drought is typically defined as a prolonged period of water scarcity, caused by large-scale climatic variability and cannot be prevented by local water management alone (van Loon and van Lanen, 2013). A specific 'hydropower drought' definition would allow researchers, policymakers, and stakeholders to focus on the unique aspects of droughts that directly affect hydropower systems and plan better climate resilience plans. Liu et al. (2023) introduced the concept of "energy droughts" for hydropower, defining energy droughts as periods where daily developed hydropower potential falls below the 20th percentile of its long-term average. They found that energy droughts in the Yangtze River basin are closely associated with El Niño-Southern Oscillation

(ENSO) patterns and that the risk of such events is projected to increase significantly under future climate scenarios. Furthermore, the study found that the propagation from meteorological droughts to energy droughts typically takes 4-7 days for most plants in the region. Approximatively 31% of energy drought and meteorological drought events occur simultaneously, highlighting the rapid response of some hydropower systems to drought conditions. The only known definition of hydropower drought is a “*drought that causes a reduction in annual […] generation for more than 10 percent relative to average*” (Turner et al. , 2022). This definition is generally encompassed within the broader category of hydrological drought, lacking specificity and context (e.g., relating the loss of energy during a drought event to the installed capacity of the hydropower scheme). Droughts that affect hydropower generation have distinct characteristics and implications compared to other forms of hydrological droughts, such as their direct impact on electricity generation from hydropower facilities. By providing clarity and specificity, a hydropower drought definition could enhance energy security and promote sustainable hydropower development in the face of changing climatic conditions.

This study aims to understand the interplay between drought and hydropower generation by creating a novel definition for hydropower drought and determining alterations in the frequency, duration and severity of hydropower drought in the future. The novel definition proposed is an operational type, allowing determination of drought characteristics, as well as the exact onset of the drought event. We focus primarily on RoR hydropower using hypothetical schemes selected across the UK as a case study, as RoR hydropower is particularly vulnerable to drought due to their direct response to changes in precipitation, snowmelt and streamflow.

5.4 Definitions and methods

The aim of this research was to address the impacts of drought on hydropower systems by focusing on the unique characteristics of hydropower droughts and developing a specific definition for ‘hydropower drought’ that captures the direct effects on hydropower generation. The objectives include gathering daily river flow data and power output from four RoR hydropower schemes during the drought period, using a threshold level approach to identify hydropower drought events based on hydro energy output falling below defined levels, analysing average values to identify patterns in the data.

5.4.1 Hydropower drought definition

Drought affects many economic and social sectors; therefore, multiple definitions of drought exist, developed by a variety of disciplines and applications. Because drought occurs with varying frequency in nearly all regions of the globe, in all types of economic systems, and in developed and developing countries alike, the approaches taken to define drought also reflect regional and ideological differences (Wilhite, 1993). Drought has, to date, largely been grouped into four predominant types as follows: meteorological, hydrological, agricultural, and socioeconomic (Wilhite and Glantz, 1985). Meteorological (or climatological) drought is expressed solely on the basis of the degree of dryness (often in comparison to some normal or average amount) and the duration of the dry period. Agricultural drought links various characteristics of meteorological drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration (ET), soil water deficits, and so forth. Hydrological droughts are associated with the effects of periods of precipitation short fall on surface or subsurface water supply (i.e., streamflow, reservoir and lake levels, groundwater) rather than with precipitation shortfalls (Dracup et al., 1980a). A comprehensive comparison between the existing hydropower drought definitions and the novel hydropower drought definition proposed in this study is presented in Table 5-1.

Table 5-1: Comparison between existing hydropower drought definitions and the novel hydropower drought definition.

	Existing drought definitions				Hydropower drought
	Meteorological drought	**Hydrological Drought**	**Agricultural Drought**	**Socioeconomic Drought**	
Definition	A period of significantly below-average precipitation	A period of below-average water availability in rivers, lakes, and reservoirs	A period of insufficient moisture affecting crop production	A period when water shortages affect the economy and society	A period of at least five consecutive days when power output from RoR hydropower schemes falls below a critical threshold
Focus	Precipitation deficits	Water flow and storage deficits	Soil moisture deficits	Economic and social impacts	***Focus on Energy Production***: **Relevance**: Directly links drought conditions to hydropower output, providing a clear operational metric. **Improvement**: Addresses the specific needs of hydropower operators, unlike traditional definitions that focus on water availability or precipitation.

	Existing drought definitions				Hydropower drought
	Meteorological drought	**Hydrological Drought**	**Agricultural Drought**	**Socioeconomic Drought**	
Metrics	Rainfall amounts, duration of dry periods	Streamflow rates, reservoir levels	Soil moisture levels, crop stress indicators	Water usage restrictions, economic losses	***Threshold-Based Approach***: **Relevance**: Uses a critical power output threshold to identify drought periods with significant operational impacts. **Improvement**: Provides a practical and actionable metric for managing hydropower resources, ensuring relevance to day-to-day operations. ***Temporal Specificity***: **Relevance**: Incorporates a minimum duration criterion (five consecutive days) to differentiate between short-term fluctuations and sustained drought conditions. **Improvement**: Enhances the practicality of the definition by focusing on periods with significant operational implications, rather than brief anomalies.

	Existing drought definitions				Hydropower drought
	Meteorological drought	Hydrological Drought	Agricultural Drought	Socioeconomic Drought	
Limitations	Indirect link to river flows and hydropower production; focuses on precipitation rather than operational impacts	Does not directly address the impact on energy production for RoR hydropower schemes	Does not consider river flows or hydropower production; primarily relevant to agriculture	Broad and indirect, with a wide range of potential impacts; not specifically focused on hydropower production	Regional specificity, climate model uncertainty, operational variability, temporal resolution constraints, hydrological complexity, stakeholder bias, dynamic environmental conditions, and data availability issues

Hydrological droughts are often out of phase or lag the occurrence of meteorological and agricultural droughts and can be hard to quantify. Droughts that specifically affect hydropower have some distinct characteristics and implications compared to the generalised definition of hydrological drought, such as their direct impact on electricity generation from hydropower facilities. A definition for hydropower drought is needed to quantify specific characteristics and thresholds crucial for recognising the onset, continuation, and conclusion of drought episodes, as well as their severity. To date, the only known attempt to use a hydropower drought definition is in Turner et al. (2022) that defines hydropower drought as a "*drought that causes a reduction in annual […] generation for more than 10 percent relative to average*". However, this definition is encompassed within the broader category of hydrological drought, lacking specificity and context (e.g., relating the loss of energy during a drought event to the installed capacity and expected energy output of the hydropower scheme).

In this study, a 'hydropower drought' definition was developed with a focus on the unique aspects of drought that directly affects hydropower systems and the energy they can generate. This definition was designed specifically for RoR hydropower given their reliance on streamflows but could be extended to other types of hydropower. Hydropower drought is defined in this analysis as:

"a period of where the available power is below a defined level"

using a threshold level approach (Yevjevich, 1967) to identify hydropower drought occurrences or events. Using this definition, a hydropower drought event is initiated when hydro energy output falls below a threshold (e.g., an energy deficit), and is ended when the hydro energy output exceeded that threshold (e.g., an energy surplus) as presented in Table 5-2.

Table 5-2: Hydropower drought type and thresholds used

Hydropower drought type	Thresholds
Extreme hydropower drought	no generation
Severe hydropower drought	power output less than 10% of installed power
Moderate hydropower drought	power output less than 30% of installed power, but above 10% of installed power

Hydropower drought type	Thresholds
Mild hydropower drought	power output less than 50% of installed power, but above 30% of installed power

5.4.2 Data and case study locations

Hydropower drought events were determined based on the definition above and daily power produced at four RoR schemes (Figure 5-1) using daily river flows from the Enhanced Future Flows and Groundwater (eFLaG) dataset (Hannaford et al., 2022). The eFLaG dataset provides nationally consistent hydrological (river flow, groundwater level and groundwater recharge) projections for the UK. This dataset is based on the latest UK Climate Projections (UKCP18; Lowe et al., 2019) considering a high emission scenario RCP8.5. The eFLaG projections span from 1981 to 2080, with an accompanying observation-driven dataset providing river flow and groundwater level/recharge simulations for 1962 (1963 for river flow) to 2018. The future projections were fed into four river flow models (GR4J, GR6J, PDM, and G2G) to simulate flows at 200 river catchments. GR4J and GR6J models, part of the airGR suite for R software, are notable for their automatic parameter optimization, which allows their application across diverse catchments. GR4J has been used globally for hydroclimate research and operational forecasting in the UK, while GR6J, with its enhanced low-flow simulation capabilities, has gained traction in UK water resource applications. Both models were calibrated using the modified Kling–Gupta efficiency, ensuring comprehensive evaluation of simulated versus observed flows.

The PDM model, known for its flexibility in configuring catchment flow regimes, incorporates soil water storage and runoff production mechanisms, and routes water using non-linear storage equations or linear reservoir cascades. Under the eFLaG project, single-zone PDM models were used, initialized with observed flow data, and optimized to achieve zero bias and maximum modified Kling-Gupta efficiency.

The G2G model, a distributed model, examines the spatial coherence and variability of floods and droughts at various scales, using observed rainfall and PET for historical and climate model-driven scenarios from 1963 to 2080. The regional climate projections were created using the Hadley Centre global climate model and regional climate models, resulting in 12 high-resolution projections covering December 1980 to November 2080.

Model evaluations were conducted in two stages: the first stage evaluated model performance against observed climate data using various metrics, and the second stage assessed model performance with climate model outputs, comparing statistical characteristics over a common baseline period. Hannaford et al. (2022) summarized the evaluation metrics performance across all catchments, noting that the GR4J model showed good performance overall, with some outliers in drought metrics. The GR6J model performed slightly better in low-flow catchments, the PDM model excelled in low-flow and drought indicators, and the G2G model, although performing well, generally scored lower due to its lack of individual catchment calibration.

Simulated eFLaG daily flow time series (for four hydrological models: G2G, GR4J/GR6J and PDM) and percentile flows for each gauge near the RoR scheme were compared to the gauged and percentile flows from the National River Flow Archive to assess the accuracy of the eFLaG dataset, using coefficient of determination (R^2) (Steel and Torrie, 1962) in Golgojan et al. (2024b). Comparison timeseries and duration curves are presented in the Supplementary Material (Figure S3 1 and Figure S3 2).

The statistical analyses and data processing were performed using MATLAB R2023a (MATLAB R2023a, 2023) using built-in MATLAB functions. Spatial data processing and visualization were conducted using a combination of QGIS version 3.22 (QGIS Development Team, 2022) and ArcGIS 10.8 (ESRI, 2023).

Gauging station ID	RoR intake ID	RoR Type	Installed power [kW]	Intake Easting	Intake Northing	Turbine type	Design flow [m^3/s]	Net head [m]	Peak turbine efficiency
83006	2509	Small	1848	239637	613901	Francis	9.05	28.4	0.89
27035	189463	Mini	328	400527	446385	Cross-flow	3.77	15.55	0.816
28082	209114	Micro	12	455224	300961	Cross-flow	0.60	3.59	0.816
39049	115426	Pico	1.5	509534	183987	Cross-flow	0.11	2.4	0.816

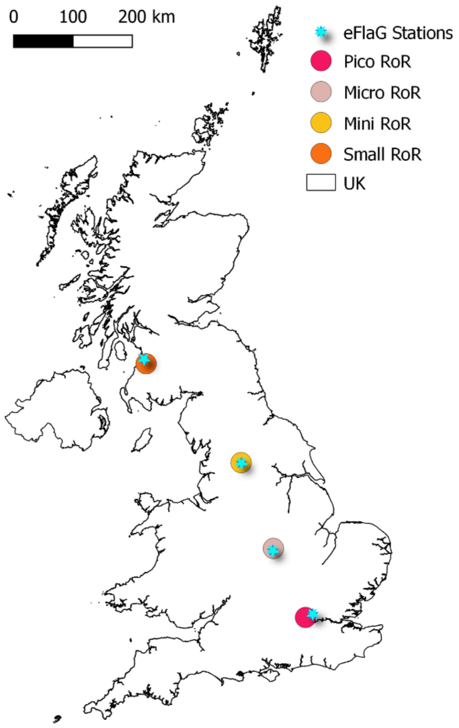

Figure 5-1: Location and characteristics of the virtual run of river (RoR) schemes used in this study. Information (RoR size, installed power, location, turbine type, design flow and head, and peak turbine efficiency) about the RoR schemes and gauging stations are taken from Golgojan et al. (2024a)*. The locations of the eFLaG gauges used in this study are also represented next to each RoR scheme.*

Four hypothetical RoR schemes across the UK (Figure 5-1) were chosen to test the hydropower drought definition and use it to assess the potential effects of climate change on hydropower drought. The RoR locations were taken from Golgojan et al. (2024a), which provides the latest dataset containing potential RoR scheme locations and characteristics (e.g., design flow, head, penstock size). The four RoR schemes used in this study are hypothetical. These simulations were designed to be as realistic as possible, based on established principles of hydropower generation and known hydrological conditions (see Golgojan et al. (2024a). However, it's important to note that while they aim to reflect actual operational conditions, there may be discrepancies due to the inherent limitations of any simulation. The four locations comprised a pico, a micro, a mini and a small RoR scheme (see Golgojan et al. (2024a) for definitions), which were selected to demonstrate various hydropower drought durations, frequencies and severities to different sizes and locations of RoR and possible climate change impacts (Figure 5-1). The RoR locations were chosen to ensure a comprehensive representation of geographical diversity across the UK. This selection spans from the north-west of England, represented by the small RoR scheme, to the central region (mini and micro RoR schemes), and extends to the south-east of England, as exemplified by the pico RoR scheme. The chosen RoR schemes exhibit a diverse range of heads, varying from 2.4 m to 28.4 m, and design flows, ranging from 0.11 m^3/s to 9.05 m^3/s. Notably, while the mini, micro, and pico RoR virtual schemes are equipped with Cross-flow turbines, the small RoR scheme utilises a Francis turbine, contributing to a comprehensive exploration of different turbine technologies. This selection ensures a robust and representative examination of hydropower drought vulnerability across varying geographic and technical contexts.

An important assumption was that the RoR schemes will not undergo periods of maintenance, or that maintenance will be done in the periods when hydropower cannot be generated. Therefore, there would be no anomalous periods of hydropower drought generated as a result of maintenance. If plant maintenance is performed when the RoR scheme could otherwise generate electricity, then those periods could be interpreted erroneously as drought. It is also a requirement to ensure that a compensation flow (also known as residual or environmental flow) is always flowing through the river where the RoR scheme is installed. In this analysis, the compensation flow was selected as Q_{95} (the flow that is exceeded 95% of the time).

5.4.3 Analytical approach

Using the above hydropower drought definition, data and thresholds, a “run-test” was used to identify drought periods and their statistical properties (duration, frequency and severity). However, minor droughts were excluded to ensure that statistics related to drought are not skewed. Minor droughts are typically short in duration and have slight deficit volumes. Different studies have excluded minor droughts in different ways. For example, (Zelenhasić and Salvai, 1987) excluded minor droughts when their deficit volume was less than a certain percentage of the maximum observed deficit volume. Madsen and Rosbjerg (2008) excluded minor droughts with deficit volumes or durations smaller than predefined percentages of the mean deficit volume or duration, respectively. Similarly, Jakubowski and Radczuk (2004) excluded minor droughts with drought duration shorter than a given minimum value. In this study, we used five days as the minimum duration for a drought, similar to Wu et al. (2015). If a drought event lasted less than five days it was excluded from the analysis, therefore hydropower drought was only considered if it occurred for at least five consecutive days.

Testing and sensitivity analysis

A sensitivity analysis of the key hydropower drought definition and power output was undertaken to determine how the threshold selection influences hydropower drought duration, frequency and severity. This approach aligns with recent studies that have examined the sensitivity of hydropower to various drought conditions (Voisin et al., 2020, 2016). The thresholds chosen for this analysis are (1) the duration threshold for an event to be considered a drought and (2) the power output thresholds for the severe, moderate and mild droughts (see Table 5-2 for definition).Sensitivity analyses serve multiple purposes, including the identification of influential input factors in a model output for prioritisation, gaining insights into model performance and output behaviour (e.g., consistency), and calibrating input factors (Nogal and Nogal, 2021). The number of minimum consecutive days for a “run-test” to qualify as a hydropower drought event were altered from three to seven days, a range that aligns with the drought durations observed in regional studies such as Liu et al. (2023), which found energy droughts for hydropower lasting 2-24 days in the Yangtze River basin. Additionally, the power output thresholds for severe, moderate, and mild drought were modified in three intervals:

- interval 1:
    - severe drought - <5% of installed power
    - moderate drought – 5%-25% of installed power

- mild drought – 25%-50% of installed power

- interval 2, which was chosen as per the definition.
- interval 3:
  - severe drought - <15% of installed power
  - moderate drought – 15%-35% of installed power
  - mild drought – 35%-50% of installed power

The threshold for extreme drought was unchanged for simplicity.

Hydropower drought events characteristics (duration, frequency, severity) were calculated for the 30-year baseline and future periods. Each drought event was characterised by its duration, frequency, and severity (see Table 5-2). The duration of each hydropower drought event was recorded, and the average hydropower drought duration for each season was determined. The number of occurrences of each hydropower drought type were obtained, with the hydropower drought frequency presented as an average number of hydropower drought events for each season. Hydropower drought severity was determined as the energy deficit (energy lost during the hydropower drought event) for each season. Furthermore, to determine if drought events were in a sequence or isolated, the average duration between events was also calculated.

Table 5-3: Hydropower drought characteristics, their method of calculation and unit

Drought characteristic	**Method of calculation**	**Unit**
Duration, D	$D = \frac{Total\ days\ of\ drought\ per\ season}{No. of\ drought\ events\ per\ season}$	days
Frequency, F	$F = \frac{No. of\ drought\ events}{30\ years\ (time\ period\ analysed)}$	-
Severity, S	$S = Drought\ event\ duration\ \cdot (Installed\ power - Actual\ power)$	kWh
Actual power refers to the power output during the hydropower drought period		

Effects of climate change on hydropower drought

The potential effects of climate change on hydropower drought were determined using the data and case study locations. Hydropower drought events were determined at each RoR scheme using daily river flows for a future 30-year period from 2030 to 2059 the eFLaG projections (Hannaford et al., 2022) (Figure 5-1).

The eFLaG dataset provides nationally consistent hydrological projections for the UK, based on the UK Climate Projections (UKCP18) under a high emission scenario (RCP8.5). This dataset uses bias-corrected 'Regional' 12km projections from UKCP18 and inputs them into four river flow models (GR4J, GR6J, PDM, and G2G) to simulate flows across 200 river catchments. The GR4J and GR6J models, part of the airGR suite for R software, are designed for effective hydrological modeling with automatic parameter optimization, where GR4J has been used globally and GR6J is tailored for improved low-flow simulations and groundwater exchange. Both models were calibrated using the modified Kling–Gupta efficiency criterion.

The Probability Distributed Model (PDM) is a lumped rainfall-runoff model that simulates various catchment flow regimes, incorporating soil water storage and runoff production. The eFLaG project used single-zone PDM models with daily time steps, focusing on optimizing model performance through an automatic calibration procedure.

The G2G model, a distributed model examining the spatial coherence and variability of floods and droughts, was run with initialization from observed rainfall and PET for historical and climate model-driven scenarios from 1963 to 2080. It covered 186 of the 200 eFLaG catchments.

The regional climate projections were generated using the Hadley Centre global climate model and regional climate models, resulting in 12 high-resolution (12km) projections consistent across the UK for the period from December 1980 to November 2080. The models were evaluated in two stages: Stage 1 involved comparing simulations driven by observed climate data against river flow and groundwater observations using various metrics, while Stage 2 assessed model performance driven by climate model outputs, focusing on statistical characteristics of river flow and groundwater levels.

Hannaford et al. (2022) summarised the evaluation metrics across all catchments, noting that the GR4J model showed good overall performance, with some outliers in drought metrics, particularly in the southeast and London. The GR6J model performed better in low-flow catchments, while 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 due to its lack of calibration to individual catchments. The eFLaG dataset has been instrumental in understanding the potential impacts of climate change on river flows and groundwater, aiding in informed decision-making and policy development.

Changes in future hydropower drought relative to the baseline period (1980-2009) were calculated based on annual and seasonal differences between hydropower drought characteristics and daily power produced.

The following equations were used to determine hydropower drought characteristics for the baseline and future periods. Let D_i represent the duration of the i^{th} hydropower drought event. The duration was recorded for each event during both the baseline ($D_i^{baseline}$) and future (D_i^{future}) periods. The average duration ($\overline{D}_{season}$) of hydropower drought events for each season was calculated by summing the durations of all events in a season ($\sum_i D_i^{season}$) and dividing by the number of events ($N_{events,season}$) in that season.

$$\overline{D}_{season} = \frac{\sum_i D_i^{season}}{N_{events,season}} \qquad \textit{Eq. (5-1)}$$

The number of occurrences ($N_{occurences,season}$) of each hydropower drought type can be determined for each season. The hydropower drought frequency (F_{season}) was then calculated as the average number of hydropower drought events for each season.

$$F_{season} = \frac{\sum_i N_{occurences,season}}{N_{events,season}} \quad \textit{Eq. (5-2)}$$

The severity (S_i) of each hydropower drought event was determined as the energy deficit, representing the energy lost during the hydropower drought event for each season. Equation 5-3 calculated the energy deficit for each day of the hydropower drought event, summed up these deficits over the entire event duration, and represented the severity of the drought event. The severity was determined by the difference between the installed power and the actual power produced during the drought event, weighted by the duration of each drought event in days, as follows:

$$S_{season} = \sum\nolimits_{t \in event} (P_{installed} - P_t) \cdot \Delta t \quad \textit{Eq. (5-3)}$$

Where, S_{season} is the severity of the hydropower drought event for each season, $P_{installed}$ is the installed power of the hydropower scheme, P_t is the power produced on day *t* during the drought event and Δ*t* is the duration of the drought event in days.

The average duration ($\overline{D}_{between\ events}$) between hydropower drought events was calculated by summing the durations between consecutive events ($\sum_i D_{between\ events,i}$) and dividing by the number of events minus one ($N_{events} - 1$).

$$\overline{D}_{between\ events} = \frac{\sum_i D_{between\ events,i}}{N_{events} - 1} \quad \textit{Eq. (5-4)}$$

The differences between the baseline period (1980-2009) and the future period (2030-2059) for hydropower drought characteristics were calculated based on the following equations:

$$\Delta D_{season,\%} = \left(\frac{\overline{D}_{season,future} - \overline{D}_{season,baseline}}{\overline{\overline{D}}_{season,baseline}}\right) \cdot 100 \qquad \textit{Eq. (5-5)}$$

Where $\overline{D}_{season,future}$ represents the average duration of hydropower drought events for each season in the future period, and $\overline{D}_{season,baseline}$ represents the corresponding average duration in the baseline period.

$$\Delta F_{season,\%} = \left(\frac{F_{season,future} - F_{season,baseline}}{F_{season,baseline}}\right) \cdot 100 \qquad \textit{Eq. (5-6)}$$

Where $F_{season,future}$represents the hydropower drought frequency for each season in the future period, and $F_{season,baseline}$represents the corresponding frequency in the baseline period.

$$\Delta S_{season,\%} = \left(\frac{S_{season,future} - S_{season,baseline}}{S_{season,baseline}}\right) \cdot 100 \qquad \textit{Eq. (5-7)}$$

Where $S_{season,future}$ represents the severity of the hydropower drought events in the future period, and $S_{season,baseline}$ represents the corresponding severity in the baseline period.

$$\Delta \overline{D}_{between\ events,\%} = \left(\frac{\overline{D}_{between\ events,future} - \overline{D}_{between\ events,baseline}}{\overline{D}_{between\ events,baseline}}\right) \cdot 100 \qquad \textit{Eq. (5-8)}$$

Where $\overline{D}_{between\ events,future}$represents the average duration between hydropower drought events in the future period, and $\overline{D}_{between\ events,baseline}$ represents the corresponding average duration in the baseline period.

These equations were used for the annual differences to track the variations in hydropower drought characteristics on a yearly basis.

5.5 Results

5.5.1 Hydropower drought definition sensitivity analysis

The threshold's minimum number of consecutive days for a hydropower drought event and the power output thresholds for severe, moderate, and mild drought were modified in three intervals. The minimum number of days required for a drought event to occur exhibits the most significant impact on drought frequency, going from approx. four occurrences per year if the minimum number of days for a drought is three down to one occurrence per year if the minimum number of days is seven, as demonstrated in Figure 5-2. However, altering the intervals for severe, moderate and mild hydropower droughts was found to have minimal impact. As would be expected, decreasing the number of minimum days required for a drought event was found to lead to an increase in severity, which is calculated as the average energy lost during a drought event, due to lower thresholds including more minor drought events. Therefore, the most important parameter when defining hydropower drought is the minimum duration threshold. While the power output thresholds may be modified to suit an operating programme, they do not affect hydropower drought characteristics. Hence, the hydropower drought definition proposed in this study is solely dependent on changes to its minimum duration threshold.

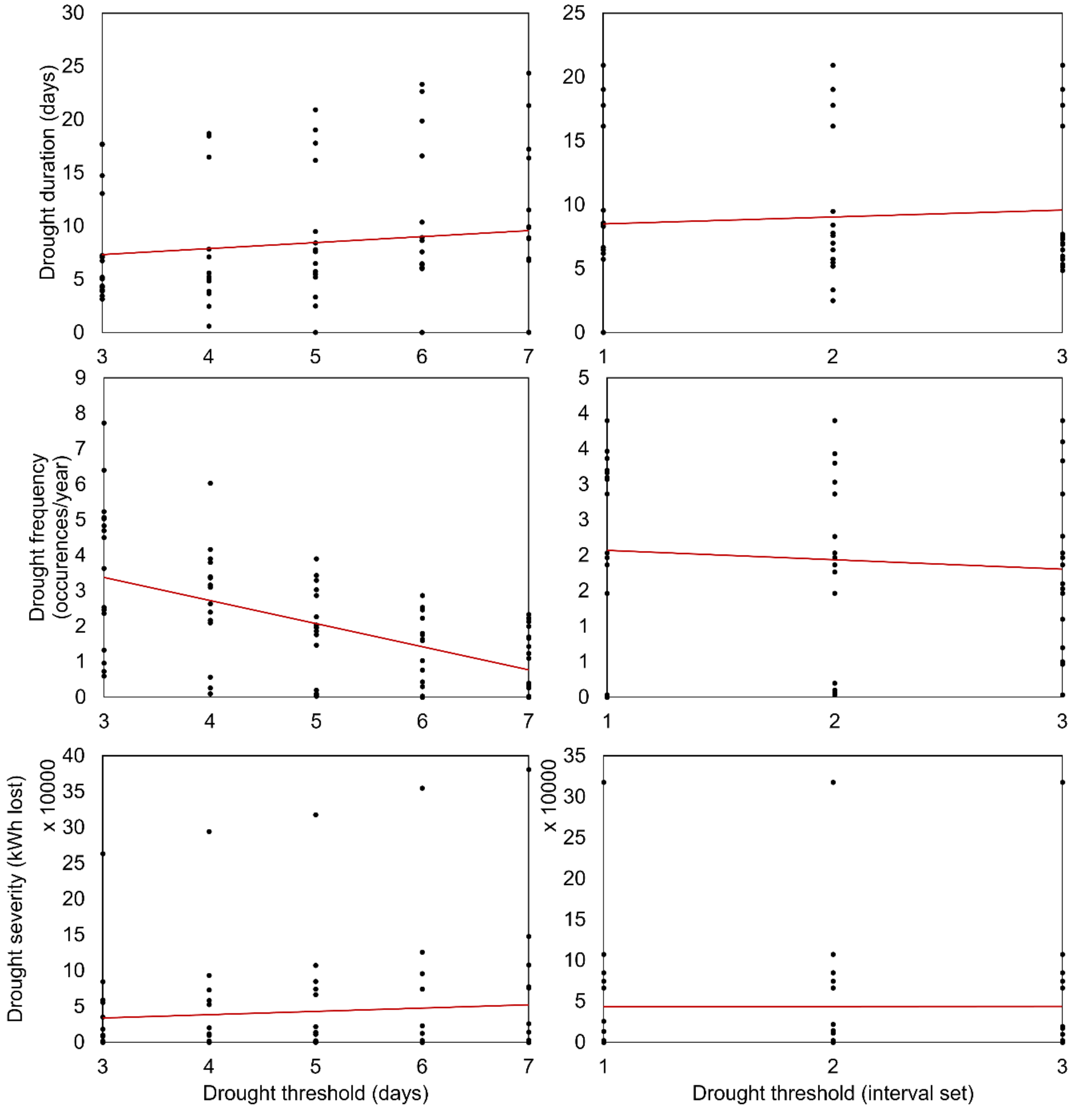

Figure 5-2: Sensitivity analysis of the thresholds chosen in the hydropower drought definition. The drought threshold (days) refers to the minimum number of consecutive days with power output below the thresholds from the definition above; the drought threshold (interval set) refers to the intervals for severe, moderate and mild drought as follows: interval 1 refers to severe droughts threshold <5% of installed capacity, moderate drought between 5% and 25% and mild drought between 25% and 50%; interval 2 is the one from the hydropower definition above and interval 3 refers to severe droughts threshold <15% of installed capacity, moderate drought between 15% and 35% and mild drought between 35% and 50%. The dots represent the values for each hydropower drought metric (duration, frequency and severity) at each of the four virtual RoR locations from this study. The linear trend that generated by the points is represented by the red line.

5.5.2 Observed hydropower drought duration, frequency and severity

Using the hydropower drought definition proposed, the duration, frequency and severity of the drought events were determined at each of the four hypothetical RoR schemes in the UK. During the analysed historical 30-year baseline interval (1980-2009), periods of hydropower drought were detected at all the RoR schemes. The average duration of a drought event was found to be 8.64 days, with an average frequency of 0.58 (occurrences/year) and an average severity (energy lost during a hydropower drought event) of 40 MWh.

The average drought duration was found to be similar at the four virtual RoR schemes, ranging from 8.24 to 9.33 days annually. The longest average duration is 12 days in spring at the pico RoR scheme, situated in the southeast of the UK. This is closely followed by the mini and small RoR schemes (English Midlands and northwest of England) with an average duration in of approx. 10 days in spring. The shortest durations are recorded in winter at all the RoR schemes. Looking at each hydropower drought type, extreme hydropower drought has the longest duration in summer – 23.3 days – at the mini RoR scheme, in the centre of England. The other types of hydropower droughts (severe, moderate, mild) have much shorter durations, with the longest duration of 10.71 days in spring at the pico RoR scheme.

Examining annual hydropower drought frequency, it ranged from 0.48 (approximately 1 event every 2 years) at the small RoR scheme to 0.73 (almost 1 event per year) at the mini RoR scheme. The frequency did not vary significantly annually across the case studies; however, there were seasonal differences among the RoR case studies. In summer, the micro RoR scheme located in the centre of the UK had the highest hydropower drought frequency (1.14 – see Figure 5-3), and all the other RoR schemes exhibited high frequencies in summer, compared to other seasons. Conversely, the lowest frequencies were observed in winter for all RoR schemes. Therefore, based on this case study, hydropower drought frequency appeared to be more dependent on the season than on geographical location or system type.

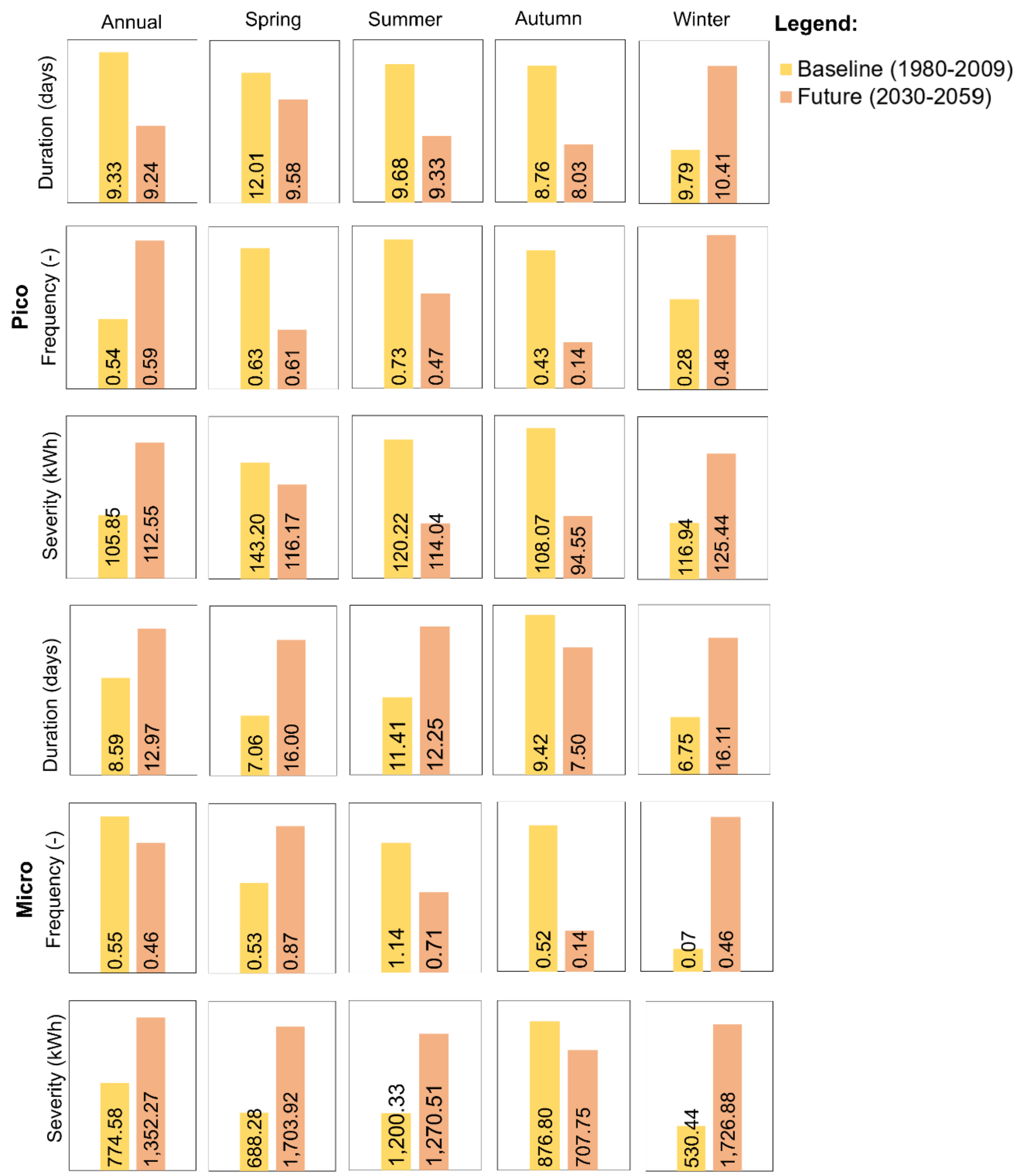

Figure 5-3: Differences between average hydropower drought metrics at all the pico and micro run of river (RoR) schemes analysed in the future from the baseline. The results show annual and seasonal changes for each drought metric.

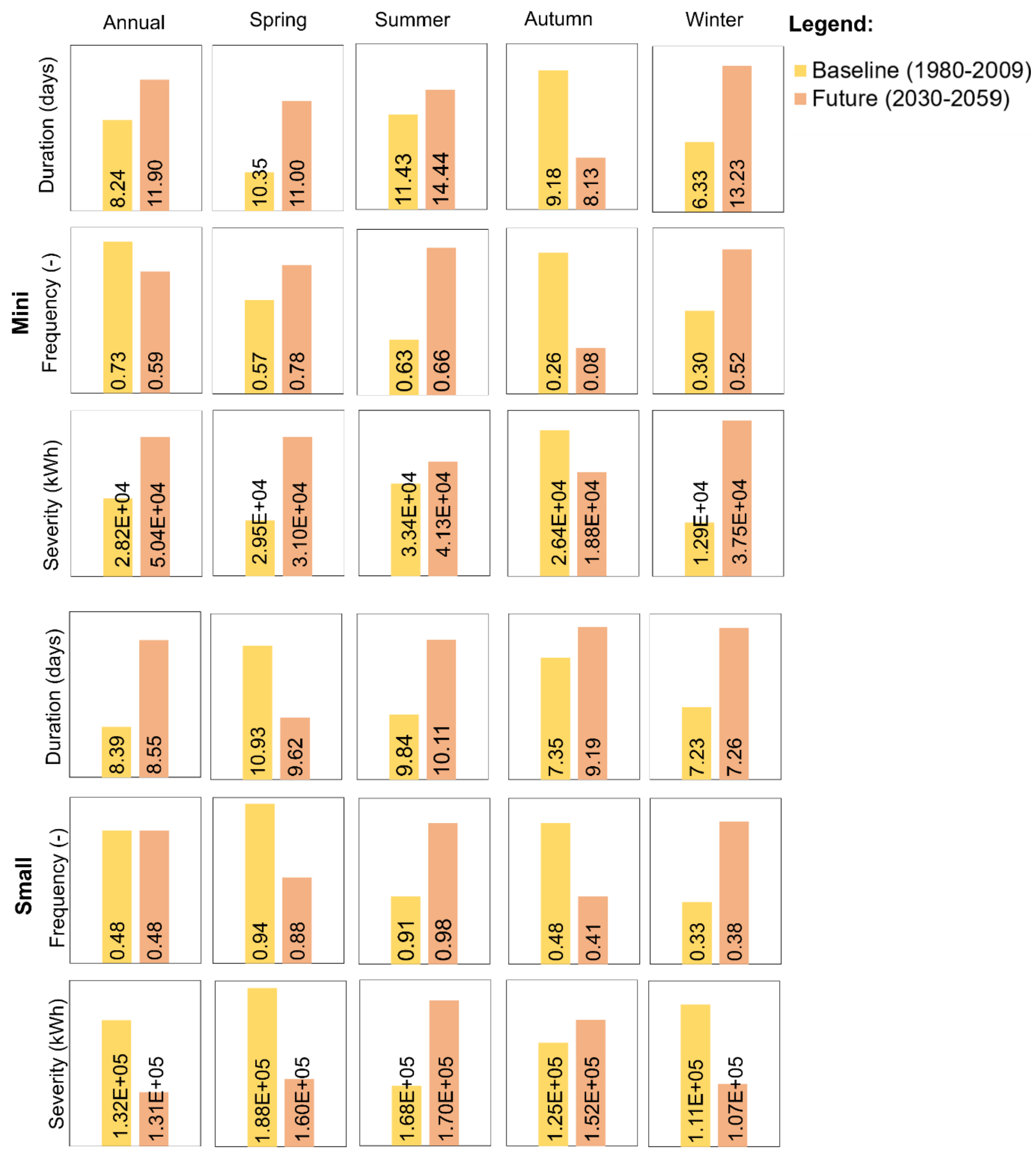

Figure 5-4: Same as Figure 5-3, for the mini and small run of river (RoR) schemes.

Hydropower severity, measured as energy lost during the drought event (refer to Table 5-3 for details), revealed variations based on RoR scheme size. The small RoR scheme, with the largest installed power of 1848 kW (refer to Figure 5-1 for details), exhibited the highest severity, with an average of 132 MWh lost over the year, approximately a 2% reduction in the expected yearly energy output. While a 2% loss may seem modest, in monetary terms, this equates to a £13,398 loss (considering the wholesale electricity price of £101.5 per MWh - (Trading Economics, 2023). A comparable yearly energy loss percentage is evident across all RoR schemes. Seasonally, the greatest hydropower drought severity occurred in summer for the micro, mini, and small RoR schemes, while the pico RoR scheme experienced the most significant energy loss during spring.

Looking at each RoR type (see Figure 5-1 for details), the pico RoR scheme (situated in southeast UK) was the most severely impacted by hydropower drought in spring, with an average of 143.2 kWh lost during the spring season (approximately 11% reduction in generation). During summer, the micro and mini RoR schemes exhibited elevated hydropower drought severity, reaching 1200 kWh and 33448 kWh, respectively, along with prolonged hydropower drought durations averaging approximately 11 days, surpassing the annual average. Conversely, the majority of RoR schemes experienced relatively shorter hydropower drought durations, ranging between 6.3 to 7.2 days, except for the pico RoR scheme, which manifested nearly 10 days of hydropower drought during winter.

When examining hydropower drought without considering the various drought types proposed (refer to Table 5-2), the characteristics appear relatively consistent across the four case studies. However, upon closer examination of each hydropower drought type individually, notable variations in results emerge. Extreme hydropower drought exhibits the longest durations and severities, with one of the highest frequencies, followed by moderate hydropower drought. Severe hydropower drought, despite having one of the shortest average durations, can manifest frequently, particularly at the small RoR scheme. Mild hydropower drought demonstrates a high frequency, accompanied by short durations and, consequently, lower severity.

On average, an event of extreme hydropower drought was found to last between 7 to 21 days in spring, 17 to 23 days in summer, 9 to 19 days in autumn, and 7 to 13 days in winter on average at the four RoR scheme locations in the UK (Figure 5-5). Extreme hydropower drought occurrences were found mostly in spring, summer and autumn, with only two of the four RoR schemes analysed encountering extreme hydropower drought in winter. Seasonally, the extreme hydropower drought frequency and severity were found to be highest in summer, with approximatively one event per summer, most likely due to both high frequency and long durations of drought events in summer. Of the schemes analysed, the mini RoR scheme (ID 189463) was found to exhibit the longest average drought duration and second highest frequency of extreme hydropower drought.

Severe hydropower drought is most common at the small RoR scheme (ID 2509) compared to the other schemes, occurring every season. For the micro RoR scheme (ID 209114), severe hydropower drought was only encountered in autumn, having an average duration of 5 days and appearing two times in the 30-year baseline period. Severe hydropower drought frequency differs greatly between RoR schemes however. For example, while the small RoR schemes have at least one hydropower drought event every spring, the other RoR schemes have none. All RoR schemes analysed display at least one severe hydropower drought event in autumn.

Moderate hydropower drought was encountered in three of the four RoR schemes analysed. It lasted on average between 5 and 11 days in spring, between 5 and 8 days in summer, between 6 and 9 days in autumn and between 5 and 9 days in winter. In spring, the frequency was found to be between 1 event every 1.5 years to 1 event every 3.75 years. In summer, depending on the RoR scheme, moderate hydropower drought is encountered from twice per season (for the pico and micro RoR schemes) to once every 6 years (for the small RoR scheme). In autumn, at the pico and micro RoR schemes, moderate hydropower drought appears once per season, and at the small RoR scheme, it was found to appear once every 5 years. In winter, moderate hydropower drought is encountered at the pico, micro and small RoR schemes. An event was encountered once a year at the micro and small RoR, and once every 3 years at the pico RoR scheme in winter. While significant, the severity of moderate hydropower drought was smaller than the severity of extreme and severe hydropower droughts.

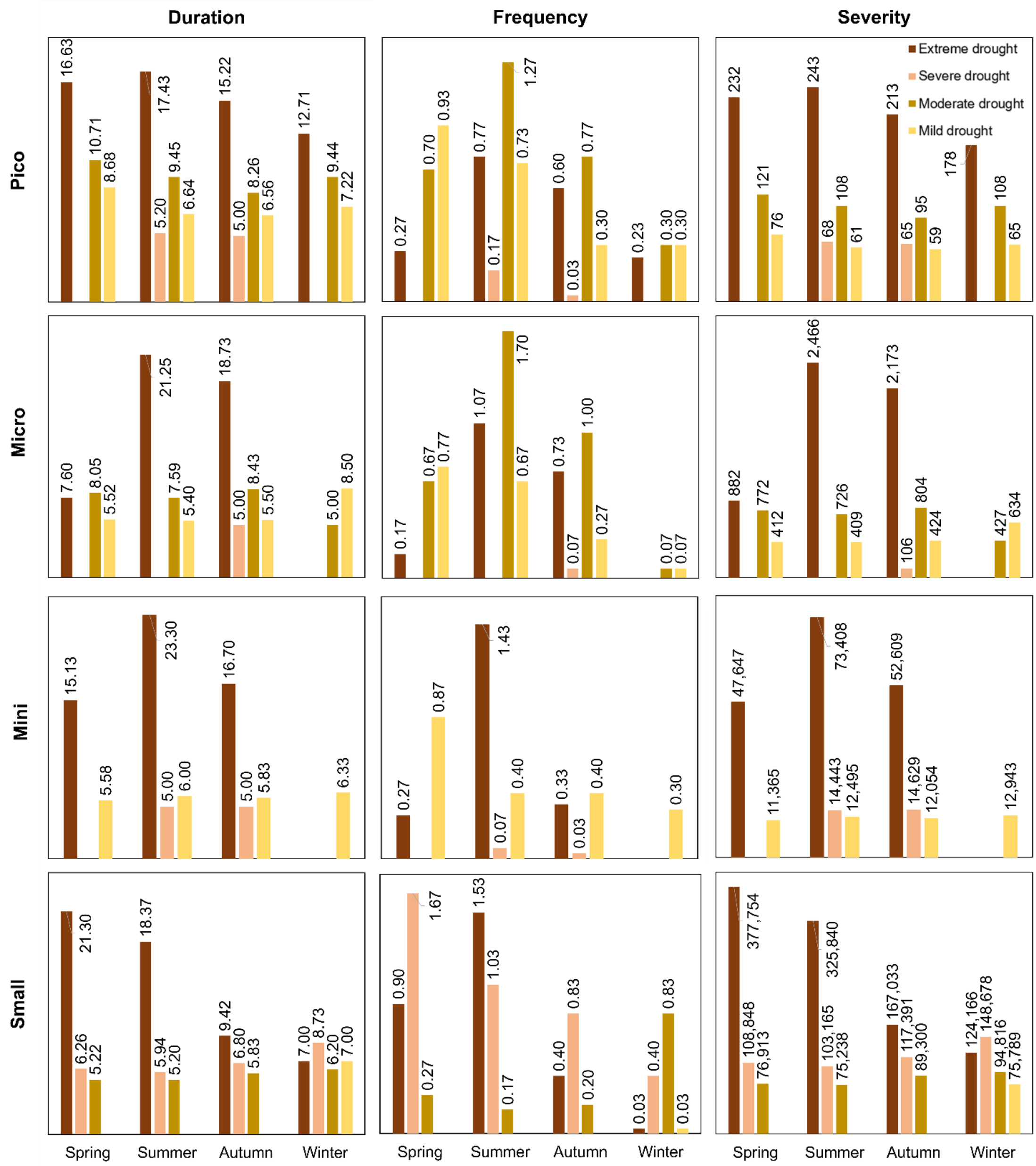

Figure 5-5: Average Duration, frequency and severity for each category of hydropower drought at all the RoR schemes in this study for the baseline (1980-2009). Duration refers to average days per hydropower drought event, frequency refers to the average number of hydropower drought events per season and severity refers to lost energy during the hydropower drought event and is measured in kWh.

Mild hydropower drought was shown to last, on average, between 5 and 9 days, depending on the season. The longest average mild hydropower drought duration was 8.68 days in spring at the pico RoR scheme. Mild hydropower drought can appear in all seasons, but it was encountered in winter at all the RoR schemes analysed. This is, however, perhaps to be expected due to the nature of this type of hydropower drought characterised by a power output ranging from 30 to 50% of the installed capacity. The frequency of mild hydropower drought was found to range from one event every year to one event every 3.75 years, depending on the season and the RoR scheme. Overall, the severity (energy lost during a hydropower drought event) of mild hydropower drought is smaller than the other types of droughts analysed in this study.

5.5.3 Climate change impacts on hydropower drought

The findings showed that annually drought event durations were anticipated to extend by approximately two days at the RoR scheme locations analysed, accompanied by a 13.5% increase in future frequency and severity (2030-2059) (Table 5-4). However, more significant future projected changes were shown seasonally, particularly during winter, where the average drought duration was projected to increase by four days per drought event, and the average frequency to nearly double with an 89.4% increment. This increase was calculated as an average value for all the four RoR schemes analysed. Conversely, in autumn, the frequency of drought events was predicted to decrease by half.

Table 5-4: Comparison between the drought metrics (duration, frequency and severity) at the four virtual RoR case studies in the future (2030-2059) from the baseline (1980-2009). The results show annual and seasonal changes for each drought metric

Season	Drought metric	Baseline (1980-2009)	Future (2030-2059)	Difference (%)
Annual	Duration (days)	8.64	10.66	23.44
	Frequency (occurrences/year)	0.75	0.66	13.29
	Severity (kWh)	40,300	45,700	13.59
Spring	Duration (days)	10.09	11.55	14.52
	Frequency (occurrences/season)	0.67	0.78	16.80
	Severity (kWh)	54,500	48,300	-11.42
Summer	Duration (days)	10.59	11.53	8.86
	Frequency (occurrences/season)	0.86	0.70	-17.86
	Severity (kWh)	50,700	53,100	4.67
Autumn	Duration (days)	8.68	8.21	-5.34
	Frequency (occurrences/season)	0.42	0.20	-53.40
	Severity (kWh)	38,000	43,000	13.06
Winter	Duration (days)	7.53	11.75	56.16
	Frequency (occurrences/season)	0.24	0.46	89.40
	Severity (kWh)	31,100	36,600	17.65

The analysis of different RoR schemes demonstrated substantial variations in their responses to future changes to drought characteristics (Figure 5-3 and Figure 5-4). For instance, the pico and small RoR schemes exhibited minimal alterations in drought duration, frequency, and severity on an annual basis compared to micro and mini RoR schemes that were projected to experience almost a twofold increase in drought event severity in the future (approximately 75% and 78% increase for micro RoR and mini RoR, respectively). Notably, during autumn, most of the virtual RoR schemes exhibit a reduction in drought duration, frequency, and severity. However, hydropower drought duration, frequency and severity show a notable increase during winter. For instance, at the micro RoR scheme (ID 209114. see Figure 5-1 for details), drought frequency was projected to increase by 580%, increasing from approximately one drought event every 15 years to one drought event every two years.

A notable increase in the duration of extreme droughts was observed across all virtual RoR systems and seasons, apart from the micro and mini virtual RoR in autumn (Figure 5-3, Figure 5-4and Figure 5-6). Although severity was also projected to increase significantly across all RoR schemes in the future (2030-2059), their frequency largely decreases. Severe hydropower droughts, however, were projected to become more variable in the future, showing a decline in severity but a rise in frequency. As a result, projecting the future likelihood of severe hydropower droughts was more uncertain than extreme hydropower droughts. No consistent trends of either future increasing or decreasing moderate or mild hydropower drought were found across various virtual RoR schemes or seasons.

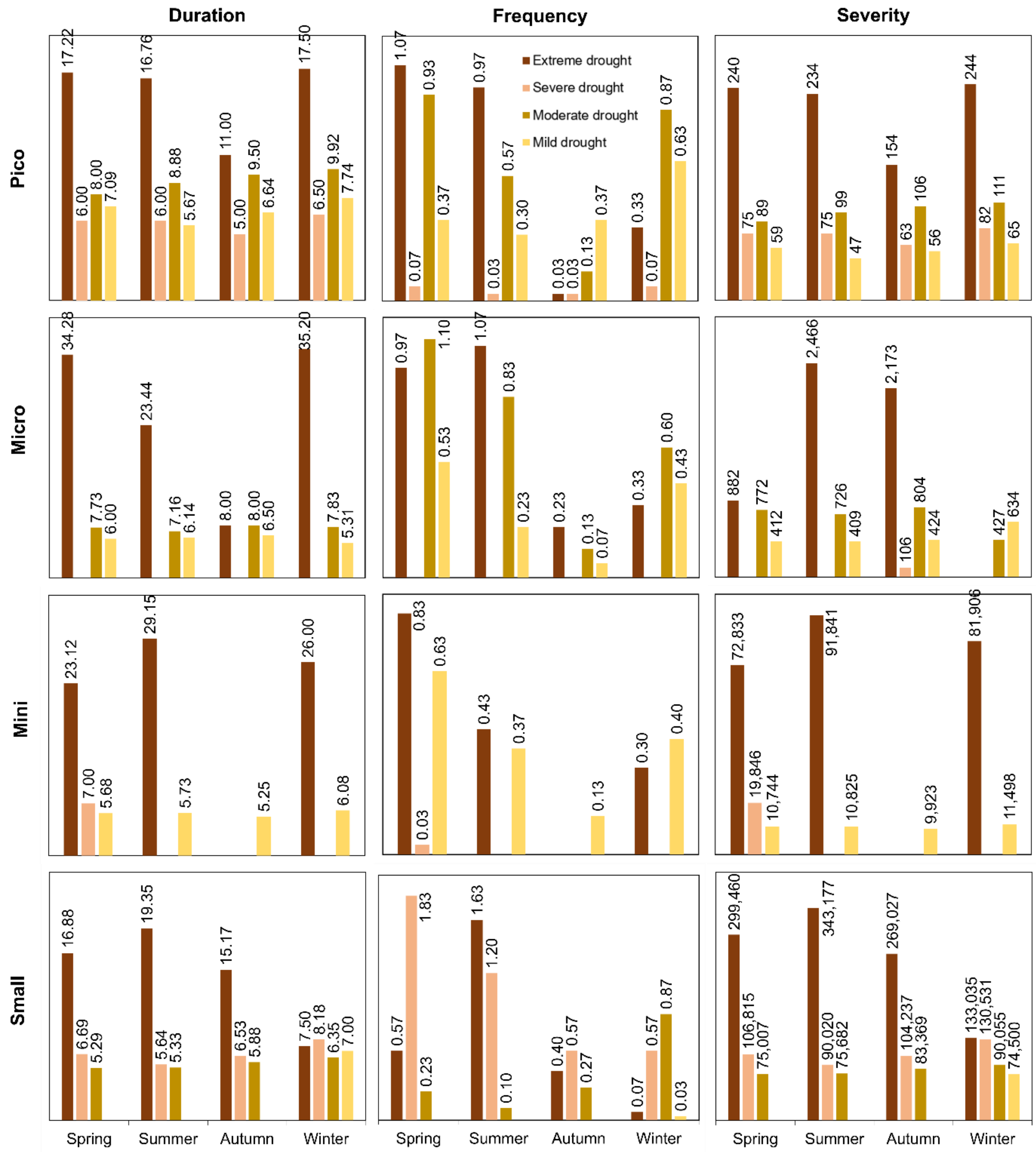

Figure 5-6: As for Figure 5-5, showing future (2030-2059) projected duration, frequency and severity for each category of hydropower drought at all the RoR schemes.

A slight future decreasing trend in the average duration between hydropower drought events was found (Table 5-5). In the future (2030-2059), the mini RoR virtual scheme experienced a nearly 50% reduction in the average duration between hydropower drought events compared to the baseline period. Conversely, both the micro and mini RoR schemes exhibit an increase of less than a day. In contrast, the pico RoR scheme showed a slight rise in the average duration between hydropower drought events, transitioning from 39.51 days in the baseline to 42.25 days in the future.

Table 5-5: Comparison between the average duration between hydropower drought events for all the RoR schemes analysed in the future (2030-2059) from the baseline (1980-2009).

RoR type	Average duration between hydropower drought events (days)		
	Baseline (1980-2009)	Future (2030-2059)	Difference (days)
Pico	39.51	42.25	2.74
Micro	40.45	39.93	-0.52
Mini	75.65	48.28	-27.37
Small	34.43	34.18	-0.25
All RoR	47.51	41.16	-6.35

5.6 Discussion

A novel definition for hydropower drought was created and tested here using four hypothetical RoR schemes. Prior to this study, the term 'hydropower drought' had only loosely been defined, often being subsumed within the broader category of hydrological drought (Turner et al., 2022b). The absence of a clear definition of hydropower drought has, to date, hindered the characterisation and understanding of how drought events affect hydropower generation. This study, for the first time, establishes a tailored definition for hydropower drought that considers the key response of the system – i.e., the hydro energy output.

Hydropower drought – defined here as a period of minimum five consecutive days when power output is below a certain level – uses a threshold level approach to identify hydropower drought events beginning when the hydro energy output falls below a threshold (i.e., when in energy deficit) and ending when the hydro energy output exceeds that threshold again. Using our novel hydropower drought definition, we identified the vulnerability to hydropower drought of four hypothetical RoR schemes in the UK (see Figure 5-1 for details). Our research findings add vital evidence that hydropower – particularly RoR systems – is highly susceptible to the adverse effects of drought in a changing climate. These vulnerabilities are further exacerbated by the influence of climate change, as substantiated by recent studies (e.g., Oxford Policy Management, 2019; Reuters, 2021; Opperman et al., 2022;). Furthermore, Cook et al. (2018) highlight that climate change has resulted in warmer temperatures, which in turn have increased evaporative losses and reduced snowfall and snowpack levels. These changes have intensified soil moisture deficits and runoff reductions, even in the face of uncertain precipitation patterns. Similarly, Abbass et al. (2022) underscore the global threat posed by climate change, noting its substantial impact on various sectors, including water resources. The implications of these findings are particularly relevant for RoR hydropower systems, which depend heavily on consistent river flows for energy generation. As Cook et al. (2018) indicate, reduced snowfall and snowpack levels, coupled with increased evaporative losses, lead to lower river flows and thus directly impact the efficiency and reliability of RoR hydropower plants.. Crucially, for the case study locations used across the UK, this study connects the changing patterns of drought with hydropower generation, indicating that hydropower drought event durations are expected to increase by two days on average, together with a 13.5% rise in frequency and severity in the future. Even though these results are specific to the RoR schemes used in this study, a rise in drought duration, frequency and severity due to climate change has been observed across the world (IPCC, 2021). For instance, Arnell and Gosling (2016) highlight the broader impacts of climate change on water resources in Europe, including reduced summer river flows which are critical for hydropower. Additionally, van Vliet et al. (2016) discuss how decreased river flow and increased water temperatures due to climate change will adversely affect hydropower production capacity globally, particularly in Europe. Moreover, Prudhomme et al. (2012) present comprehensive scenarios showing how future hydrological droughts will likely become more frequent and severe under various climate change projections. Their research supports our findings that hydropower systems will face increased challenges due to longer and more intense drought periods. Furthermore, (Gaudard et al., 2013) investigate the implications of climate change for Swiss hydropower, finding similar trends of increased drought frequency and severity, which aligns with the projections for the UK presented in our study. The methods used here can be applied to analyse drought vulnerability of hydropower facilities in other regions, informing climate adaptation planning. Furthermore, coupling hydropower impacts with improved drought projections from climate models may be crucial for long-term resilience planning (Kim et al., 2022).

While the novel definition of hydropower drought focused on RoR hydropower schemes offers several advantages, it also has certain limitations. The threshold for defining hydropower drought is based on specific historical data (eFLaG and NRFA) and stakeholder input (Drax, 2023; Hannaford et al., 2022; NRFA, 2023; SSE, 2023), which may not be universally applicable across different regions or hydropower systems. This regional specificity limits the generalisability of the definition. The future projections of river flows and subsequent hydropower drought events rely on climate models (Lowe et al., 2018), which are inherently uncertain, and variability in climate model outputs can affect the accuracy of projected drought characteristics. The definition assumes consistent operational practices and infrastructure conditions throughout the analysis period, but changes in operational strategies, maintenance schedules, or upgrades to infrastructure could impact the applicability of the drought threshold and duration criteria. The definition focuses on drought events with a minimum duration of five consecutive days, which, while helpful in distinguishing significant droughts from short-term fluctuations, may overlook shorter yet potentially impactful hydropower production deficits. The hydropower drought definition is based on daily river flows and power output, which may not fully capture complex hydrological processes and interactions, such as groundwater contributions, upstream reservoir management, or inter-basin water transfers that can influence river flows and hydropower generation. The definition was developed through consultations with stakeholders, primarily hydropower operators (Drax, 2023; SSE, 2023), ensuring practical relevance, but it may introduce biases that overlook broader environmental, social, or economic considerations. The fixed threshold for power output may not adequately account for dynamic environmental conditions, such as changes in sediment load, river morphology, or ecological requirements, which can affect both river flows and hydropower generation efficiency. The robustness of the definition depends on the availability and quality of historical river flow and hydropower production data, making its application challenging in regions with limited data availability. Addressing these limitations through further research and adaptive management strategies will be crucial for enhancing the resilience and sustainability of hydropower systems

This study considers Q_{95} (the flow that is exceeded on average 95 percent of the time) as the compensation or residual flow, which influenced the results. Although this is a common residual flow requirement for RoR schemes, there are some RoR schemes that have a different residual flow requirement, e.g., Q_{75} or one third of the mean summer flow (Kuriqi et al., 2019). Furthermore, the methodology assumes that if the river flow is sufficient, the RoR scheme will generate power and does not consider periods of plant maintenance. A source of uncertainty comes from the simulated daily river flows (Hannaford et al., 2022) and the assumptions made in the daily power calculations. In comparison with actual hydropower generation, the daily power calculated here is not affected by socio-economic factors such as energy demand, various water consumptions or periods of plant maintenance. Furthermore, turbine efficiency can vary in real-world conditions. For example, turbine efficiency can be affected by wear and tear.

An uncontrolled factor in our analysis was the use of an existing future flows database (Hannaford et al., 2022). Although this dataset has undergone quality checks, it introduces uncertainties into the analysis due to its reliance on a single climate change model (UKCP18) and a single emissions pathway (RCP8.5). The use of multiple climate models and emission scenarios is generally recommended to capture a broader range of potential future conditions and to reduce uncertainty (Kay et al., 2020; Kendon et al., 2021; Shen et al., 2018; Smith et al., 2009). Potential biases stemming from the use of a single climate model and emissions pathway could affect the robustness of our projections. For instance, the choice of RCP8.5 as the emissions scenario represents a high greenhouse gas concentration pathway, which might overestimate the frequency and severity of future drought conditions compared to lower emissions scenarios. Additionally, the reliance on UKCP18 means that any model-specific biases inherent in UKCP18, such as regional precipitation patterns or temperature sensitivities, could influence our results.

However, these uncertainties and potential biases do not invalidate the findings but highlight areas for further investigation and refinement in future studies. By acknowledging these limitations, we aim to provide a more nuanced and accurate understanding of hydropower generation optimisation.

More broadly, while our investigation primarily focuses on RoR hydropower, it is important to acknowledge that impoundment hydropower is also susceptible to drought (Balting et al., 2021). Extending the application of the hydropower drought definition proposed in this study to assess hydropower systems with reservoirs can contribute to a more comprehensive understanding and offer valuable insights into enhancing the reliability and resilience of hydropower generation. This is particularly important given the rise in variable renewable generation (IEA, 2020) and the role hydropower schemes play in balancing and ensuring energy mix balance (Mujjuni et al., 2023). Identifying potential vulnerabilities in hydropower generation is imperative in the context of evolving energy landscapes. The findings will be helpful for policymakers and energy experts in devising effective strategies to mitigate the adverse effects of drought on hydropower generation and enhance overall energy mix balance

While our current methodology provides valuable insights into historical and near-term drought patterns, future research could benefit from incorporating machine learning (ML) techniques to enhance predictive capabilities, particularly for the 2030-2059 period. ML models, such as Random Forests, Support Vector Machines, and Long Short-Term Memory (LSTM) networks, have shown promise in hydrological forecasting and drought prediction (Dehghani et al., 2014; Fung et al., 2020). These models could be trained on historical streamflow data, climate indices, and meteorological variables to improve prediction accuracy (Soh et al., 2018). An ensemble approach, combining multiple ML models, could provide more robust forecasts of drought periods (Poornima and Pushpalatha, 2019). Integration of ML techniques with the latest climate projections from UKCP18 could account for potential changes in climate patterns during the 2030-2059 period. This ML-enhanced approach would complement our current methodology, offering a more dynamic and comprehensive assessment of future drought risks for hydropower generation in the UK.

While this study provides an important first step in defining hydropower drought and demonstrating its use, further work is needed to validate and extend the findings of this analysis beyond the UK, including quantifying how climate change will affect future hydropower drought validated using additional real-life RoR and reservoir hydropower schemes. Furthermore, understanding the characteristics and trends of different hydropower drought types is crucial for effective water resource management and sustainable hydropower operations. Proactive planning and adaptive strategies are essential to address the challenges posed by extreme drought events, especially as future projections indicate potential changes in river flow (Dilling et al., 2023).

5.7 Conclusions

This study created a novel definition for ‘hydropower drought’ focused on RoR hydropower schemes, which are vulnerable to drought due to their reliance on streamflow. We demonstrated its utility using four hypothetical RoR schemes of varying sizes across the UK to show the effects of drought on hydropower generation in a changing climate.

A historical baseline analysis spanning 1980-2009 revealed occurrences of hydropower drought across all four of the UK RoR schemes studied. Noteworthy variations between hydropower drought types (Table 5-2) were also observed in hydropower drought characteristics when considering different drought types. Extreme hydropower drought displayed the longest durations, severities, and higher frequencies, followed by moderate hydropower drought. Results showed that, historically, annual hydropower drought frequency ranged from 0.48 to 0.73 across case studies, displaying limited annual variation. The average drought duration was 8.64 days, with a frequency of 0.58 occurrences per year and an average severity of 40 MWh. In the future (2030-2059), the duration of hydropower drought events annually was found to increase by approximately two days when compared to the baseline period (1980-2009), accompanied by a 13.5% rise in both frequency and severity for the four RoR locations in this study.

In the future, seasonal variations in hydropower drought characteristics were found to be more substantial than annual changes, particularly during winter, where a four-day increase in average drought duration per event and an 89.4% surge in drought frequency was observed. Variations in scheme size and impact relationships were observed across the four RoR schemes studied, with the pico RoR scheme found to be most severely impacted during spring, the micro and mini RoR schemes witnessing elevated severity in summer and shorter drought durations for the majority of RoR schemes, except for the pico RoR scheme in winter. Severity, measured as energy lost during drought events, varied based on RoR scheme size, with the small RoR scheme exhibiting the highest hydropower drought severity.

This research and the defining of hydropower drought create a solid foundation for optimising RoR hydropower generation in the face of varying hydrological conditions including drought, supporting the transition towards a more resilient and efficient energy landscape. Further studies can build upon these findings to develop robust and region-specific hydropower drought mitigation approaches that ensure reliable and sustainable hydropower generation.

Chapter 6 DISCUSSION

6.1 Significance and wider implications of the results

As the world seeks sustainable electricity sources, comprehensive assessments of hydropower's current state and future prospects are imperative. Hydropower assessments are vital tools for understanding the performance, environmental impact, and future potential of hydropower systems. Evaluations of energy yield are essential for contributing to informed decision-making, aiding policymakers, investors, and energy planners in optimising hydropower utilisation.

6.1.1 Run of river hydropower potential assessment

This thesis presents a comprehensive evaluation of the future trajectory of RoR hydropower systems using GB as a case study, with a particular focus on the effects of climate change, and explores various dimensions, ranging from RoR hydropower assessments to future projections and implications for both the energy sector and the environment. The methodology employed in this thesis (Chapter 3) aligns with recent international assessments of hydropower potential, reinforcing its robustness and relevance. Notable works by Garegnani et al. (2018), Sammartano et al. (2019) and Zaidi and Khan (2018) have created comprehensive assessments using methodologies similar to those adopted here. However, they have limitations such as: not considering financial indicators (Garegnani et al., 2018), low resolution Digital Elevation Models (Sammartano et al., 2019) or using an approach not rooted in an optimisation framework that may limit the accuracy of the estimated maximum hydropower potential (Zaidi and Khan, 2018). This thesis addresses these limitations and contributes to the broader global landscape of hydropower assessment by introducing a novel framework to assess hydrological and realisable RoR potential alongside financial and technical metrics.

The replicability of the methods used here mean that they could be used to determine RoR potential in other countries that have similar net zero ambitions and similar hydrological conditions, such as Canada, New Zealand or France (Beck et al., 2018;

The Guardian, 2021). This comprehensive approach (Chapter 3), a departure from previous studies (Duncan, 2012; Forrest, 2008; Salford Civil Engineering, 1989), primarily focuses on technical and financial viability and provides a complete understanding of RoR hydropower potential. It addresses critical questions regarding the implications of solely relying on financial viability criteria, exposing potential underestimations arising from neglecting broader benefits such as emissions reduction, job creation, and health improvements. Comparing the financial potential results with previous studies reveals consistencies and deviations. The alignment with the Salford Civil Engineering (1989) and Department of Energy & Climate Change (2010) studies underscores the robustness of this work's estimates. Methodological differences in considering feed-in tariffs and prioritising financial viability in other studies highlight the need for a balanced approach, considering both financial and environmental dimensions.

The spatial distribution insights from the assessment can guide policymakers to strategically plan for hydropower development. Assessing a GB-wide financially viable potential of ~390-420 MW, this study supports the development of RoR hydropower as a renewable generation source. While pico and micro schemes exhibit significant hydrological and technical potential, their financial and realisable potential is null. This emphasises the challenge of economic viability for smaller-scale RoR projects, prompting considerations for policy support and innovative financing models. The geographic distribution of potential RoR schemes, with clusters in Wales and England where RoR hydropower potential has not been reached (Kennedy et al., 2023), has implications for regional energy strategies. Decision-makers can use this information to strategically plan and allocate resources, considering the varying potential across different regions.

6.1.2 The effects of climate change on run of river hydropower potential

The RoR hydropower potential, evaluated in this thesis (Chapter 3), lays the foundation for anticipating and adapting to future challenges (Chapter 4). As climate change impacts river flows, the assessed potential becomes a baseline against which the evolving landscape can be measured. The impacts of climate change on hydropower are multifaceted and diverse, reflecting the complex interactions between the climate system and water resources (Shu et al., 2018). Globally, climate change trends project a decrease in annual river flows, with a notable decrease in summer (Solaun and Cerdá, 2019). The results from this thesis, using GB as an example, corroborates this, emphasising the importance of seasonal variations in river flows for RoR hydropower potential. While there is an overall decrease in available power in both the near and far future, some RoR locations (Figure 4-4) exhibit increased power output compared to the baseline. A clear relationship emerges when comparing future seasonal changes in flows with changes in RoR hydropower power output. Although this thesis identified this relationship in GB, it is evident globally (e.g., South Korea - Jung et al., 2021; China - Li et al., 2020). The seasonal variations in power output align with changes in river flows, emphasising the dependency of RoR hydropower on river flow dynamics. However, spring exhibits an intriguing dynamic, with decreased river flows coinciding with increased power output. This discrepancy is attributed to the fluctuating monthly and daily flows during spring. However, this discrepancy could not be found in other similar studies (e.g., Dhaubanjar et al., 2023).

The turbine sizes for each RoR location play a critical role in determining the efficiency, environmental impact, and economic viability of RoR hydropower projects. This thesis identifies (Chapter 4) a significant limitation in capitalising on projected heightened winter river flows for hydropower generation. The increase in river flows surpasses the capacity of many turbines installed in RoR hydropower locations (see Section 4.6) meaning that excess water cannot be effectively converted into electricity, leading to untapped potential and reduced productivity during these periods. This is also supported by the wider literature (Carvajal et al., 2017; Casale et al., 2020). Carvajal et al. (2017) presents a framework to assess the sensitivity of hydropower generation in Ecuador to changes in water availability driven by future climate change. The authors develop a hydrological-electricity model and apply it to 10 major hydropower stations in Ecuador, representing over 85% of the country's capacity. The model is forced with output from 40 global climate models under the RCP4.5 scenario for 1971-2000 (baseline) and 2071-2100. Results show that future annual inflows could vary from -85% to +277% depending on the climate model. Hydropower generation is found to vary between -55% and +39% of historical levels when considering one standard deviation of climate model projections, mirroring the same discrepancy between the rise in flows and the rise in future hydropower generation (Table 4-4). Conversely, Casale et al. (2020) estimated the future potential of small hydropower (SHP) in South Korea for the period 2021-2100, considering the impacts of climate change. It found that the SHP potential for the near future period of 2021-2040 showed a tendency to increase compared to present levels. The highest increase was estimated to be 23.4% at the Deoksong SHP plant. For the longer term periods of 2061-2100, the impacts of climate change on SHP potential were more uncertain. But there was still a projected increase in potential compared to present levels for most periods and plants. This is in contrast to the results from Chapter 4 (see Section 4.5.3), which found that the hydropower potential is projected to decrease in the near and far future, by approx. -4.51%, respectively by - -4.56%, compared to the baseline. However, this discrepancy is most likely due to the smaller sample size of the Casale et al. (2020) study, which is limited at three RoR schemes.

This incongruity underscores the urgency for proactive measures to align RoR hydropower infrastructure with evolving climate conditions. Potential strategies include upgrading existing turbines to handle increased flows or designing new turbines capable of accommodating larger discharges. Such adaptations are deemed essential to fully exploit the augmented river flows in winter for optimal hydropower operations and to limit the effects of climate change.

Looking beyond hydropower, climate change has far-reaching implications for various renewable resources, altering their availability, efficiency, and overall viability (Solaun and Cerdá, 2019). Rising temperatures due to climate change can enhance the efficiency of solar panels but may also lead to more frequent and prolonged heatwaves, potentially affecting the durability and performance of solar infrastructure (Bazyomo et al., 2016). Alterations in cloud cover and precipitation patterns can impact solar irradiance, causing fluctuations in electricity production. Increased cloud cover may reduce the predictability of solar power generation (Huld et al., 2008). Climate change can influence wind patterns, affecting the consistency and strength of wind resources. Regional variations in wind speed and direction may impact the efficiency of wind turbines and require adjustments in the design and placement of wind farms (Pryor and Barthelmie, 2010). More frequent and severe weather events, such as hurricanes and typhoons, can pose risks to wind turbines (Kulkarni et al., 2014). Climate change influences the growth and health of biomass feedstocks. Changes in temperature and water availability can affect crop yields and the overall sustainability of biomass energy sources (Haberl et al., 2011). Geothermal generation experiences common climate change impacts shared with other energy sources, such as changes in water availability, infrastructure damages, flooding, and a rise in ambient temperature (Solaun and Cerdá, 2019). The interconnected risks across renewable resources highlight the need for ongoing research, innovation, and strategic planning to ensure their resilience in the face of a dynamically changing climate. For example, the global interconnectedness of the energy market—acutely highlighted, for example, by the Russian invasion of Ukraine in February 2022—predisposes energy companies to various cross-border and systemic impacts of climate change that may be difficult to foresee and prepare for (Juhola et al., 2023).

6.1.3 The effects of climate change on hydropower drought

Aside from impacts on renewable energy and water resources, climate change has manifested in various environmental shifts, with one notable consequence being the exacerbation of drought conditions. Although droughts are generally well studied (Freire-González et al., 2017; Hanel et al., 2018), the impacts of drought on hydropower are less understood. A knowledge gap on the definition of hydropower drought emerged when considering the unique challenges posed by droughts in the context of hydropower generation (Chapter 5). Prior to the present study, the term ‘hydropower drought’ had been loosely defined, often being subsumed within the broader category of hydrological drought (Turner et al., 2022a). Previous studies (e.g., Liu et al., 2023; Otero et al., 2022; Raynaud et al., 2018) that examined energy drought have used a definition based on energy demand drought (e.g., when the demand exceeds the supply of energy). The necessity to establish a distinct and standardised definition for ‘hydropower drought’ is crucial for comprehensively assessing and addressing the specific impacts of drought on hydropower generation. This is evident from the growing climate risks associated with hydropower, as highlighted by various studies and real-world examples. For instance, in Zambia, a

2015 drought led to a significant decline in hydropower generation, causing national electricity generation to drop by 40%, resulting in rolling blackouts and immense economic disruption (Forbes, 2022). Similar vulnerabilities were observed in California, where a historic drought led to a 40% reduction in hydropower generation, significantly impacting the electricity supply. These examples demonstrate how drought can reveal vulnerabilities in energy and economic systems, particularly in regions heavily dependent on hydropower for electricity generation (Kern et al., 2020). This thesis established a clearer definition, employing a threshold-level approach that considers the key response of the system – i.e., the hydro energy output. By employing the novel hydropower drought definition (Chapter 5), this thesis assessed the drought susceptibility of four hypothetical RoR schemes within the UK (Figure 5-1), highlighting the pronounced vulnerability of hydropower, particularly RoR systems, to the detrimental impacts of drought amid evolving climatic conditions, corroborating evidence from recent studies (e.g., Opperman et al., 2022; Oxford Policy Management, 2019; Reuters, 2021). The work undertaken in this thesis connects the changing patterns of drought with hydropower generation, indicating that hydropower drought event durations are expected to increase by around two days, along with a 13.5% rise in frequency and severity at the case study locations in the UK (Table 5-4). Even though these results are specific to the RoR schemes from this thesis, a rise in drought duration, frequency and severity due to climate change is observed across the world (IPCC, 2021).

Although this thesis focused on hydropower drought, the term ‘energy drought’ has been mentioned in the literature (Otero et al., 2022). Energy drought refers to a situation where the availability of energy resources, is insufficient to meet the demands of a given region or community. This phenomenon is closely linked to climate change, which can impact the reliability and sustainability of energy generation (Liu et al., 2023). Changes in precipitation patterns, reduced river flows, and altered hydrological cycles can lead to fluctuations in water resources, contributing to energy shortages. For example, water is not only used for hydropower generation, but for the cooling of nuclear reactors and in other generation sources, such as geothermal energy (Qiu et al., 2023).

In the context of decarbonising the UK energy grid by 2035, the insights from this thesis could prove valuable. Although hydropower is not the main contributor to the 100% renewable energy grid, it could still play a role alongside other renewable electricity sources, such as wind and solar (Jurasz et al., 2018; Sample et al., 2015; Tarroja et al., 2019).

6.2 Assumptions and limitations

The findings contained in this thesis should be considered within the context of their settings and methods, which have limitations broadly discussed in the individual chapters. When assessing the RoR hydropower potential in GB, the lack of a map of the network grid did not allow for accurate transmission lines pricing, leading to uncertainty in the financial potential results (in Chapter 3, a fixed price for grid connection was used – see Appendix 1.2 for details). The assumption of a capacity factor of 40% for calculating the energy output may not reflect real hydropower generation. Although the capacity factor is similar to the real one (DUKES, 2018), a daily flow series would be more accurate when calculating the energy output. This capacity factor assumption was carried through the thesis (Chapters 3, 4 and 5). When assessing climate change effects on RoR hydropower (Chapters 4 and 5), simulated daily river flow series (Hannaford et al., 2022) allowed for an accurate estimation of the daily power and energy produced by the RoR schemes. However, when determining the RoR potential (Chapter 3), the use of a monthly river flow dataset (Bell et al., 2018), limited the accuracy of the results, especially when calculating the energy produced by the RoR schemes. Nonetheless, the geographical coverage of the river flow data used in Chapter 3 allowed for a comprehensive analysis of the RoR potential in GB. Conversely, the river flow data used in Chapters 4 and 5 was available only at gauged locations in GB, therefore limiting the number and potential locations of RoR schemes that were used in those chapters. The work undertaken in Chapters 4 and 5 determined the potential for RoR hydropower and the potential impacts of climate change on it. The same simulated river flows as in Chapter 4 was used in Chapter 5 providing continuity but also potentially carrying the same uncertainties.

The findings presented in Chapter 3 provide valuable insights into the magnitude and spatial distribution of the RoR hydropower potential in GB, with the discovery of untapped potential in Wales and England. They have formed the basis for the determining the future changes to RoR potential (Chapter 4). In Chapter 4, the river flow dataset focuses solely on the RCP8.5 emission scenario and a single climate model, which could introduce some uncertainty into the calculations of power and energy output. Nonetheless, the simulated river flows have been validated and demonstrate a strong correlation with gauged percentile flows (Figure 4-2).

6.3 Recommendations for future research

While the research presented in this thesis furthers the understanding of the potential effects of climate change on RoR hydropower, identifying the declining hydropower potential in the summer and autumn seasons, coupled with the emergence of phenomena like hydropower drought, areas for further research have been identified as follows:

1. Further research could improve on the results from the RoR hydropower potential assessment (Chapter 3) by using a daily flow series as an input rather than the monthly flow series used in this thesis. Using a rainfall-runoff hydrological model to calculate daily flows and predicted future flows could improve on the accuracy of the results in Chapters 3, 4 and 5. Additionally, as newer, more efficient turbine technologies become available, the technical potential, and the financially viable and realisable potentials respectively could be recalculated to reflect these improvements in technology.
2. Further research could investigate the possibility of using RoR hydropower schemes in cascade on long river stretches, where the head is too high for the available penstocks and turbines, therefore increasing the technical potential.
3. The potential to mitigate reductions in hydropower capacity caused by climate change through the installation of larger turbines could be explored, assessing whether this approach effectively offsets anticipated declines in energy production determined in Chapter 4.

4. In Chapters 4 and 5, the eFLaG dataset (Hannaford et al., 2022) was used to determine climate changes in river flows, and, consequently, in hydropower generation. However, the use of this dataset limited the RoR schemes which could be analysed (only the ones in proximity to eFLaG gauges were considered). Future research could improve on the results from Chapter 4 by using a rainfall-runoff hydrological model with climate forcings and creating a dataset of river flows spanning over the UK, not just at gauged locations. This will make the inclusion of all RoR schemes from Chapter 3 possible, therefore improving the results coverage. Furthermore, using multiple rainfall-runoff and climate models could remove some of the uncertainties that came from using the eFLaG dataset.
5. Hydropower drought is a phenomenon that is not well understood and researched. While the work from Chapter 5 is an important first step in understating hydropower drought and its associated risk, there are still multiple areas for further research. Applying the hydropower drought definition from Chapter 5 to more real-life examples and to hydropower with reservoirs and perhaps pumped storage hydro could improve understanding of this phenomenon.
6. The impacts of hydropower drought are discussed in Chapter 5, however, a succession of drought events could have an increased negative impact (Boca et al., 2022). The risk for hydropower drought succession (or sequencing) should be investigated alongside the possible impacts on hydropower generation.
7. The methods used in this thesis aid the understanding of the effects of climate change on RoR hydropower in GB. However, the methodology developed here could be applied to other countries or regions with similar climate and precipitation patterns, such as Canada, New Zealand or France, to gain further knowledge of hydropower potential and risks there. Using the same methodology over multiple regions could help create a consistent database containing RoR hydropower potential information.

CHAPTER 7 CONCLUSIONS

7.1 Summary of key findings

The aim of this thesis was to enhance the understanding of run of river hydropower potential and the possible effects of climate change will have on this type of renewable electricity generation. The research questions posed in Chapter 1.2 (Table 1-1) have been addressed in this thesis as follows:

RQ 1. How can the potential for RoR hydropower be determined using the latest available data and technologies?

Previous studies have determined the potential for RoR hydropower basing their criteria on technical and financial viability, ignoring the hydrological and realisable potentials. In this thesis, a framework that assesses the hydrological and realisable RoR potentials alongside financial and technical potentials for GB was presented to address this gap (identified in Chapter 2). In Chapter 3, the integration of geospatial data techniques such as Geographic Information System and remote sensing, coupled with an algorithm for site selection, enabled the accurate assessment of potential RoR sites. The methodology involved utilising Q_{40} flows, which are usually chosen for RoR design, and the latest available turbine technologies. Using the methodology proposed in Chapter 3, the hydropower potential identified in GB is as follows: hydrological potential at 20 GW, technical potential at 11 GW, financially viable potential between 320 MW to 420 MW, and the realisable potential between 290 MW to 320 MW. This approach aligns with contemporary international studies on hydropower potential (Garegnani et al., 2018; Zaidi and Khan, 2018), ensuring consistency and comparability.

RQ 2. How are temperature and rainfall pattern changes influencing river flows, both now and in the future, including seasonality and low environmental flows (Q_{95})?

The results from Chapter 4 show that annual river flows are projected to be reduced by -5.65 % in the near future (2030-2059) and by -6.78 % in the far future (2050-2079) across GB using future climate scenarios. Seasonally, the results indicate a small possible decrease in spring in the near future (-0.26 %), a significant decrease in the summer and autumn in the near future (-26.98 % in summer, -20.14 % in autumn) and a slight increase in winter in the near future (1.59 %). For the far future (2050-2079), spring flows are shown to potentially increase by 4.66 %, summer and autumn flows decrease even more than in the near future (-37.06 % decrease in summer flows and -31.08 % decrease in autumn flows), and winter flows are likely to increase by 8.19 %. Environmental flows (Q_{95}) are shown to decrease by -16.4 % in the near future and decrease by -23.3 % in the far future.

RQ 3. What are the effects of climate change on RoR hydropower schemes which lack impoundment? How are changes in river flows affecting the power and energy output of this kind of schemes?

The results from Chapter 4 reveal that RoR hydropower potential in both summer and autumn across GB is anticipated to decrease, mirroring projected future declines in river flows at the locations analysed in Chapter 4. RoR locations in the south-east and east of GB are likely to exhibit reduced power output throughout the entire season, with declines surpassing -50%. Conversely, RoR hydropower potential exhibits modest increases in spring and winter, approximately +1.60% and +1.70%, respectively. However, these increases are outweighed by substantial decreases in summer (-19%) and autumn (-11%). Consequently, the findings suggest an overall reduction in the RoR hydropower potential in GB in the future, which raises concerns about the ability of hydropower to meet electricity demands, especially during peak periods.

RQ 4. Is there a necessity to establish a distinct and standardised definition for 'hydropower drought' to comprehensively assess and address the specific impacts of drought on hydropower generation?

Droughts have been primarily classified into four main categories: meteorological, hydrological, agricultural, and socioeconomic (Wilhite and Glantz, 1985). Meteorological drought, also known as climatological drought, is defined solely by the level of dryness, often compared to a standard or average amount, and the length of the dry spell. Agricultural drought connects various aspects of meteorological drought to agricultural effects, with a focus on lack of rainfall, disparities between actual and potential evapotranspiration, soil water shortages, etc. Hydrological droughts are linked with the impacts of periods of low rainfall on surface or underground water resources (such as streamflow, reservoir and lake levels, groundwater), rather than with rainfall deficits (Dracup et al., 1980b).

Hydrological droughts frequently lag or are out of sync with meteorological and agricultural droughts, making them difficult to measure. Droughts that specifically impact hydropower have unique characteristics and consequences compared to the general definition of hydrological drought, including their direct effect on electricity production from hydropower plants. A specific definition for hydropower drought was required to quantify particular characteristics and thresholds that are essential for identifying the beginning, continuation, and end of drought episodes, as well as their intensity. This could enable better preparedness, risk management, and policy development to address the vulnerabilities associated with hydropower during periods of water scarcity and drought.

RQ 5. To what extent does climate change influence the risks associated with hydropower generation, including the emergence of the condition referred to as "hydropower drought"? (Addressed in Chapter 5)

Climate change significantly influences the risks associated with hydropower generation, including the emergence of the condition referred to as ‘hydropower drought’. Using the case study RoR locations described in Chapter 5, the results show that the baseline annual hydropower drought frequency ranged from 0.48 to 0.73, displaying limited annual variation but distinct seasonal differences, notably with higher frequencies in summer. The duration of hydropower drought events annually was projected to increase by approximately two days in the future (2030-2059) compared to the baseline (1980-2009), accompanied by a 13.5% rise in both frequency and severity for the four RoR locations in this study. The seasonal projected variations in the future in hydropower drought characteristics are more substantial, particularly during winter. A possible four-day increase in average drought duration per event and an 89.4% surge in drought frequency in winter in the future highlights the need for preparedness in managing energy resources during this critical period. Conversely, the potential reduction in drought frequency during autumn, albeit accompanied by increased severity, presents a season-specific challenge that requires targeted strategies for risk mitigation.

7.2 Concluding remarks

In conclusion, the work undertaken in this thesis made significant progress in advancing the understanding of RoR hydropower potential and its susceptibility to climate change impacts. By addressing the research questions outlined at the onset, this thesis has provided valuable insights into various facets of RoR hydropower generation and its future outlook in the context of changing environmental conditions.

Firstly, a comprehensive framework was developed (Chapter 3) to assess the potential for RoR hydropower across GB, integrating hydrological, technical, financial, and realisable potentials. This methodological approach, combined with geospatial data techniques, allowed for the accurate identification of potential RoR sites, laying the groundwork for informed decision-making in RoR hydropower development.

Secondly, the impacts of climate change on river flows and RoR hydropower potential were investigated. The findings from Chapter 4 reveal a nuanced picture, with projected decreases in RoR hydropower potential during summer and autumn, offset by modest increases in spring and winter. These results underscore the importance of considering seasonal variations and climate projections in hydropower planning and management strategies.

Furthermore, the concept of "hydropower drought" and its implications for energy generation was explored in Chapter 5. By establishing a distinct definition tailored to hydropower systems, this thesis highlighted the unique challenges posed by drought conditions and emphasized the need for proactive measures to mitigate risks and enhance resilience. Lastly, this thesis examined the influence of climate change on the emergence of hydropower droughts. Through a case study analysis, seasonal variations in drought characteristics and projected future trends were identified, emphasising the importance of adaptive strategies to ensure energy security in the face of evolving climate patterns.

This thesis contributes to the growing body of knowledge on RoR hydropower and climate change adaptation, providing valuable insights for policymakers, stakeholders, and researchers alike. By integrating the latest data and technologies, this thesis aims to support the sustainable development of RoR hydropower resources and facilitate the transition towards net zero. The methodology outlined in this thesis holds promise for broader application in regions sharing comparable climate and precipitation characteristics, such as Canada, New Zealand, or France. By leveraging this approach across diverse geographic contexts, researchers can enhance their understanding of RoR hydropower potential and associated risks.

REFERENCES

Abbasi, T., Abbasi, S.A., 2011. Small hydro and the environmental implications of its extensive utilization. Renew. Sustain. Energy Rev. 15, 2134–2143. https://doi.org/10.1016/j.rser.2010.11.050

Abbass, K., Qasim, M.Z., Song, H., Murshed, M., Mahmood, H., Younis, I., 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ. Sci. Pollut. Res. 2022 2928 29, 42539–42559. https://doi.org/10.1007/S11356-022-19718-6

Agostinho, A.A., Gomes, L.C., Fernandez, D.R., Suzuki, H.I., 2002. Efficiency of fish ladders for neotropical ichthyofauna. River Res. Appl. 18, 299–306. https://doi.org/10.1002/rra.674

Ali, R., Kuriqi, A., Abubaker, S., Kisi, O., 2019. Long-Term Trends and Seasonality Detection of the Observed Flow in Yangtze River Using Mann-Kendall and Sen's Innovative Trend Method. Water 2019, Vol. 11, Page 1855 11, 1855. https://doi.org/10.3390/W11091855

Allan, G.J., McGrane, S.J., Roy, G., Baer, T.M., 2020. Scotland's industrial water use: Understanding recent changes and examining the future. Environ. Sci. Policy 106, 48–57. https://doi.org/10.1016/j.envsci.2020.01.005

Amponsah, N.Y., Troldborg, M., Kington, B., Aalders, I., Hough, R.L., 2014. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renew. Sustain. Energy Rev. 39, 461–475. https://doi.org/10.1016/j.rser.2014.07.087

Arnell, N.W., Gosling, S.N., 2016. The impacts of climate change on river flood risk at the global scale. Clim. Change 134, 387–401. https://doi.org/10.1007/s10584-014-1084-5

Atilgan, B., Azapagic, A., 2016. Renewable electricity in Turkey: Life cycle environmental impacts. Renew. Energy 89, 649–657. https://doi.org/10.1016/j.renene.2015.11.082

Balting, D.F., AghaKouchak, A., Lohmann, G., Ionita, M., 2021. Northern Hemisphere drought risk in a warming climate. npj Clim. Atmos. Sci. 2021 41 4, 1–13. https://doi.org/10.1038/s41612-021-00218-2

Bazyomo, S.D.Y.B., Lawin, E.A., Coulibaly, O., Ouedraogo, A., 2016. Forecasted changes in West Africa photovoltaic energy output by 2045. Climate 4. https://doi.org/10.3390/CLI4040053

BBC, 2022. Climate change: Drought highlights dangers for electricity supplies [WWW Document]. URL https://www.bbc.co.uk/news/science-environment-62524551 (accessed 7.13.23).

BBC News, 2023. £100m boost for biggest UK hydro scheme in decades - BBC News [WWW Document]. URL https://www.bbc.co.uk/news/uk-scotland-highlands-islands-65015217?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-03-21&utm_campaign=Daily+Briefing+-+21+03+2023 (accessed 3.21.23).

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci. Data 5. https://doi.org/10.1038/SDATA.2018.214

Bell, V.A., Kay, A.L., Cole, S.J., Jones, R.G., Moore, R.J., Reynard, N.S., 2012. How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. J. Hydrol. 442–443, 89–104. https://doi.org/10.1016/j.jhydrol.2012.04.001

Bell, V.A., Kay, A.L., Jones, R.G., Moore, R.J., Reynard, N.S., 2009. Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. J. Hydrol. 377, 335–350. https://doi.org/10.1016/J.JHYDROL.2009.08.031

Bell, V.A., Kay, A.L., Rudd, A.C., Davies, H.N., 2018. The MaRIUS-G2G datasets: Grid-to-Grid model estimates of flow and soil moisture for Great Britain using observed and climate model driving data. Geosci. Data J. 5, 63–72. https://doi.org/10.1002/GDJ3.55

Bergström, D., Malmros, C., 2005. Finding potential sites for small-scale hydro power in Uganda: a step to assist the rural electrification by the use of GIS. Geobiosph. Sci. Centre, Dep. … 95.

Bhaga, T.D., Dube, T., Shekede, M.D., Shoko, C., 2020. Impacts of Climate Variability and Drought on Surface Water Resources in Sub-Saharan Africa Using Remote Sensing: A Review. Remote Sens. 2020, Vol. 12, Page 4184 12, 4184. https://doi.org/10.3390/RS12244184

Bobat, A., 2015. Thermal Pollution Caused by Hydropower Plants. Bilge A., Toy A., Günay M. Energy Syst. Manag. 19–32. https://doi.org/10.1007/978-3-319-16024-5

Bobat, Alaeddin, 2015. Thermal Pollution Caused by Hydropower Plants, in: Bilge, A.N., Toy, A.Ö., Günay, M.E. (Eds.), Energy Systems and Management. Springer International Publishing, Cham, pp. 19–32.

Boca, A.D., White, C., Bertram, D., 2022. A review of the risks to water resources in Scotland in response to climate change. Aberdeen.

Bocchiola, D., Manara, M., Mereu, R., 2020. Hydropower potential of run of river schemes in the himalayas under climate change: A case study in the dudh koshi basin of Nepal. Water (Switzerland) 12. https://doi.org/10.3390/W12092625

British Hydro Association, 2022a. HYDRO FACTS - British Hydro Association [WWW Document]. URL https://www.british-hydro.org/hydro-facts/ (accessed 7.26.22).

British Hydro Association, 2022b. TYPES OF HYDRO - British Hydro Association

[WWW Document]. URL https://www.british-hydro.org/types-of-hydro/ (accessed 7.26.22).

Burke, M.J., Stephens, J.C., 2018. Political power and renewable energy futures: A critical review. Energy Res. Soc. Sci. 35, 78–93. https://doi.org/10.1016/J.ERSS.2017.10.018

Business Electricity Prices, 2021. UK Wholesale Electricity Prices - Business Electricity Prices [WWW Document]. URL https://www.businesselectricityprices.org.uk/retail-versus-wholesale-prices/ (accessed 3.24.22).

Byers, E.A., Coxon, G., Freer, J., Hall, J.W., 2020. Drought and climate change impacts on cooling water shortages and electricity prices in Great Britain. Nat. Commun. 11, 1–12. https://doi.org/10.1038/s41467-020-16012-2

Calderón, A., Barreneche, C., Prieto, C., Segarra, M., Fernández, A.I., 2021. Concentrating Solar Power Technologies: A Bibliometric Study of Past, Present and Future Trends in Concentrating Solar Power Research. Front. Mech. Eng. 7, 682592. https://doi.org/10.3389/FMECH.2021.682592/BIBTEX

Capon, S.J., Stewart-Koster, B., Bunn, S.E., 2021. Future of Freshwater Ecosystems in a 1.5°C Warmer World. Front. Environ. Sci. 9, 784642. https://doi.org/10.3389/FENVS.2021.784642/BIBTEX

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y., Lissner, T.K., Liu, J., Gunn, E.L., Morgan, R., S., M., S., S., 2022a. Chapter 4:Water, Water. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbec. https://doi.org/10.1016/S0376-7361(05)80031-7

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., Betts, R.A., Gelfan, A., Hirabayashi, Y., Lissner, T.K., Liu, J.G., Gunn, E.L., Morgan, R., S., M., S., S., Lopez, E., Morgan, R., Mwanga, S., Supratid, S., 2022b. Water. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Water. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbec. https://doi.org/10.1017/9781009325844.006

Carless, D., Whitehead, P.G., 2013. The potential impacts of climate change on hydropower generation in Mid Wales. Hydrol. Res. 44, 495–505. https://doi.org/10.2166/nh.2012.012

Carvajal, P.E., Anandarajah, G., Mulugetta, Y., Dessens, O., 2017. Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble—the case of Ecuador. Clim. Change 144, 611–

624. https://doi.org/10.1007/s10584-017-2055-4

Casale, F., Bombelli, G.M., Monti, R., Bocchiola, D., 2020. Hydropower potential in the Kabul River under climate change scenarios in the XXI century. Theor. Appl. Climatol. 139, 1415–1434. https://doi.org/10.1007/s00704-019-03052-y

Chaudhari, S., Pokhrel, Y., 2022. Alteration of River Flow and Flood Dynamics by Existing and Planned Hydropower Dams in the Amazon River Basin. Water Resour. Res. 58, e2021WR030555. https://doi.org/10.1029/2021WR030555

Christierson, B. v., Vidal, J.P., Wade, S.D., 2012. Using UKCP09 probabilistic climate information for UK water resource planning. J. Hydrol. 424–425, 48–67. https://doi.org/10.1016/j.jhydrol.2011.12.020

Ciavarella, A., Mccarthy, M., 2020. An attribution study of the UK mean temperature in year 2023.

Climate Change Committee, 2023. Delivering a reliable decarbonised power system.

Climate Change Committee, 2021. The Third UK Climate Change Risk Assessment Technical Report' In: Independent Assessment of UK Climate Risk: Advice to Government [Betts, R. A., Haward, A. B. and Pearson, K. V. (eds.)]. Prepared for the Climate Change Committee, London.

Cole, S.J., Moore, R.J., 2009. Distributed hydrological modelling using weather radar in gauged and ungauged basins.

Cook, B.I., Mankin, J.S., Anchukaitis, K.J., 2018. Climate Change and Drought: From Past to Future. Springer. https://doi.org/https://doi.org/10.1007/s40641-018-0093-2

Copernicus, 2016. EU-DEM v1.1 — Copernicus Land Monitoring Service [WWW Document]. URL https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1?tab=metadata (accessed 8.2.22).

Correia, M.S., 2018. Sustainability: An Overview of the Triple Bottom Line and Sustainability Implementation. Int. J. Strateg. Eng. 2, 29–38. https://doi.org/10.4018/IJOSE.2019010103

Crootof, A., Shrestha, R., Albrecht, T., Ptak, T., Scott, C.A., 2021. Sacrificing the local to support the national: Politics, sustainability, and governance in Nepal's hydropower paradox. Energy Res. Soc. Sci. 80, 102206. https://doi.org/10.1016/J.ERSS.2021.102206

Dallison, R.J.H., Patil, S.D., Williams, A.P., 2021. Impacts of climate change on future water availability for hydropower and public water supply in Wales, UK. J. Hydrol. Reg. Stud. 36, 100866. https://doi.org/10.1016/j.ejrh.2021.100866

de Oliveira, V.A., de Mello, C.R., Viola, M.R., Srinivasan, R., 2017. Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande river basin, Southeastern Brazil. Int. J. Climatol. 37, 5005–5023. https://doi.org/10.1002/joc.5138

Dehghani, M., Saghafian, B., Nasiri Saleh, F., Farokhnia, A., Noori, R., 2014. Uncertainty analysis of streamflow drought forecast using artificial neural networks and Monte-Carlo simulation. Int. J. Climatol. 34, 1169–1180. https://doi.org/10.1002/JOC.3754

Dellinger, G., Garambois, P.A., Dufresne, M., Terfous, A., Vazquez, J., Ghenaim, A., 2016. Numerical and experimental study of an Archimedean Screw Generator. IOP Conf. Ser. Earth Environ. Sci. 49. https://doi.org/10.1088/1755-1315/49/10/102002

Department for Business Energy & Industrial Strategy, 2021. Plans unveiled to decarbonise UK power system by 2035 - GOV.UK [WWW Document]. URL https://www.gov.uk/government/news/plans-unveiled-to-decarbonise-uk-power-system-by-2035 (accessed 4.3.23).

Department for Business Energy and Industrial Strategy, 2022. Energy Trends June 2022.

Department for Energy Security and Net Zero, 2024. 2020 UK Greenhouse Gas Emissions, Final Figures.

Department for Energy Security and Net Zero, 2023a. Energy Trends March 2023.

Department for Energy Security and Net Zero, 2023b. Shapps sets out plans to drive multi billion pound investment in energy revolution - GOV.UK.

Department of Energy & Climate Change, 2010. England and Wales Hydropower Resource Assessment 33.

Department of Energy and Climate Change, 2010. 2010 to 2015 government policy: UK energy security - GOV.UK [WWW Document]. URL https://www.gov.uk/government/publications/2010-to-2015-government-policy-uk-energy-security/2010-to-2015-government-policy-uk-energy-security#appendix-2-maintaining-security-of-electricity-supply (accessed 11.17.20).

Dhaubanjar, S., Lutz, A.F., Gernaat, D.E.H.J., Nepal, S., Smolenaars, W., Pradhananga, S., Biemans, H., Ludwig, F., Shrestha, A.B., Immerzeel, W.W., 2021. A systematic framework for the assessment of sustainable hydropower potential in a river basin – The case of the upper Indus. Sci. Total Environ. 786, 147142. https://doi.org/10.1016/j.scitotenv.2021.147142

Dhaubanjar, S., Lutz, A.F., Smolenaars, W.J., Khanal, S., Jamil, M.K., Biemans, H., Ludwig, F., Shrestha, A.B., Immerzeel, W.W., 2023. Quantification of run-of-river hydropower potential in the Upper Indus basin under climate change. Front. Water 5, 1256249. https://doi.org/10.3389/FRWA.2023.1256249/BIBTEX

Dilling, L., Daly, M.E., Travis, W.R., Ray, A.J., Wilhelmi, O. V., 2023. The role of adaptive capacity in incremental and transformative adaptation in three large U.S. Urban water systems. Glob. Environ. Chang. 79, 102649. https://doi.org/10.1016/J.GLOENVCHA.2023.102649

Dolan, F., Lamontagne, J., Link, R., Hejazi, M., Reed, P., Edmonds, J., 2021.

Evaluating the economic impact of water scarcity in a changing world. Nat. Commun. 2021 121 12, 1–10. https://doi.org/10.1038/s41467-021-22194-0

Dracup, J.A., Lee, K.S., Paulson, E.G., 1980a. On the statistical characteristics of drought events. Water Resour. Res. 16, 289–296. https://doi.org/10.1029/WR016I002P00289

Dracup, J.A., Lee, K.S., Paulson, E.G., 1980b. On the definition of droughts. Water Resour. Res. 16, 297–302. https://doi.org/10.1029/WR016I002P00297

Drax, 2023. Private communications with Martin Mcghie from Drax.

Drax, 2018. The great balancing act: what it takes to keep the power grid stable - Drax [WWW Document]. URL https://www.drax.com/technology/great-balancing-act-takes-keep-power-grid-stable/ (accessed 7.3.20).

DUKES, 2022. Load factors for renewable electricity generation [WWW Document]. URL https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fgovernment%2Fuploads%2Fsystem%2Fuploads%2Fattachment_data%2Ffile%2F1006822%2FDUKES_6.5.xls&wdOrigin=BROWSELINK (accessed 7.26.22).

DUKES, 2018. Digest of UK Energy Statistics (Chapter 5). Natl. Stat. 80–107.

Duncan, N., 2012. Mapping Scotland’s Hydropower Resource. Dr. Philos. Diss. Univ. Edinburgh, Edinburgh.

Duratorre, T., Bombelli, G.M., Menduni, G., Bocchiola, D., 2020. Hydropower potential in the alps under climate change scenarios. The Chavonne plant, Val D’Aosta. Water (Switzerland) 12, 1–20. https://doi.org/10.3390/w12072011

Ebi, K.L., Vanos, J., Baldwin, J.W., Bell, J.E., Hondula, D.M., Errett, N.A., Hayes, K., Reid, C.E., Saha, S., Spector, J., Berry, P., 2021. Extreme Weather and Climate Change: Population Health and Health System Implications. Annu. Rev. Public Health 42, 293. https://doi.org/10.1146/ANNUREV-PUBLHEALTH-012420-105026

Eccles, R., Zhang, H., Hamilton, D., 2019. A review of the effects of climate change on riverine flooding in subtropical and tropical regions. J. Water Clim. Chang. 10, 687–707. https://doi.org/10.2166/WCC.2019.175

Edenhofer, O., Madruga, R.P., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C., 2011. Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change, Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/CBO9781139151153

ESRI, 2023. ArcGIS | Geospatial Platform - GIS Software for Business & Government.

European Commission, 2023. Consequences of climate change [WWW Document].

URL https://climate.ec.europa.eu/climate-change/consequences-climate-change_en (accessed 1.12.24).

European Environment Agency, 2022. Natura 2000 data - the European network of protected sites — European Environment Agency [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/data/natura-13 (accessed 8.2.22).

Firbank, L.G., 2008. Assessing the Ecological Impacts of Bioenergy Projects. BioEnergy Res. 1, 12–19. https://doi.org/10.1007/s12155-007-9000-8

Flury, K., Frischknecht, R., 2012. Life Cycle Inventories of Hydroelectric Power Generation.

Forbes, 2022. Hydropower And Water Scarcity: The Growing Climate Risks Of A Climate Solution.

Formetta, G., Prosdocimi, I., Stewart, E., Bell, V., 2018. Estimating the index flood with continuous hydrological models: an application in Great Britain. Hydrol. Res. 49, 123–133. https://doi.org/10.2166/NH.2017.251

Forrest, N., 2008. Scottish Hydropower Resource Study. Victoria 57.

Freire-González, J., Decker, C., Hall, J.W., 2017. The Economic Impacts of Droughts: A Framework for Analysis. Ecol. Econ. 132, 196–204. https://doi.org/10.1016/J.ECOLECON.2016.11.005

Fung, K.F., Huang, Y.F., Koo, C.H., Soh, Y.W., 2020. Drought forecasting: A review of modelling approaches 2007–2017. J. Water Clim. Chang. 11, 771–799. https://doi.org/10.2166/WCC.2019.236

Garegnani, G., Sacchelli, S., Balest, J., Zambelli, P., 2018. GIS-based approach for assessing the energy potential and the financial feasibility of run-off-river hydro-power in Alpine valleys. Appl. Energy 216, 709–723. https://doi.org/10.1016/J.APENERGY.2018.02.043

Gaudard, L., Gilli, M., Romerio, F., 2013. Climate Change Impacts on Hydropower Management. Water Resour. Manag. 27, 5143–5156. https://doi.org/10.1007/S11269-013-0458-1/METRICS

Golgojan, A.-D., White, C.J., Bertram, D., 2024a. An assessment of run of river hydropower potential in Great Britain. Proc. Inst. Civ. Eng. Water Manag. 178, 42–61. https://doi.org/10.1680/jwama.23.00056.

Golgojan, A.-D., White, C.J., Bertram, D., 2024b. Future impacts of river flow on hydropower generation in Great Britain. J. Water Clim. Chang. 15, 4840–4861. https://doi.org/10.2166/wcc.2024.355

Gosal, A.S., Evans, P.M., Bullock, J.M., Redhead, J., Charlton, M.B., Cord, A.F., Johnson, A., Ziv, G., 2022. Understanding the accuracy of modelled changes in freshwater provision over time. https://doi.org/10.1016/j.scitotenv.2022.155042

Gosling, R., 2014. Assessing the impact of projected climate change on drought vulnerability in Scotland. Hydrol. Res. 45, 806–816.

https://doi.org/10.2166/nh.2014.148

GOV UK, 2024. Construction near protected areas and wildlife - GOV.UK [WWW Document]. URL https://www.gov.uk/guidance/construction-near-protected-areas-and-wildlife (accessed 1.17.25).

GOV UK, 2016. Protected sites and areas: how to review planning applications - GOV.UK [WWW Document]. URL https://www.gov.uk/guidance/protected-sites-and-areas-how-to-review-planning-applications (accessed 1.17.25).

GOV UK, 2013. Sites of special scientific interest: managing your land - GOV.UK [WWW Document]. URL https://www.gov.uk/guidance/protected-areas-sites-of-special-scientific-interest (accessed 1.17.25).

Green Tech Media, 2020. Pumped Hydro Moves to Retain Storage Market Leadership | Greentech Media [WWW Document]. URL https://www.greentechmedia.com/articles/read/pumped-hydro-moves-to-retain-storage-market-leadership?utm_campaign=gtmsocial&utm_medium=social&utm_source=twitter (accessed 11.29.20).

Gudmundsson, L., Boulange, J., Do, H.X., Gosling, S.N., Grillakis, M.G., Koutroulis, A.G., Leonard, M., Liu, J., Schmied, H.M., Papadimitriou, L., Pokhrel, Y., Seneviratne, S.I., Satoh, Y., Thiery, W., Westra, S., Zhang, X., Zhao, F., 2021. Globally observed trends in mean and extreme river flow attributed to climate change. Science (80-.). 371, 1159–1162. https://doi.org/10.1126/SCIENCE.ABA3996/SUPPL_FILE/ABA3996_GUDMUNDSSON_SM.PDF

Haberl, H., Erb, K.H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C., Steinberger, J.K., 2011. Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. Biomass and Bioenergy 35, 4753–4769. https://doi.org/10.1016/J.BIOMBIOE.2011.04.035

Haile, G.G., Tang, Q., Hosseini-Moghari, S.M., Liu, X., Gebremicael, T.G., Leng, G., Kebede, A., Xu, X., Yun, X., 2020. Projected Impacts of Climate Change on Drought Patterns Over East Africa. Earth's Futur. 8, e2020EF001502. https://doi.org/10.1029/2020EF001502

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., Kumar, R., 2018. Revisiting the recent European droughts from a long-term perspective. Sci. Rep. 8, 1–11. https://doi.org/10.1038/s41598-018-27464-4

Hannaford, J., Mackay, J.D., Ascott, M., Chitson, T., Cole, S., Counsell, C., Durant, M., Jackson, C.R., Kay, A.L., Lane, R.A., Moore, R., Parry, S., Rudd, A.C., Facer-Childs, K., Turner, S., Wallbank, J.R., Wells, S., Wilcox, A., 2022. eFLaG: enhanced future FLows and Groundwater. A national dataset of hydrological projections based on UKCP18. Earth Syst. Sci. Data Discuss. 1–40.

Harrigan, S., Hannaford, J., Muchan, K., Marsh, T.J., 2018. Designation and trend analysis of the updated UK Benchmark Network of river flow stations: The

UKBN2 dataset. Hydrol. Res. 49, 552–567. https://doi.org/10.2166/nh.2017.058

Hasan, H.H., Razali, S.F.M., Muhammad, N.S., Ahmad, A., 2019. Research Trends of Hydrological Drought: A Systematic Review. Water 2019, Vol. 11, Page 2252 11, 2252. https://doi.org/10.3390/W11112252

He, X., Feng, K., Li, X., Craft, A.B., Wada, Y., Burek, P., Wood, E.F., Sheffield, J., 2019. Solar and wind energy enhances drought resilience and groundwater sustainability. Nat. Commun. 2019 101 10, 1–8. https://doi.org/10.1038/s41467-019-12810-5

Higgins, A.J., Bryan, B.A., Overton, I.C., Holland, K., Lester, R.E., King, D., Nolan, M., Connor, J.D., 2011. Integrated modelling of cost-effective siting and operation of flow-control infrastructure for river ecosystem conservation. Water Resour. Res. 47, 5519. https://doi.org/10.1029/2010WR009919

HM Government, 2023. The Third National Adaptation Programme (NAP3) and the Fourth Strategy for Climate Adaptation Reporting.

HM Government, 2021. Net Zero Strategy: Build Back Greener.

Hoes, O.A.C., Meijer, L.J.J., Van Der Ent, R.J., Van De Giesen, N.C., 2017. Systematic high-resolution assessment of global hydropower potential. PLoS One 12, 1–10. https://doi.org/10.1371/journal.pone.0171844

Hofman, E., Van Der Gaast, W., Oikonomou, V., Flamos, A., Karakosta, C., 2014. The role of social acceptance Project Coordinator Project Dissemination.

Huld, T., Šúri, M., Dunlop, E.D., 2008. Geographical variation of the conversion efficiency of crystalline silicon photovoltaic modules in Europe. Prog. Photovoltaics Res. Appl. 16, 595–607. https://doi.org/10.1002/PIP.846

Hyland, M., Russ, J., 2019. Water as destiny – The long-term impacts of drought in sub-Saharan Africa. World Dev. 115, 30–45. https://doi.org/10.1016/j.worlddev.2018.11.002

IEA, 2020. Electricity security in tomorrow's power systems – Analysis - IEA [WWW Document]. URL https://www.iea.org/articles/electricity-security-in-tomorrow-s-power-systems (accessed 11.24.20).

Intergovernmental Panel on Climate Change, 2014. Climate Change 2014 Mitigation of Climate Change, Climate Change 2014 Mitigation of Climate Change. https://doi.org/10.1017/cbo9781107415416

International Energy Agency, 2020. Global Energy Review 2020, Iea.

International Hydropower Association, 2023. Pumped storage hydropower [WWW Document]. URL https://www.hydropower.org/factsheets/pumped-storage (accessed 3.21.23).

International Hydropower Association, 2022a. With hydropower, we can create a renewable and resilient energy system [WWW Document]. URL https://www.hydropower.org/blog/with-hydropower-we-can-create-a-renewable-and-resilient-energy-system (accessed 2.20.24).

International Hydropower Association, 2022b. Country profile - United Kingdom [WWW Document]. URL https://www.hydropower.org/country-profiles/united-kingdom (accessed 4.5.22).

International Hydropower Association, 2022c. Facts about Hydropower [WWW Document]. URL https://www.hydropower.org/iha/discover-facts-about-hydropower (accessed 7.26.22).

International Renewable Energy Agency, 2021. Renewable Power Generation Costs in 2021, International Renewable Energy Agency. https://doi.org/10.1007/SpringerReference_7300

IPCC, 2021. Climate Change 2022: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press 3949.

Jackson, N.D., Gunda, T., 2021. Evaluation of extreme weather impacts on utility-scale photovoltaic plant performance in the United States. Appl. Energy 302, 117508. https://doi.org/10.1016/J.APENERGY.2021.117508

Jakubowski, W., Radczuk, L., 2004. Hydrological Drought Processes and Estimation Methods for Streamflow and Groundwater edited by: Tallaksen, LM and van Lanen, HAJ, Elsevier Sciences BV, Amsterdam,[CD-ROM].

Juhola, S., Laurila, A.G., Groundstroem, F., Klein, J., 2023. Climate risks to the renewable energy sector: Assessment and adaptation within energy companies. Bus. Strateg. Environ. https://doi.org/10.1002/BSE.3580

Jung, J., Jung, S., Lee, J., Lee, M., Kim, H.S., 2021. Analysis of small hydropower generation potential: (2) future prospect of the potential under climate change. Energies 14. https://doi.org/10.3390/en14113001

Jurasz, J., Mikulik, J., Krzywda, M., Ciapała, B., Janowski, M., 2018. Integrating a wind- and solar-powered hybrid to the power system by coupling it with a hydroelectric power station with pumping installation. Energy 144, 549–563. https://doi.org/10.1016/j.energy.2017.12.011

Kabalci, E., Boyar, A., Kabalci, Y., 2021. Centralized power generation. https://doi.org/10.1016/B978-0-12-821724-5.00002-7

Karapici, V., Trojer, A., Lazarevikj, M., Pluskal, T., Chernobrova, A., Nezirić, E., Zuecco, G., Alerci, A.L., Seydoux, M., Doujak, E., Rudolf, P., 2024. Opportunities of hidden hydropower technologies towards the energy transition. Energy Reports 12, 5633–5647. https://doi.org/10.1016/J.EGYR.2024.11.039

Kay, A.L., 2021. Simulation of river flow in Britain under climate change: Baseline performance and future seasonal changes. Hydrol. Process. 35, 1–10. https://doi.org/10.1002/hyp.14137

Kay, A.L., Bell, V.A., Guillod, B.P., Jones, R.G., Rudd, A.C., 2018. National-scale analysis of low flow frequency: historical trends and potential future changes.

Clim. Change 147, 585–599. https://doi.org/10.1007/s10584-018-2145-y

Kay, A.L., Griffin, A., Rudd, A.C., Chapman, R.M., Bell, V.A., Arnell, N.W., 2021a. Climate change effects on indicators of high and low river flow across Great Britain. Adv. Water Resour. 151, 103909. https://doi.org/10.1016/j.advwatres.2021.103909

Kay, A.L., Rudd, A.C., Fry, M., Nash, G., Allen, S., 2021b. Climate change impacts on peak river flows: Combining national-scale hydrological modelling and probabilistic projections. Clim. Risk Manag. 31, 100263. https://doi.org/10.1016/j.crm.2020.100263

Kay, A.L., Watts, G., Wells, S.C., Allen, S., 2020. The impact of climate change on U. K. river flows: A preliminary comparison of two generations of probabilistic climate projections. Hydrol. Process. 34, 1081–1088. https://doi.org/10.1002/hyp.13644

Kchouk, S., Melsen, L.A., Walker, D.W., Van Oel, P.R., 2021. A review of drought indices: predominance of drivers over impacts and the importance of local context. Nat. Hazards Earth Syst. Sci. https://doi.org/10.5194/nhess-2021-152

Kemp, L., Xu, C., Depledge, J., Ebi, K.L., Gibbins, G., Kohler, T.A., Rockstrom, J., Scheffer, M., Schellnhuber, H.J., Steffen, W., Lenton, T.M., 2022. Climate Endgame: Exploring catastrophic climate change scenarios. Proc. Natl. Acad. Sci. U. S. A. 119, e2108146119. https://doi.org/10.1073/PNAS.2108146119/SUPPL_FILE/PNAS.2108146119.SAPP.PDF

Kendon, E.J., Prein, A.F., Senior, C.A., Stirling, A., Office, M., Centre, H., 2021. Challenges and outlook for convection-permitting climate modelling. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 379. https://doi.org/10.1098/rsta.2019.0547

Kennedy, C., Bertram, D., White, C.J., 2023. A review of the current onshore (hydropower) and offshore (tidal energy) resource of the United Kingdom. Renew. Sustain. Energy Rev.

Kern, J.D., Su, Y., Hill, J., 2020. A retrospective study of the 2012-2016 California drought and its impacts on the power sector. Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/AB9DB1

Kim, S.J., Asadzadeh, M., Stadnyk, T.A., 2022. Climate change impact on water supply and hydropower generation potential in Northern Manitoba. J. Hydrol. Reg. Stud. 41, 101077. https://doi.org/10.1016/J.EJRH.2022.101077

King, A.D., Reid, K.J., Saunders, K.R., 2023. Communicating the link between climate change and extreme rain events. Nat. Geosci. 2023 167 16, 552–554. https://doi.org/10.1038/s41561-023-01223-1

Kouadio, C.A., Kouassi, K.L., Diedhiou, A., Obahoundje, S., Amoussou, E., Kamagate, B., Paturel, J.E., Coulibaly, T.J.H., Coulibaly, H.S.J.P., Didi, R.S., Savane, I., 2022. Assessing the Hydropower Potential Using Hydrological

Models and Geospatial Tools in the White Bandama Watershed (Côte d'Ivoire, West Africa). Front. Water 4, 1–14. https://doi.org/10.3389/frwa.2022.844934

Kouloumpis, V., Stamford, L., Azapagic, A., 2015. Decarbonising electricity supply: Is climate change mitigation going to be carried out at the expense of other environmental impacts? Sustain. Prod. Consum. 1, 1–21. https://doi.org/10.1016/j.spc.2015.04.001

Kulkarni, S., Deo, M.C., Ghosh, S., 2014. Changes in the design and operational wind due to climate change at the Indian offshore sites. Mar. Struct. 37, 33–53. https://doi.org/10.1016/J.MARSTRUC.2014.02.005

Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Bejarano, M.D., Garrote, L., 2021. Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition. Renew. Sustain. Energy Rev. 142. https://doi.org/10.1016/j.rser.2021.110833

Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Garrote, L., 2019. Flow regime aspects in determining environmental flows and maximising energy production at run-of-river hydropower plants. Appl. Energy 256, 113980. https://doi.org/10.1016/j.apenergy.2019.113980

Lane, R.A., Coxon, G., Freer, J., Seibert, J., Wagener, T., 2022. A large-sample investigation into uncertain climate change impacts on high flows across Great Britain. Hydrol. Earth Syst. Sci. 26, 5535–5554. https://doi.org/10.5194/HESS-26-5535-2022

Lenzen, M., 2010. Current state of development of electricity-generating technologies: A literature review. Energies 3, 462–591. https://doi.org/10.3390/en3030462

Leung, D.Y.C., Yang, Y., 2012. Wind energy development and its environmental impact: A review. Renew. Sustain. Energy Rev. 16, 1031–1039. https://doi.org/10.1016/j.rser.2011.09.024

Li, J., Wang, Z., Wu, X., Ming, B., Chen, L., Chen, X., 2020. Evident response of future hydropower generation to climate change. J. Hydrol. 590, 125385. https://doi.org/10.1016/j.jhydrol.2020.125385

Liu, X., Yuan, X., Ma, F., Xia, J., 2023. The increasing risk of energy droughts for hydropower in the Yangtze River basin. J. Hydrol. 621, 129589. https://doi.org/10.1016/j.jhydrol.2023.129589

Lobanova, A., Liersch, S., Nunes, J.P., Didovets, I., Stagl, J., Huang, S., Koch, H., Rivas López, M. del R., Maule, C.F., Hattermann, F., Krysanova, V., 2018. Hydrological impacts of moderate and high-end climate change across European river basins. J. Hydrol. Reg. Stud. 18, 15–30. https://doi.org/10.1016/J.EJRH.2018.05.003

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Edwards, T., Fosser, G., Fung, F., Gohar, L., Good, P., Gregory, J., Harris, G., Howard, T., Kaye, N., Kendon, E., Krijnen, J., Maisey, P., Mcdonald, R., Mcinnes, R., Mcsweeney, C., Mitchell, J.F.B., Murphy, J., Palmer, M., Roberts, C., Rostron, J., Thornton, H., Tinker, J., Tucker, S., Yamazaki, K., Belcher, S., Eagle, K., Edwards, T., Fosser, G., others, 2018. UKCP18 science overview report. Met Off. Hadley Cent. Exet. UK 2018, 1–73.

Madsen, H., Rosbjerg, D., 2008. On the modelling of extreme droughts.

Marshall, A.M., Chen, J.M., 2018. IOP Conference Series: Earth and Environmental Science Impacts of climate change on hydropower development and sustainability: a review You may also like Impacts of changing snowfall on seasonal complementarity of hydroelectric and solar power. IOP Conf. Ser. Earth Environ. Sci 163, 12126. https://doi.org/10.1088/1755-1315/163/1/012126

MATLAB R2023a, 2023. MATLAB.

McEwen, L., Bryan, K., Black, A., Blake, J., Afzal, M., 2021. Science-Narrative Explorations of “Drought Thresholds” in the Maritime Eden Catchment, Scotland: Implications for Local Drought Risk Management. Front. Environ. Sci. 9, 589980. https://doi.org/10.3389/FENVS.2021.589980/BIBTEX

Met Office, 2014. What is the wettest city in the UK? | Official blog of the Met Office news team [WWW Document]. URL https://blog.metoffice.gov.uk/2014/10/20/what-is-the-wettest-city-in-the-uk/ (accessed 8.2.22).

Michels-Brito, A., Rodriguez, D.A., Cruz Junior, W.L., Nildo de Souza Vianna, J., 2021. The climate change potential effects on the run-of-river plant and the environmental and economic dimensions of sustainability. Renew. Sustain. Energy Rev. 147. https://doi.org/10.1016/j.rser.2021.111238

Mohor, G.S., Rodriguez, D.A., Tomasella, J., Siqueira Júnior, J.L., 2015. Exploratory analyses for the assessment of climate change impacts on the energy production in an Amazon run-of-river hydropower plant. J. Hydrol. Reg. Stud. 4, 41–59. https://doi.org/10.1016/J.EJRH.2015.04.003

Montanari, A., Nguyen, H., Rubinetti, S., Ceola, S., Galelli, S., Rubino, A., Zanchettin, D., 2023. Why the 2022 Po River drought is the worst in the past two centuries. Sci. Adv. 9. https://doi.org/10.1126/SCIADV.ADG8304/SUPPL_FILE/SCIADV.ADG8304_SM.PDF

Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J., Verbruggen, A., 2011. 2011: Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stecho. Cambridge, United Kingdom and New York, NY, USA.

Moore, D.S., Notz, W.I., Flinger, M.A., 2013. The Basic Practice of Statistics (6th ed.).

Moore, R.J., 2007. The PDM rainfall-runoff model. Hydrol. Earth Syst. Sci. 11, 483–499. https://doi.org/10.5194/HESS-11-483-2007

Moore, R.J., Cole, S.J., Bell, V.A., Jones, D.A., 2006. Issues in flood forecasting: Ungauged basins, extreme floods and uncertainty. IAHS-AISH Publ. 103–122.

Mosier, T.M., Sharp, K. V., Hill, D.F., 2016. The Hydropower Potential Assessment Tool (HPAT): Evaluation of run-of-river resource potential for any global land area and application to Falls Creek, Oregon, USA. Renew. Energy 97, 492–503. https://doi.org/10.1016/j.renene.2016.06.002

Mosley, L.M., 2015. Drought impacts on the water quality of freshwater systems; review and integration. Earth-Science Rev. 140, 203–214. https://doi.org/10.1016/J.EARSCIREV.2014.11.010

Mujjuni, F., Betts, T., Blanchard, R., 2023. Uganda's Hydropower System Resilience to Extreme Climate Variability. Clim. 2023, Vol. 11, Page 177 11, 177. https://doi.org/10.3390/CLI11090177

Murphy, J., Harris, G., Sexton, D., Kendon, E., Bett, P., Clark, R., Eagle, K., Fosser, G., Fung, F., Lowe, J., McDonald, R., McInnes, R., McSweeney, C., Mitchell, J., Rostron, J., Thornton, H., Tucker, S., Yamazaki, and K., 2019. UKCP18 Land report. UKCP18 L. Proj. Sci. Rep. 2018.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T.P., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A., 2009. UK Climate Projections Science Report: Climate change projections, Met Office Hadley Centre: Exeter, UK. https://doi.org/10.1787/9789264086876-5-en

Mutsindikwa, T.C., Yira, Y., Bossa, A.Y., Hounkpè, J., Salack, S., Saley, I.A., Rabani, A., 2021. Modeling climate change impact on the hydropower potential of the Bamboi catchment. Model. Earth Syst. Environ. 7, 2709–2717. https://doi.org/10.1007/s40808-020-01052-w

National River Flow Archive, 2014. Hydrometric areas for Great Britain and Northern Ireland. NERC-Environmental Inf. Data Cent.

Neachell, E., 2014. Book Review - Environmental flows: Saving rivers in the thrid millennium. River Res. Appl. 30, 132–133. https://doi.org/10.1002/rra

Nogal, M., Nogal, A., 2021. Sensitivity method for extreme-based engineering problems 216, 107997. https://doi.org/10.1016/J.RESS.2021.107997

NRFA, 2023. NRFA Categories and Networks | National River Flow Archive [WWW Document]. URL https://nrfa.ceh.ac.uk/nrfa-categories-networks (accessed 8.3.23).

NRFA, 2021. Catchment Rainfall | National River Flow Archive [WWW Document]. URL https://nrfa.ceh.ac.uk/catchment-rainfall (accessed 9.27.22).

OECD, 2018. Climate-resilient Infrastructure.

Ofgem, 2019. Feed-in Tariffs (FIT) | Ofgem [WWW Document]. URL https://www.ofgem.gov.uk/environmental-programmes/fit (accessed 6.29.20).

Ölz, S., Sims, R., Kirchner, N., 2007. Contribution of Renewables to Energy Security - International Energy Agency. IEA Inf. Pap. 74.

Opperman, J., Camargo, R., Laporte-Bisquit, A., Zarfl, C., Morgan, A.J., 2022. Using the WWF Water Risk Filter to Screen Existing and Projected Hydropower Projects for Climate and Biodiversity Risks. Water (Switzerland) 14, 721. https://doi.org/10.3390/w14050721

Opperman, J.J., Camargo, R.R., Laporte-Bisquit, A., Zarfl, C., Morgan, A.J., 2022. Using the WWF Water Risk Filter to Screen Existing and Projected Hydropower Projects for Climate and Biodiversity Risks. Water (Switzerland) 14, 721. https://doi.org/10.3390/w14050721

Ordnance Survey, 2022. OS Open Rivers | High Level View of Watercourses| Vector Map Data | Free Download [WWW Document]. URL https://www.ordnancesurvey.co.uk/business-government/products/open-map-rivers (accessed 8.2.22).

Osman, R., Ferrari, E., Mcdonald, S., 2016. Water Scarcity and Irrigation Efficiency in Egypt. Water Econ. Policy 2. https://doi.org/10.1142/S2382624X16500090

Otero, N., Martius, O., Allen, S., Bloomfield, H., Schaefli, B., 2022. A copula-based assessment of renewable energy droughts across Europe. Renew. Energy 201, 667–677. https://doi.org/10.1016/j.renene.2022.10.091

Oxford Policy Management, 2019. The impact of climate change on hydropower in Africa [WWW Document]. URL https://www.opml.co.uk/blog/the-impact-of-climate-change-on-hydropower-in-africa (accessed 7.20.23).

Paltan, H.A., Pant, R., Plummer Braeckman, J., Dadson, J.S., 2021. Increased Water Risks to Global Hydropower in 1.5°C and 2.0°C warmer worlds. J. Hydrol. 599, 1–33.

Pandey, A., Lalrempuia, D., Jain, S.K., 2015. Evaluation du potentiel hydroélectrique utilisant la technologie spatiale et le modèle SWAT pour la rivière Mat, dans le sud Mizoram, Inde. Hydrol. Sci. J. 60, 1651–1665. https://doi.org/10.1080/02626667.2014.943669

Pang, M., Zhang, L., Ulgiati, S., Wang, C., 2015. Ecological impacts of small hydropower in China: Insights from an emergy analysis of a case plant. Energy Policy 76, 112–122. https://doi.org/10.1016/j.enpol.2014.10.009

Pasha, M.F.K., Yeasmin, D., Kao, S.-C., Hadjerioua, B., Wei, Y., Smith, B.T., 2014. Stream-Reach Identification for New Run-of-River Hydropower Development through a Merit Matrix–Based Geospatial Algorithm. J. Water Resour. Plan. Manag. 140, 04014016. https://doi.org/10.1061/(asce)wr.1943-5452.0000429

Pereira, Geraldo, Magela, 2021. Design of Hydroelectric Power Plants – Step by Step. Des. Hydroelectr. Power Plants – Step by Step. https://doi.org/10.1201/9781003161325

Perera, N., Boyd Gill Wilkins, E., Phillips Itty, R., 2015. Literature Review on Energy Access and Adaptation to Climate Change.

Pokhrel, Y., Burbano, M., Roush, J., Kang, H., Sridhar, V., Hyndman, D.W., 2018. A Review of the Integrated Effects of Changing Climate, Land Use, and Dams on Mekong River Hydrology. Water 2018, Vol. 10, Page 266 10, 266. https://doi.org/10.3390/W10030266

Poornima, S., Pushpalatha, M., 2019. Drought prediction based on SPI and SPEI with varying timescales using LSTM recurrent neural network. Soft Comput. 23, 8399–8412. https://doi.org/10.1007/S00500-019-04120-1/METRICS

Pörtner, H.-O., D.C. Roberts, Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B., 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change e, Climate Change 2021: The Physical Science Basis. https://doi.org/10.1017/9781009325844.Front

Prudhomme, C., Young, A., Watts, G., Haxton, T., Crooks, S., Williamson, J., Davies, H., Dadson, S., Allen, S., 2012. The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. Hydrol. Process. 26, 1115–1118. https://doi.org/10.1002/hyp.8434

Pryor, S.C., Barthelmie, R.J., 2010. Climate change impacts on wind energy: A review. Renew. Sustain. Energy Rev. 14, 430–437. https://doi.org/10.1016/J.RSER.2009.07.028

Pushpalatha, R., Perrin, C., Le Moine, N., Mathevet, T., Andréassian, V., 2011. A downward structural sensitivity analysis of hydrological models to improve low-flow simulation. J. Hydrol. 411, 66–76. https://doi.org/10.1016/J.JHYDROL.2011.09.034

QGIS Development Team, 2022. Spatial without Compromise · QGIS Web Site [WWW Document]. QGIS Geogr. Inf. Syst. Open Source Geospatial Found. Proj. URL https://qgis.org/ (accessed 7.15.24).

Qiu, M., Ratledge, N., Azevedo, I.M.L., Diffenbaugh, N.S., Burke, M., 2023. Drought impacts on the electricity system, emissions, and air quality in the western United States. Proc. Natl. Acad. Sci. U. S. A. 120, e2300395120.

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., Laaksonen, A., 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Commun. Earth Environ. 2022 31 3, 1–10. https://doi.org/10.1038/s43247-022-00498-3

Rapleys, 2021. Habitats regulation changes as a result of Brexit [WWW Document]. URL https://rapleys.com/habitats-regulation-changes-as-a-result-of-brexit/ (accessed 8.2.22).

Raynaud, D., Hingray, B., François, B., Creutin, J.D., 2018. Energy droughts from variable renewable energy sources in European climates. Renew. Energy 125, 578–589. https://doi.org/10.1016/j.renene.2018.02.130

RETScreen, 2022. RETScreen Clean Energy Management Software [WWW Document]. URL https://www.nrcan.gc.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465 (accessed 8.2.22).

Reuters, 2021. Insight: Droughts shrink hydropower, pose risk to global push to clean energy [WWW Document]. URL https://www.reuters.com/business/sustainable-business/inconvenient-truth-droughts-shrink-hydropower-pose-risk-global-push-clean-energy-2021-08-13/ (accessed 7.20.23).

Ritchie, H., Roser, M., Rosado, P., 2020. CO_2 and Greenhouse Gas Emissions [WWW Document]. Our World Data. URL https://ourworldindata.org/emissions-by-sector (accessed 11.24.20).

Rojanamon, P., Chaisomphob, T., Bureekul, T., 2009. Application of geographical information system to site selection of small run-of-river hydropower project by considering engineering/economic/environmental criteria and social impact. Renew. Sustain. Energy Rev. 13, 2336–2348. https://doi.org/10.1016/j.rser.2009.07.003

Roson, R., Damania, R., 2017. The macroeconomic impact of future water scarcity: An assessment of alternative scenarios. J. Policy Model. 39, 1141–1162. https://doi.org/10.1016/j.jpolmod.2017.10.003

Rudd, A.C., Kay, A.L., Bell, V.A., 2019. National-scale analysis of future river flow and soil moisture droughts: potential changes in drought characteristics. Clim. Change 156, 323–340. https://doi.org/10.1007/s10584-019-02528-0

Sahu, I., Prasad, A.D., 2018. Assessment of hydro potential using integrated tool in QGIS. ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 4, 115–119. https://doi.org/10.5194/isprs-annals-IV-5-115-2018

Salford Civil Engineering, 1989. Small Scale Hydroelectric Generation Potential In the UK.

Sammartano, V., Liuzzo, L., Freni, G., 2019. Identification of potential locations for run-of-river hydropower plants using a GIS-based procedure. Energies 12, 1–20. https://doi.org/10.3390/en12183446

Sample, J.E., Duncan, N., Ferguson, M., Cooksley, S., 2015. Scotland's hydropower: Current capacity, future potential and the possible impacts of climate change. Renew. Sustain. Energy Rev. 52, 111–122. https://doi.org/10.1016/j.rser.2015.07.071

Schneider, S.H., Root, T.L., Mastrandrea, M.D., Oxford University Press, 2011. Encyclopedia of climate and weather.

Schroders, 2022. The impact of droughts on the energy mix [WWW Document]. URL https://www.schroders.com/en-gb/uk/institutional/insights/the-impact-of-droughts-on-the-energy-mix/ (accessed 7.13.23).

Seneviratne, S.I., Zhang, Adnan, Badi, Dereczynski, Di Luca, Ghosh, Iskandar, Kossin, Lewis, Otto, Pinto, Satoh, Vicente-Serrano, W., Zhou, 2023. Weather and Climate Extreme Events in a Changing Climate., in: In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 1513–1766. https://doi.org/10.1017/9781009157896.013.1514

Sheffield, J., Wood, E.F., 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim. Dyn. 31, 79–105. https://doi.org/10.1007/S00382-007-0340-Z/TABLES/5

Shen, M., Chen, J., Zhuan, M., Chen, H., Xu, C.Y., Xiong, L., 2018. Estimating uncertainty and its temporal variation related to global climate models in quantifying climate change impacts on hydrology. J. Hydrol. 556, 10–24. https://doi.org/10.1016/j.jhydrol.2017.11.004

SHEPD, 2011. Statement of Methodology and Charges for Connection to Scottish Hydro Electric Power Distribution PLC’s Electricity Distribution System. Technical report.

Shu, J., Qu, J.J., Motha, R., Xu, J.C., Dong, D.F., 2018. Impacts of climate change on hydropower development and sustainability: A review. IOP Conf. Ser. Earth Environ. Sci. 163. https://doi.org/10.1088/1755-1315/163/1/012126

Siddiqui, O., Dincer, I., 2017. Comparative assessment of the environmental impacts of nuclear , wind and hydro-electric power plants in Ontario : A life cycle assessment. J. Clean. Prod. 164, 848–860. https://doi.org/10.1016/j.jclepro.2017.06.237

Sinagra, M., Sammartano, V., Aricò, C., Collura, A., Tucciarelli, T., 2014. Cross-Flow turbine design for variable operating conditions. Procedia Eng. 70, 1539–1548. https://doi.org/10.1016/j.proeng.2014.02.170

Siri, R., Mondal, S.R., Das, S., 2020. Hydropower: A Renewable Energy Resource for Sustainability in Terms of Climate Change and Environmental Protection. Handb. Environ. Chem. 99, 93–113. https://doi.org/10.1007/698_2020_635

Smith, K.A., Barker, L.J., Tanguy, M., Parry, S., Harrigan, S., Legg, T.P., Prudhomme, C., Hannaford, J., 2019. A multi-objective ensemble approach to hydrological modelling in the UK: An application to historic drought reconstruction. Hydrol. Earth Syst. Sci. 23, 3247–3268. https://doi.org/10.5194/HESS-23-3247-2019

Smith, R.L., Tebaldi, C., Nychka, D., Mearns, L.O., 2009. Bayesian modeling of uncertainty in ensembles of climate models. J. Am. Stat. Assoc. 104, 97–116. https://doi.org/10.1198/jasa.2009.0007

Soh, Y.W., Koo, C.H., Huang, Y.F., Fung, K.F., 2018. Application of artificial intelligence models for the prediction of standardized precipitation evapotranspiration index (SPEI) at Langat River Basin, Malaysia. Comput. Electron. Agric. 144, 164–173. https://doi.org/10.1016/J.COMPAG.2017.12.002

Solanki, Y.P., Kumar, V., Sharma, K.V., Deshmukh, A., Tiwari, D.K., 2024. Flood hazard analysis in Mumbai using geospatial and multi-criteria decision-making techniques. J. Water Clim. Chang. 15, 2484–2500. https://doi.org/10.2166/WCC.2024.053

Solaun, K., Cerdá, E., 2019. Climate change impacts on renewable energy generation. A review of quantitative projections. Renew. Sustain. Energy Rev. 116, 109415. https://doi.org/10.1016/J.RSER.2019.109415

Sovacool, B.K., Andersen, R., Sorensen, S., Sorensen, K., Tienda, V., Vainorius, A., Schirach, O.M., Bjørn-Thygesen, F., 2016. Balancing safety with sustainability: Assessing the risk of accidents for modern low-carbon energy systems. J. Clean. Prod. 112, 3952–3965. https://doi.org/10.1016/j.jclepro.2015.07.059

SSE, 2023. Private communication with David Crookall from SSE.

SSE Renewables, 2023. The Project — Coire Glas [WWW Document]. URL https://www.coireglas.com/project (accessed 4.3.23).

Steel, R.G.D., Torrie, J.H., 1962. Principles and Procedures of Statistics. (With special Reference to the Biological Sciences.). Biom. Z. 4, 207–208. https://doi.org/10.1002/BIMJ.19620040313

Stevens, S., Turner, S., Sankar, S., 2019. About Drought Handbook 60.

Sugg, M., Runkle, J., Leeper, R., Bagli, H., Golden, A., Handwerger, L.H., Magee, T., Moreno, C., Reed-Kelly, R., Taylor, M., Woolard, S., 2020. A scoping review of drought impacts on health and society in North America. Clim. Change 162, 1177–1195. https://doi.org/10.1007/S10584-020-02848-6/METRICS

Tabari, H., 2020. Climate change impact on flood and extreme precipitation increases with water availability. Sci. Reports 2020 101 10, 1–10. https://doi.org/10.1038/s41598-020-70816-2

Tarife, R.P., Tahud, A.P., Gulben, E.J.G., Macalisang, H.A.R.C.P., Ignacio, M.T.T., 2017. Application of Geographic Information System (GIS) in Hydropower Resource Assessment: A Case Study in Misamis Occidental, Philippines. Int. J. Environ. Sci. Dev. 8, 507–511. https://doi.org/10.18178/ijesd.2017.8.7.1005

Tarroja, B., Forrest, K., Chiang, F., AghaKouchak, A., Samuelsen, S., 2019. Implications of hydropower variability from climate change for a future, highly-renewable electric grid in California. Appl. Energy 237, 353–366. https://doi.org/10.1016/j.apenergy.2018.12.079

The Guardian, 2021. Why New Zealand's climate is seen as Great Britain's southerly equivalent | New Zealand | The Guardian [WWW Document]. URL https://www.theguardian.com/news/2021/feb/23/why-new-zealands-climate-is-seen-as-great-britains-southerly-equivalent (accessed 3.6.24).

Tian, Y., Zhang, F., Yuan, Z., Che, Z., Zafetti, N., 2020. Assessment power generation potential of small hydropower plants using GIS software. Energy Reports 6, 1393–1404. https://doi.org/10.1016/j.egyr.2020.05.023

Trading Economics, 2023. United Kingdom Electricity Price - Quote - Chart - Historical Data - News [WWW Document]. URL https://tradingeconomics.com/united-kingdom/electricity-price (accessed 12.4.23).

Trisos, C.H., Adelekan, I.O., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N.P., Zakieldeen, S., 2022. Africa. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenb, Cambridge University Press. https://doi.org/10.1017/9781009325844.011.1286

Tsoutsos, T., Frantzeskaki, N., Gekas, V., 2005. Environmental impacts from the solar energy technologies. Energy Policy 33, 289–296. https://doi.org/10.1016/S0301-4215(03)00241-6

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew. Sustain. Energy Rev. 28, 555–565. https://doi.org/10.1016/j.rser.2013.08.013

Turner, S.W.D., Voisin, N., Nelson, K., Tidwell, V., 2022a. Drought Impacts on Hydroelectric Power Generation in the Western United States.

Turner, S.W.D., Voisin, N., Nelson, K., Tidwell, V., Turner, S.W.D., Voisin, N., Nelson, K., Tidwell, V., 2022b. Drought Impacts on Hydroelectric Power Generation in the Western United States.

UK Centre for Ecology & Hydrology, 2023. National Changes in River Flow [WWW Document]. URL https://www.ceh.ac.uk/national-changes-river-flow (accessed 1.11.24).

UK Government, 2019. Climate Change Act 2008. Statute Law Database.

UKCEH, 2022. PDM (Probability Distributed Model) | UK Centre for Ecology & Hydrology [WWW Document]. URL https://www.ceh.ac.uk/services/pdm-probability-distributed-model (accessed 9.28.22).

van Loon, A.F., van Lanen, H.A.J., 2013. Making the distinction between water scarcity and drought using an observation-modeling framework. Water Resour. Res. 49, 1483–1502. https://doi.org/10.1002/WRCR.20147

Van Vliet, M.T.H., Franssen, W.H.P., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P., Kabat, P., 2013. Global river discharge and water temperature under climate change. Glob. Environ. Chang. 23, 450–464. https://doi.org/10.1016/J.GLOENVCHA.2012.11.002

van Vliet, M.T.H., van Beek, L.P.H., Eisner, S., Flörke, M., Wada, Y., Bierkens, M.F.P., 2016. Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Glob. Environ. Chang. 40, 156–170. https://doi.org/10.1016/j.gloenvcha.2016.07.007

Vautard, R., Van Aalst, M., Boucher, O., Drouin, A., Haustein, K., Kreienkamp, F., Van Oldenborgh, G.J., Otto, F.E.L., Ribes, A., Robin, Y., Schneider, M., Soubeyroux, J.M., Stott, P., Seneviratne, S.I., Vogel, M.M., Wehner, M., 2020. Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe. Environ. Res. Lett. 15, 094077. https://doi.org/10.1088/1748-9326/ABA3D4

Venus, T.E., Hinzmann, M., Bakken, T.H., Gerdes, H., Godinho, F.N., Hansen, B., Pinheiro, A., Sauer, J., 2020. The public's perception of run-of-the-river hydropower across Europe. Energy Policy 140, 111422. https://doi.org/10.1016/j.enpol.2020.111422

Verán-Leigh, D., Vázquez-Rowe, I., 2019. Life cycle assessment of run-of-river hydropower plants in the Peruvian Andes: a policy support perspective. Int. J. Life Cycle Assess. 24, 1376–1395. https://doi.org/10.1007/s11367-018-01579-2

Visser-Quinn, A., Beevers, L., Lau, T., Gosling, R., 2021. Mapping future water scarcity in a water abundant nation: Near-term projections for Scotland. Clim. Risk Manag. 32, 100302. https://doi.org/10.1016/j.crm.2021.100302

Voisin, N., Dyreson, A., Fu, T., O'Connell, M., Turner, S.W.D., Zhou, T., Macknick, J., 2020. Impact of climate change on water availability and its propagation through the Western U.S. power grid. Appl. Energy 276, 115467. https://doi.org/10.1016/J.APENERGY.2020.115467

Voisin, N., Kintner-Meyer, M., Skaggs, R., Nguyen, T., Wu, D., Dirks, J., Xie, Y., Hejazi, M., 2016. Vulnerability of the US western electric grid to hydro-climatological conditions: How bad can it get? Energy 115, 1–12. https://doi.org/10.1016/j.energy.2016.08.059

Wan, W., Zhao, J., Popat, E., Herbert, C., Döll, P., 2021. Analyzing the Impact of Streamflow Drought on Hydroelectricity Production: A Global-Scale Study. Water Resour. Res. 57. https://doi.org/10.1029/2020WR028087

Wang, Y., Li, Huixin, Sun, B., Chen, H., Li, Hua, Luo, Y., 2020. Drought Impacts on Hydropower Capacity Over the Yangtze River Basin and Their Future Projections under 8, 1–13. https://doi.org/10.3389/feart.2020.578132

Ward, F.A., 2014. Economic impacts on irrigated agriculture of water conservation programs in drought. J. Hydrol. 508, 114–127. https://doi.org/10.1016/j.jhydrol.2013.10.024

Watts, G., Battarbee, R.W., Bloomfield, J.P., Crossman, J., Daccache, A., Durance, I., Elliott, J.A., Garner, G., Hannaford, J., Hannah, D.M., Hess, T., Jackson, C.R., Kay, A.L., Kernan, M., Knox, J., Mackay, J., Monteith, D.T., Ormerod, S.J., Rance, J., Stuart, M.E., Wade, A.J., Wade, S.D., Weatherhead, K., Whitehead, P.G., Wilby, R.L., 2015. Climate change and water in the UK – past changes and future prospects. Prog. Phys. Geogr. 39, 6–28. https://doi.org/10.1177/0309133314542957

Werritty, A., 2002. Living with uncertainty: Climate change, river flows and water resource management in Scotland. Sci. Total Environ. 294, 29–40.

https://doi.org/10.1016/S0048-9697(02)00050-5

Whitehead, P.G., Jin, L., Bussi, G., Voepel, H.E., Darby, S.E., Vasilopoulos, G., Manley, R., Rodda, H., Hutton, C., Hackney, C., Tri, V.P.D., Hung, N.N., 2019. Water quality modelling of the Mekong River basin: Climate change and socioeconomics drive flow and nutrient flux changes to the Mekong Delta. Sci. Total Environ. 673, 218–229. https://doi.org/10.1016/J.SCITOTENV.2019.03.315

Wilhite, D., Svoboda, M.D., 2000. Drought early warning systems in the context of drought preparedness and mitigation. Early Warn. Syst. drought Prep. drought Manag. 1–21.

Wilhite, D.A., 1993. Drought Assessment, Management, and Planning: Theory and Case Studies. Drought Assessment, Manag. Plan. Theory Case Stud. 293. https://doi.org/10.1007/978-1-4615-3224-8

Wilhite, D.A., Glantz, M.H., 1985. Understanding: The drought phenomenon: The role of definitions. Water Int. 10, 111–120. https://doi.org/10.1080/02508068508686328

Williams, R., Downs, P., Moir, H., Lavarini, C., 2022. Sediment continuity through run-of-river hydropower schemes.

World Health Organization, 2023. Drought [WWW Document]. URL https://www.who.int/health-topics/drought#tab=tab_1 (accessed 11.26.23).

Wu, Z., Lin, Q., Lu, G., He, H., Qu, J.J., 2015. Analysis of hydrological drought frequency for the Xijiang River Basin in South China using observed streamflow data. Nat. Hazards 77, 1655–1677. https://doi.org/10.1007/s11069-015-1668-z

Yalcin, E., 2024. Assessing future changes in flood frequencies under CMIP6 climate projections using SWAT modeling: a case study of Bitlis Creek, Turkey. J. Water Clim. Chang. 15, 2212–2231. https://doi.org/10.2166/WCC.2024.646

Yamba, F.D., Walimwipi, H., Jain, S., Zhou, P., Cuamba, B., Mzezewa, C., 2011. Climate change/variability implications on hydroelectricity generation in the Zambezi River Basin. Mitig. Adapt. Strateg. Glob. Chang. 16, 617–628. https://doi.org/10.1007/S11027-011-9283-0/FIGURES/9

Yevjevich, V., 1967. An Objective Approach to Definitions and Investigations of Continental Hydrologic Droughts.

YoosefDoost, A., Asghari, H., Abunuri, R., Sadegh Sadeghian, M., 2018. Comparison of CGCM3, CSIRO MK3 and HADCM3 Models in Estimating the Effects of Climate Change on Temperature and Precipitation in Taleghan Basin. Am. J. Environ. Prot. 6, 28–34. https://doi.org/10.12691/ENV-6-1-5

YoosefDoost, A., Lubitz, W.D., 2020. Archimedes screw turbines: A sustainable development solution for green and renewable energy generation-a review of potential and design procedures. Sustain. 12. https://doi.org/10.3390/SU12187352

Zafirakis, D.P., 2010. Overview of energy storage technologies for renewable energy systems, Stand-Alone and Hybrid Wind Energy Systems. Woodhead Publishing Limited. https://doi.org/10.1533/9781845699628.1.29

Zaidi, A.Z., Khan, M., 2018. Identifying high potential locations for run-of-the-river hydroelectric power plants using GIS and digital elevation models. Renew. Sustain. Energy Rev. 89, 106–116. https://doi.org/10.1016/J.RSER.2018.02.025

Zelenhasić, E., Salvai, A., 1987. A method of streamflow drought analysis. Water Resour. Res. 23, 156–168. https://doi.org/10.1029/WR023I001P00156

Zhou, Y., Hejazi, M., Smith, S., Edmonds, J., Li, H., Clarke, L., Calvin, K., Thomson, A., 2015. A comprehensive view of global potential for hydro-generated electricity. Energy Environ. Sci. 8, 2622–2633. https://doi.org/10.1039/c5ee00888c

APPENDICES

Appendix 1 – Chapter 3 Appendices

Appendix 1 has been submitted as part of the publication '*An assessment of run of river hydropower potential in Great Britain*' (presented as Chapter 3 in this thesis):

Corresponding publication: Golgojan, A.D., White, C.J., Bertram, D., 2024. An assessment of run of river hydropower potential in Great Britain. Proc. Inst. Civ. Eng. - Water Manag. 178, 42–61, https://doi.org/10.1680/jwama.23.00056.

Appendix 1.1 – Technical potential equations

Penstock diameter selection

An initial estimate of penstock diameter d (m) was calculated using the Manning formula for a fully closed circular cross section, considering a head loss of 4% of the gross head between the intake and the powerhouse using the following formula:

$$d = 2.69 \cdot (\frac{\varepsilon^2 \cdot Q_d^2 \cdot L}{H})^{0.1875} \qquad \textit{Eq. (A1-1)}$$

where d is the penstock diameter in m; ε is the roughness coefficient for the GRP pipe and is equal to 0.029; Q_d is the design flow which is equal to Q_{40}-Q_{95} in m^3/s; H is the gross head between the intake and the powerhouse in m and L is the penstock length which is calculated using Eq. (A1-2)

$$L = \sqrt{(X_{intake} - X_{powerhouse})^2 + (Y_{intake} - Y_{powerhouse})^2 + (Z_{intake} - Z_{powerhouse})^2} \qquad \textit{Eq. (A1-2)}$$

where X_{intake}, Y_{intake} and Z_{intake} are the coordinates of the intake; $X_{powerhouse}$, $Y_{powerhouse}$ and $Z_{powerhouse}$ are the coordinates of the powerhouse in m. This first estimate was used as a starting point by setting minimum and maximum diameter limits of ±10% to determine the nominal diameter from a penstock database for available diameters. The average water velocity V in the penstock was calculated using the flowing formula:

$$V = \frac{4 \cdot Q_d}{\pi \cdot d^2} \qquad \textit{Eq. (A1-3)}$$

The Reynolds Number R_e was calculated:

$$R_e = \frac{d \cdot V}{\nu} \qquad \textit{Eq. (A1-4)}$$

where v is the kinematic viscosity of water and is equal to 1.31 x 10^{-6} m^2/s. Using the Reynolds Number, the Darcy friction factor f was calculated by solving the Colebrook White equation:

$$\frac{1}{\sqrt{f}} = -2 \cdot \log_{10}\left(\frac{\frac{\varepsilon}{d}}{3.7} + \frac{2.51}{R_e \cdot \sqrt{f}}\right) \qquad \textit{Eq. (A1-5)}$$

Using the Darcy-Weisbach equation, the head loss was calculated:

$$hf = f \cdot \left(\frac{L}{d} \cdot \frac{V^2}{2 \cdot g}\right) \qquad \textit{Eq. (A1-6)}$$

The net head for each RoR scheme was calculated using the head loss from Eq. (A1-6)

$$H_{net} = H - hf \qquad \textit{Eq. (A1-7)}$$

The pressure rating of the penstock was chosen based upon the calculated surge head that may be experienced by the penstock. Surge head, h_s was calculated by multiplying the penstock pressure wave celerity rating α in m/s and the maximum flow velocity V.

$$h_s = \frac{\alpha \cdot V}{g} \qquad \textit{Eq. (A1-8)}$$

The total head was then calculated:

$$H_{Total} = h_s + H \qquad \textit{Eq. (A1-9)}$$

The total head was transformed in bars and then the pressure class for each diameter is chosen from a catalogue.

Reaction turbine peak efficiency

After a turbine was chosen, the next step was to calculate its peak efficiency to determine the installed power. For the Francis and Kaplan turbines, which are reaction turbines, the peak efficiency was calculated by determining the runner size and the specific speed. Runner size was calculated using the following formula based on the design flow Q_d in m^3/s:

$$d = k \cdot Q_d^{0.473} \qquad \textit{Eq. (A1-10)}$$

where k is an empirical constant with a value of 0.46 for $Q_d < 1.8\ m^3/s$ or 0.41 for $Q_d \geq 1.8\ m^3/s$. The specific speed n_q was then calculated using the following equation based on net head (H):

$$n_q = k_q \cdot H^{-0.5} \qquad \textit{Eq. (A1-11)}$$

where k_q is a constant based on the turbine type and is 800 for Kaplan and 600 for Francis turbines. Before calculating the peak efficiency, an adjustment to the peak efficiency $\hat{e}_{nq}$ must be calculated using the specific speed n_q.

$$\hat{e}_{nq} = \left[\frac{(n_q - 56)}{256}\right]^2 \qquad \textit{Eq. (A1-12)}$$

A similar adjustment needs to be made based on the runner size d:

$$\hat{e}_d = \left(0.081 + \hat{e}_{nq}\right) \cdot (1 - 0.789 \cdot d^{-0.2}) \qquad \textit{Eq. (A1-13)}$$

Turbine peak efficiency e_p was then calculated:

$$e_p = \left(0.919 - \hat{e}_{nq} + \hat{e}_d\right) - 0.0305 + 0.005 \cdot R_m \qquad \textit{Eq. (A1-14)}$$

where R_m is a turbine design coefficient which considers the characteristics of different manufacturers and was considered 0.45 in this project. The peak efficiency flow, Q_p is less than the design flow, Q_d and was calculated as follow:

$$Q_p = 0.65 \cdot Q_d \cdot n_q^{0.05} \qquad \textit{Eq. (A1-15)}$$

Impulse turbine efficiency

The number of jets is a key configuration for the impulse turbine. In this analysis, the Pelton turbine was considered for this calculation. For simplicity, all Pelton turbines analysed only have one jet. The rotational speed *n* was calculated:

$$n = 31 \cdot \left(H \cdot \frac{Q_d}{j}\right)^{0.5} \qquad \textit{Eq. (A1-16)}$$

where H is the net head in m; Q_d is the design flow in m^3/s; j is the number of jets. Runner diameter d was calculated considering the rotational speed n:

$$d = \frac{49.4 \cdot H^{0.5} \cdot j^{0.02}}{n} \qquad \textit{Eq. (A1-17)}$$

The turbine peak efficiency was calculated using the following formula:

$$e_p = 0.864 \cdot d^{0.04} \qquad \textit{Eq. (A1-18)}$$

The peak efficiency flow Q_p is less than the design flow Q_d and was calculated using the following formula:

$$Q_p = (0.662 + 0.001 \cdot j) \cdot Q_d \qquad \textit{Eq. (A1-19)}$$

Crossflow turbine efficiency

Crossflow turbines are impulse turbines, which means that the rotor is spinning air and is not fully flooded like in a reaction (e.g. Kaplan) turbine (Sinagra et al., 2014). However, the operation is different from other impulse turbines, such as Pelton and the efficiency does not vary as much with the flowrate. Nevertheless, the peak efficiency is less than in a Pelton turbine and the literature around the calculation of the peak efficiency is minimal. Considering this, the peak efficiency was taken from experimental data as shown in Figure S1-2. The peak efficiency for this type of turbine was 81.6% and the flow at which peak efficiency occurs was 70% of the design flow Q_d.

Archimedean Screw turbine efficiency

An Archimedean screw hydropower scheme allows transforming potential energy of a fluid into mechanical energy and is convenient for low-head hydraulic sites. As it is a less common technology, there are few references dealing with their design and performance optimisation (Dellinger et al., 2016). Similar to the Cross-flow turbine, experimental data was taken to determine the peak efficiency and flow. The peak efficiency was found to be 82.8% and the peak flow was determined to be 78% of the design flow (Figure S1 3).

After the peak efficiencies and flows have been calculated for all turbine types, the power is recalculated using these new values to determine the technically viable power.

Appendix 1.2 – Financial potential costs

Turbine, generator and control cost

Generator costs is common for all turbine types and was calculated using the following formula:

$$C_1 = 0.82 \cdot n^{0.96} \cdot \left(\frac{P_d}{H_g^{0.28}}\right)^{0.9} \cdot 10^6 \cdot C_{ex} \qquad \textit{Eq. (A2-1)}$$

Where *n* is the number of turbines, in this case 1, P_d is the design power in *MW,* H_g is the gross head. The turbine costs are depended on the turbine type. For the reaction turbines the following formulas were used:

For Kaplan turbines:

$$C_2 = 0.27 \cdot n^{0.96} \cdot d^{1.47} \cdot \left(1.17 \cdot {H_g}^{0.12} + 2\right) \cdot 10^6 \cdot C_{ex} \qquad \textit{Eq. (A2-2)}$$

Where *d* is the runner diameter in m. Similarly, for a Francis turbine:

$$C_2 = 0.17 \cdot n^{0.96} \cdot d^{1.47} \cdot \left[\left(13 + 0.001 \cdot H_g\right)^{0.3} + 3\right] \cdot 10^6 \cdot C_{ex} \qquad \textit{Eq. (A2-3)}$$

For the impulse turbines, RETScreen provides two equations based on the installed power to net head ratio. However, in this analysis only one of the equations was considered for the Pelton turbine since the small Pelton turbine cost made it much higher than the other turbines analysed. Furthermore, a 0.5 coefficient was used to estimate the cost of a Pelton turbine and governor:

$$C_2 = 3.47 \cdot n^{0.96} \cdot \left(\frac{MW_u}{H_g^{0.5}}\right)^{0.44} \cdot 0.5 \cdot 10^6 \cdot C_{ex} \qquad \textit{Eq. (A2-4)}$$

Where MW_u is installed MW/unit and has the values in Table A2-1.

Table A2-1: MWu value based on RoR scheme size

RoR scheme size	MWu
Small	$8.522 \cdot Q_u \cdot H_g/1000$
Mini	$7.79 \cdot Q_u \cdot H_g/1000$
Micro/Pico	$7.53 \cdot Q_u \cdot H_g/1000$

Q_u is the design flow (maximum flow used by the generating station in m^3/s

The cost of Cross-flow turbine was taken as the cost of the Pelton turbine. The cost for the Archimedean Screw turbine was considered to be 22% less than the Pelton turbine (YoosefDoost and Lubitz, 2020). Installation costs for the turbine, governor and generator were obtained using the following formula:

$$C_3 = 0.15 \cdot (C_1 + C_2) \qquad \textit{Eq. (A2-5)}$$

Penstock

For the hydropower schemes analysed in this study, only GRP (glass reinforced plastic) pipes were considered for the technical potential and the financial potential. The prices for penstock pipes were, however, difficult to find so an estimation based upon Duncan (2012) was made for both rigidity classes considered in this project (SN 5000 and SN 10000). The prices are presented in the figure in the Supplementary Material (Figure S1 4). The installation cost for penstock was based on its weight:

$$C_5 = 5 \cdot W^{0.88} \cdot C_{inf} \qquad \textit{Eq. (A2-6)}$$

Where *W* is the penstock weight in *kg.*

Civil structures cost

The civil structures cost includes the weir, intake works, powerhouse and tailrace and was calculated using the following formula:

$$C_6 = 1.97 \cdot n^{-0.04} \cdot \left(\frac{P_d}{{H_g}^{0.3}}\right) \cdot (1 + 0.01 \cdot l_b) \cdot \left(1 + 0.005 \cdot \frac{l_d}{H_g}\right) \cdot 10^6 \cdot C_{inf} \qquad \text{Eq. (A2-7)}$$

Where l_b is the distance to borrow pits, assumed here 0.5 km, l_d is the length of the crest of the dam, assumed to be 10 m.

Substation and transformer cost

A substation and transformer are required to increase the voltage at the generator terminals from 1000 V to the transmission voltage. Their cost was assessed using the following formula:

$$C_7 = 0.0025 \cdot {n_{gen}}^{0.95} + 0.002 \cdot (n_{gen} + 1) \cdot \left(\frac{P_d}{0.95}\right)^{0.9} \cdot V^{0.3} \cdot 10^6 \cdot C_{inf} \qquad \text{Eq. (A2-8)}$$

Where n_{gen} is the number of generators, chosen as 1 in this case, V is the transmission voltage, here assumed to be 33 kW. The installation costs for the substation and transformer were calculated as a percentage of the cost of the substation and transformer.

$$C_8 = 0.15 \cdot C_7 \qquad \text{Eq. (A2-9)}$$

Transmission cost

Transmission cost is fixed at C_9 = *£ 150,091.5* considering the transmission line length to be 1 km and it is assumed that connections will be made to primary substations with a 33 kV busbar or to existing 33 kV lines. Connections to lines at voltages in excess of 33 kV typically require a new substation costing in excess of £1,000,000. For these reasons only connection at 33 kV is considered. Costs for 33 kV overhead line is based on published utility cost data suggest a range of costs from £1,550 to £8,715 for a 70 m span line giving a range of 22£/m to 124.5£/m (SHEPD, 2011). The midpoint of this range gives a cost of 73.25£/m which has been taken as the unit cost of transmission line. When connecting to an existing 33 kV line, it is assumed that a simple tee connection can be made. This is priced at £50,000 based on the cost of two additional sets of utility switchgear, one at the tee and a second at the hydro scheme step up transformer. When connecting at a primary substation it is assumed that an additional connection can be made to an existing 33 kV busbar at a cost of £150,000 based upon the example 7A provided in SHEPD (2011). In both cases, an additional factor of 1.25 was applied to lone costs to represent non-ideal line routing. This gives the cost functions for substation connections which is considered in this study to be the conservative approach.

Access road cost

Access road costs were based on the following equation:

$$C_{10} = 0.25 \cdot T \cdot A^2 \cdot {l_a}^{0.9} \cdot 10^6 \cdot C_{inf} \qquad \textit{Eq. (A2-10)}$$

Where *T* is a cost reduction factor for unpaved roads, assumed here 0.25, *A* represents access difficulty set between 1 to 6 based on the terrain, assumed here to be 2, l_a is the distance to the nearest road calculated as the nearest; this method does not consider existing water bodies or elevations.

Engineering cost

Engineering costs were calculated using the following formula:

$$C_{11} = 0.37 \cdot n^{0.1} \cdot E \cdot \left(\frac{P_d}{{H_g}^{0.3}}\right) \cdot 10^6 \qquad \textit{Eq. (A2-11)}$$

Where E is an engineering cost factor which is 0.67 if a dam already exists at the location and 1 if a dam does not exist, in this case it is assumed to be 1.

Development cost

Development costs were assumed to be the costs associated with obtaining the necessary permits to allow work and they depend on the other previous costs:

$$C_{12} = 0.04 \cdot \sum_{i=1}^{11} C_i \qquad \textit{Eq. (A2-12)}$$

Feasibility study cost

Feasibility study costs were calculated based on the other costs using the following formula:

$$C_{13} = 0.032 \cdot \sum_{i=1}^{12} C_i \qquad \textit{Eq. (A2-13)}$$

Miscellaneous costs

Miscellaneous costs represent unforeseen costs which may occur during the construction of the project and were calculated based on an interest rate *i* assumed to be 10% in this case.

$$C_{14} = 0.25 \cdot i \cdot H^{0.35} \cdot 1.1 \cdot \sum_{i=1}^{12} C_i + 0.1 \cdot \sum_{i=1}^{10} C_i \qquad \textit{Eq. (A2-14)}$$

Total costs and cost per kW installed

Total cost was the sum of all the previous costs:

$$C_{tot} = \sum_{i=1}^{14} C_i \qquad \textit{Eq. (A2-15)}$$

Cost per kW was calculated by diving the total cost by the installed power:

$$C_{kW} = \frac{C_{tot}}{Pd} \qquad \textit{Eq. (A2-16)}$$

Appendix 1.3 – '*An assessment of run of river hydropower potential in Great Britain*' Supplementary information

Introduction

The figures included in the Supplementary Information complement the text from the manuscript and are referenced within.

Figures S1-1 to S1-5

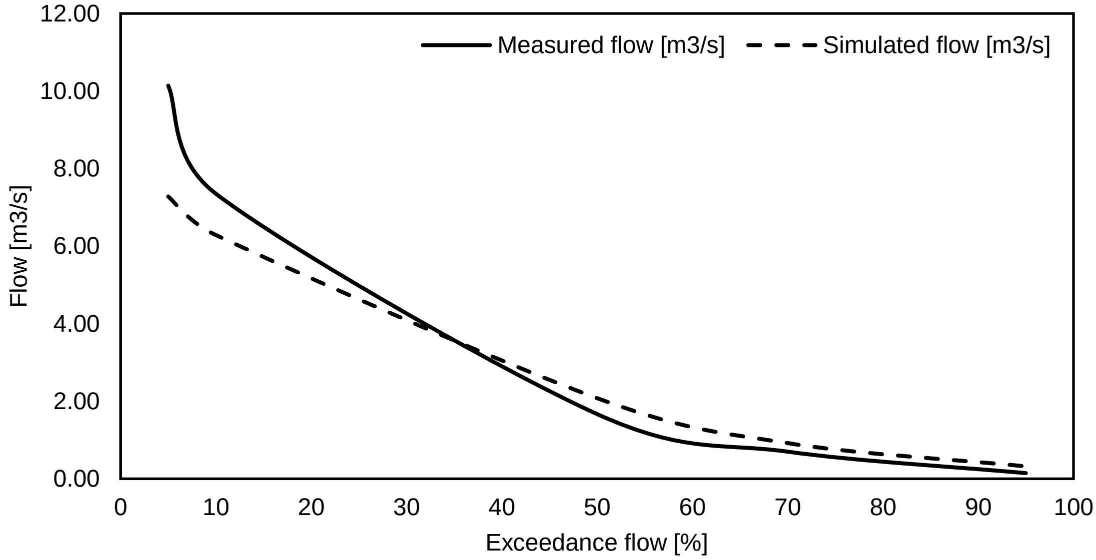

Figure S1 1: An example of percentile measured and simulated flows at Gauge 1001 (includes Q5%, $Q_{10\%}$, $Q_{50\%}$, $Q_{70\%}$, and $Q_{95\%}$).

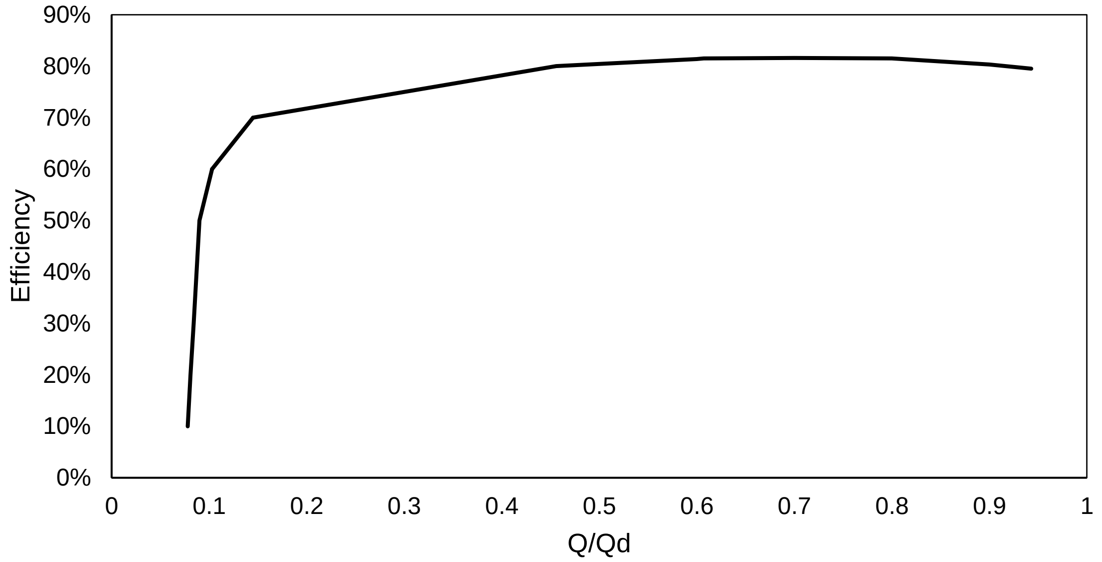

Figure S1 2: Efficiency curve for Crossflow turbine. After Sinagra et al. (2014)

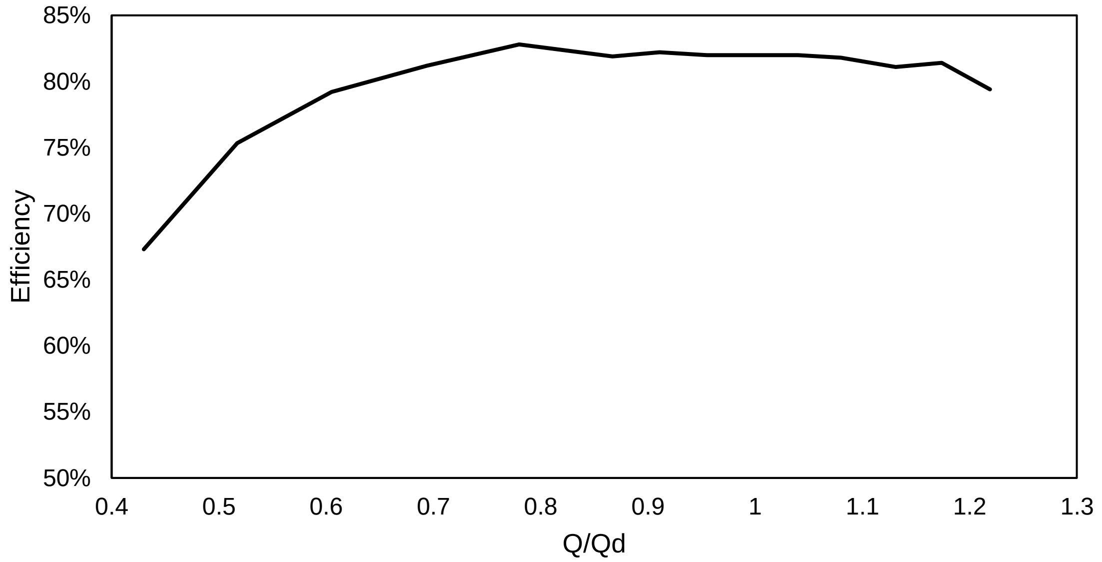

Figure S1 3: Efficiency curve for Archimedean turbine. After Dellinger et al. (2016)

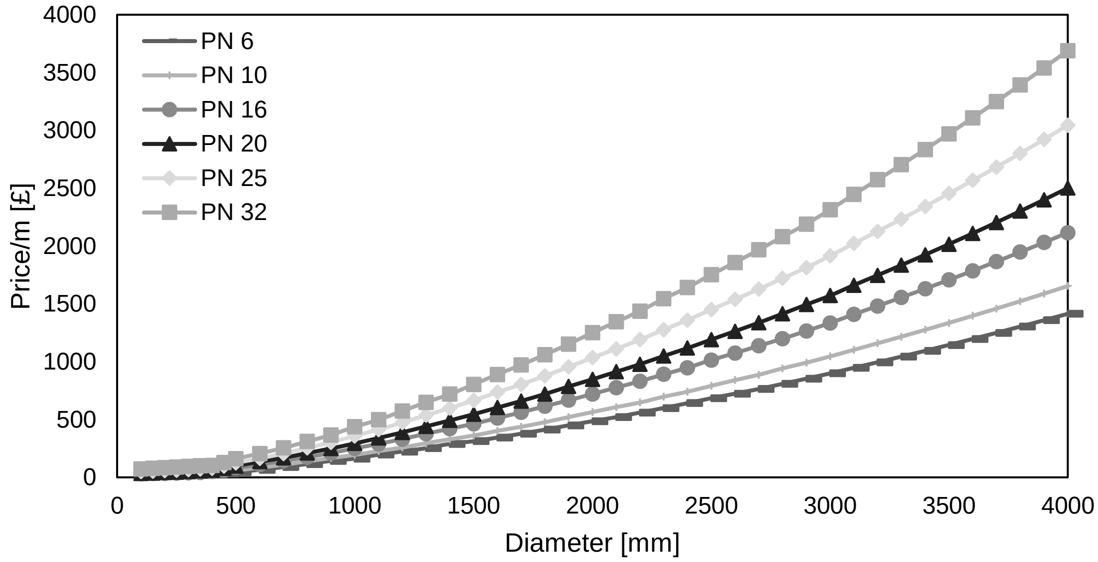

Figure S1 4: Penstock price per diameter. After Duncan (2012)

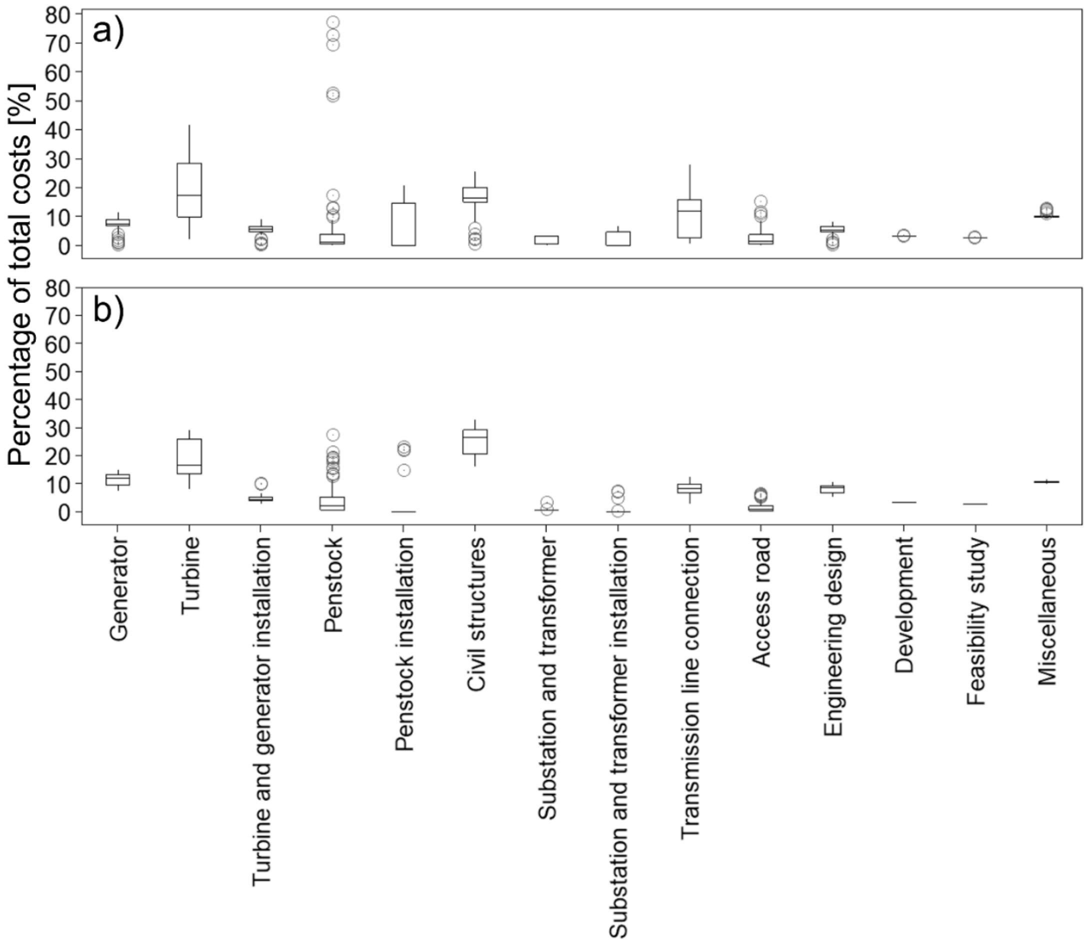

Figure S1 5: Boxplots of all the initial costs considered in this analysis for the financially viable a) mini and b) small RoR schemes.

Tables S1-1 to S1-2

Table S1 1:Hydrometric areas number, name and area (National River Flow Archive, 2014)

Area No.	Area Name.	Area [m^2]
1	Wick Group	892.68
2	Helmsdale Group	1357.20
3	Shin Group	1915.84
4	Conon Group	2183.77
5	Beauly	1077.46
6	Ness	1987.44
7	Findhorn Group	1815.15
8	Spey	2984.05

Area No.	Area Name.	Area [m²]
9	Deveron Group	1560.04
10	Ythan Group	1421.26
11	Don (Aberdeenshire)	1323.94
12	Dee (Aberdeenshire)	2113.12
13	Esk Group	2021.10
14	Firth of Tay Group	1053.15
15	Tay	5093.17
16	Earn	969.18
17	Firth of Forth Group	1471.11
18	Forth	1609.55
19	Almond Group	924.30
20	Tyne (Lothian)	666.03
21	Tweed	5332.29
22	Coquet Group	2049.99
23	Tyne (Northumberland)	2929.05
24	Wear	1190.95
25	Tees Group	2235.25
26	Hull Group	2142.58
27	Ouse (Yorkshire)	11348.47
28	Trent	10398.21
29	Ancholme Group	1948.75
30	Witham and Steeping	3356.50
31	Welland	1642.03
32	Nene	2339.96
33	Great Ouse	8571.27
34	Norfolk Rivers Group	3726.29
35	East Suffolk Rivers	1598.17
36	Stour (Essex and Suffolk)	1032.61
37	Essex Rivers Group	3155.01
38	Lee	1428.60
39	Thames	10923.50
40	Kent Rivers Group	4771.37
41	Sussex Rivers Group	3086.66
42	Hampshire Rivers Group	2730.44
43	Avon and Stour	2993.57
44	Frome Group	1303.88
45	Exe Group	2249.79
46	Dart Group	1509.13
47	Tamar Group	1819.27
48	Fal Group	1567.16
49	Camel Group	1260.37
50	Taw and Torridge	2162.72
51	East Lyn Group	525.43
52	Somerset Rivers Group	2782.95
53	Avon (Bristol)	2221.40

Area No.	Area Name.	Area [m^2]
54	Severn	11413.23
55	Wye (Hereford)	4179.83
56	Usk	1745.86
57	Taff Group	919.15
58	Mid-Glamorgan Group	1041.16
59	Loughor Group	865.98
60	Towy Group	2067.13
61	Cleddau Group	1456.33
62	Teifi	1010.27
63	Ystwyth Group	857.65
64	Dyfi Group	1346.95
65	Glaslyn Group	1318.82
66	Conway and Clwyd	1502.53
67	Dee (Cheshire)	2127.67
68	Cheshire Rivers Group	1883.28
69	Mersey and Irwell	2699.87
70	Douglas Group	628.21
71	Ribble	1485.12
72	Wyre and Lune	1662.81
73	Kent Group	1209.81
74	Esk Group (Cumbria)	912.48
75	Derwent Group (Cumbria)	1237.49
76	Eden (Cumbria)	2403.88
77	Esk (Dumfriesshire)	1369.12
78	Annan	965.72
79	Nith	1482.17
80	Dee (Galloway)	1535.16
81	Cree Group	2050.24
82	Doon Group	1081.82
83	Irvine and Ayr	1529.80
84	Clyde	3020.58
85	Leven (Dumbartonshire)	831.58
86	Firth of Clyde Group	1001.86
87	Fyne Group	714.78
88	Add Group	822.72
89	Awe and Etive	1412.09
90	Loch Linnhe Group	1163.80
91	Lochy (Invernesshire)	1337.42
92	Loch Shiel Group	1171.75
93	Loch Alsh Group	1664.99
94	Loch Maree group	1084.19
95	Laxford Group	2226.11
96	Naver group	1961.02
97	Thurso Group	913.50
101	Isle of Wight	380.89

Area No.	Area Name.	Area [m^2]
102	Anglesey	714.19
103	Isle of Man	572.55
104	Kintyre Group	2299.22
105	Inner Hebrides	2993.96
106	Outer Hebrides	3098.85
107	Orkneys	1013.01
108	Shetlands	1472.65
201	Foyle	2009.29
202	Faughan-Roe	894.81
203	Bann	5405.28
204	Bush	903.58
205	Lagan-Quaille	1984.66
206	Newry-Dee	931.80
226	Upper Shannon	7.04
235	Sligo Bay-Drowes	118.59
236	Erne	1904.10
239	Lough Swilly	21.35

Table S1 2: MWu value based on RoR scheme size

RoR scheme size	MWu
Small	$8.522 \cdot Q_u \cdot H_g/1000$
Mini	$7.79 \cdot Q_u \cdot H_g/1000$
Micro/Pico	$7.53 \cdot Q_u \cdot H_g/1000$

Q_u is the design flow (maximum flow used by the generating station in *m*

Appendix 2 – Chapter 4 Appendices

Appendix 2 has been submitted as the Supplementary Information of the publication ‘. Future impacts of river flow on hydropower generation in Great Britain’ (presented as Chapter 4 in this thesis).

Corresponding publication: Golgojan, A.-D., White, C.J., Bertram, D., 2024. Future impacts of river flow on hydropower generation in Great Britain. J. Water Clim. Chang. 15, 4840–4861, https://doi.org/10.2166/WCC.2024.355.

Appendix 2.1 Supplementary text - eFLaG Dataset characteristics

Catchment Selection

The catchments selected for the eFLaG dataset were chosen based on data quality, representativeness, water industry relevance and to ensure good geographical coverage of GB (Hannaford et al., 2022). . Metadata compiled included membership of key national strategic networks (e.g. near-natural Benchmark (UKBN2;Harrigan et al. (2018) and previous studies/datasets and recent modelling endeavours through the Drought and Water Scarcity Programme projects; 'Historic Droughts', 'IMPETUS' (Stevens et al., 2019) and 'MaRIUS' (Bell et al. (2018).

UKCP Data Processing and Bias Correction

eFLaG uses GBCP18 Regional projections created by the Met Office (Murphy et al., 2019). They were computed using perturbed-parameter runs of the Hadley Centre global climate model (GCM) and regional climate models (HadGEM3-GC3.05 and HadREM3-GA705 respectively). These provide a set of 12 high-resolution (12km) spatially-consistent climate projections over GB, covering the period December 1980 to November 2080. The UKCP18 RCM output was processed to provide both the 1km gridded and catchment-average time-series of precipitation and potential evaporation required for hydrological and groundwater modelling. The 1km gridded time-series of precipitation and PE were then used to produce the time-series of catchment-averages required for each of the eFLaG catchments. The catchment average values were derived using the standard UK National River Flow Archive approach for catchment average rainfalls, as described in (NRFA, 2021).

Hydrological models used

eFLaG uses four hydrological models (GR4J/GR6J, PDM and G2G), All of these models are used to provide 'at site' simulations at the catchment.

G2G

The Grid-to-Grid (G2G) hydrological model is an established area-wide distributed model that has been used to investigate the spatial coherence and variability of floods and droughts at catchment, regional and national scales. Model output typically consists of natural river flows at both gauged and ungauged locations, and can be provided as both time-series for specific locations or 1km× 1km grids. The G2G model has been used for climate impacts modelling of floods (Bell et al., 2012, 2009), low flows (Kay et al., 2018) and droughts (Rudd et al., 2019) and is used operationally for flood forecasting (Cole and Moore, 2009; Moore et al., 2006).

GR4J/GR6J

GR4J (Génie Rural à 4 paramètres Journalier) is a simple daily lumped conceptual model with only four free parameters. GR4J has been used for hydro-climate change research across the globe, and has demonstrated good performance in a diverse set of catchments across GB. The model has been applied across GB for operational seasonal forecasting, as well as for long-term drought reconstructions nationwide (Harrigan et al., 2018; Smith et al., 2019). GR6J (Génie Rural à 6 paramètres Journalier) (Pushpalatha et al., 2011) is a six parameter variant of the GR modelling suite that was developed to improve low flow simulation and groundwater exchange.

Recently, GR6J has increasingly been applied in UK water resources applications (e.g. Anglian Water Drought Plan.

PDM

The Probability Distributed Model or PDM (Moore, 2007; UKCEH, 2022) is a simple, very widely used lumped rainfall-runoff model that can be configured to a variety of catchment flow regimes. PDM may be thought of as a toolkit of model components representing a range of runoff production and flow routing behaviours, and with a choice of time-step.

Appendix 2.2 Supplementary text – Changes to future river flows across GB

Results show annual river flows reduce by -5.65 % in the near future (2030-2059) and by -6.78 % in the far future (2050-2079) across GB relative to the baseline (1980-2009). Seasonally, however, typical river flows are shown to increase in winter and spring but reduce in summer and autumn

For all the eFLaG gauges, the results show a small decrease in spring in the near future (-0.26 %), a significant decrease in the summer and autumn in the near future (-26.98 % in summer, -20.14 % in autumn) and a slight increase in winter in the near future (1.59 %). For the far future (2050-2079), spring flows may increase by 4.66 %, summer and autumn flows decrease even more than in the near future (-37.06 % decrease in summer flows and -31.08 % decrease in autumn flows), and winter flows may increase by 8.19 %. However, these results are averaged over all the RCMs, over all the eFLaG gauges. Putting these results in boxplots (**Figure S2-2**), shows the uncertainty in the results: the spring and winter results contain a lot of outliers, but have smaller quartiles, whereas for the summer and autumn changes in flows, the quartiles are larger, but there are less outliers. This suggests that the decreases in flows in summer and autumn are more likely to be all over GB, while in spring and winter, the changes in flows will depend on location.

In the southeast region, some gauges (e.g., 38003, 38017, 39010, 39014, 39019, 39027, 39088, 39089, 39127) show a decrease in future flows all year. This is consistent with the predicted rainfall decreases in the south of GB (Boca et al., 2022). However, all these gauges are in the hydrometric area 39, also known as the Thames basin, which is well served in terms of gauges and heavily impacted by human intervention that may affect the hydrological and climate model's ability to simulate and predict flows.

Appendix 2.3 Supplementary figures and tables

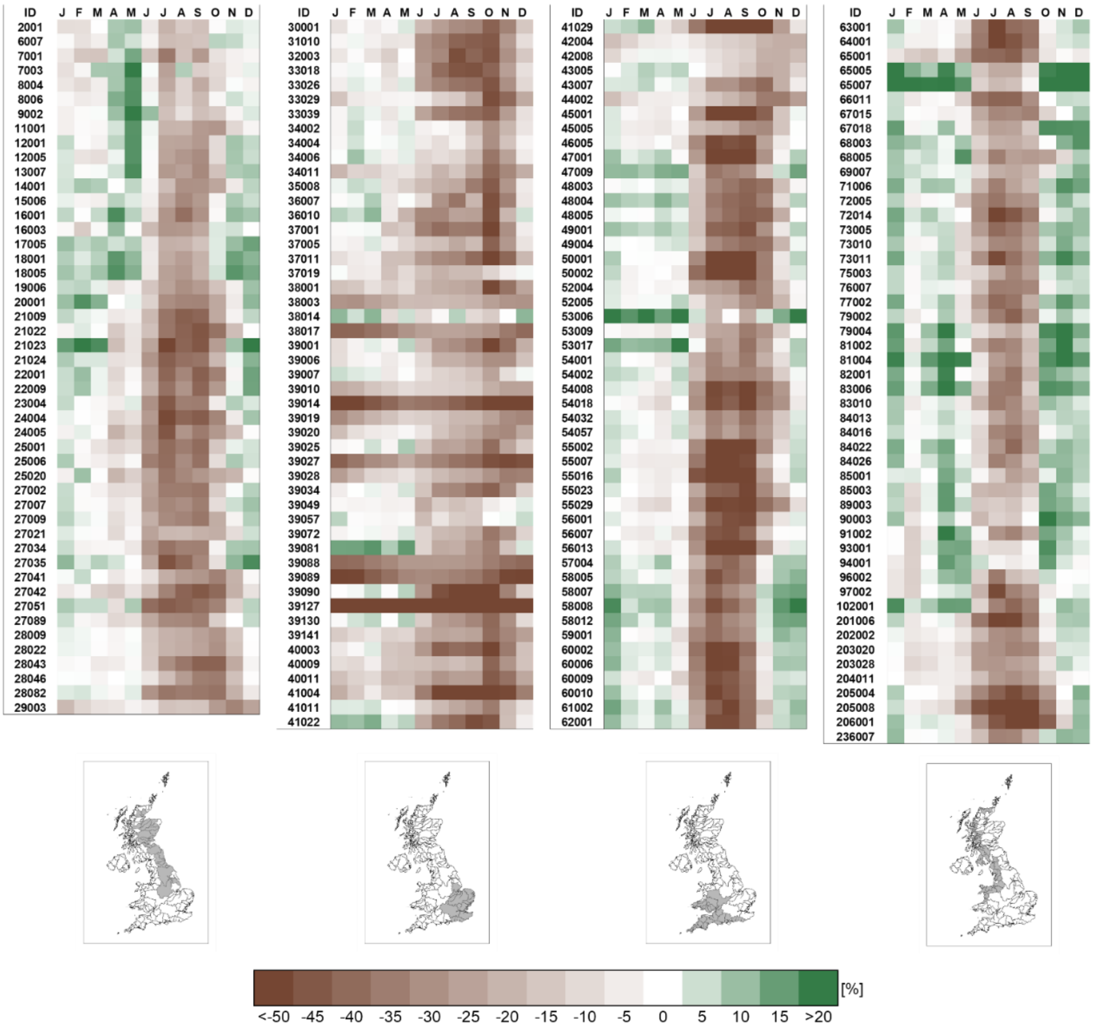

Figure S2 1: Monthly percentage changes in river flows at the gauging station from the eFLaG dataset. The baseline flows are the flows simulated using the GR6J hydrological model for the period 1980-2009. The near future flows are the mean for all the RCM simulated flows for the period 2030-2059. The maps below show the catchments where the gauges are in each column. The legend refers to percentage change in mean monthly flows in the future from the baseline.

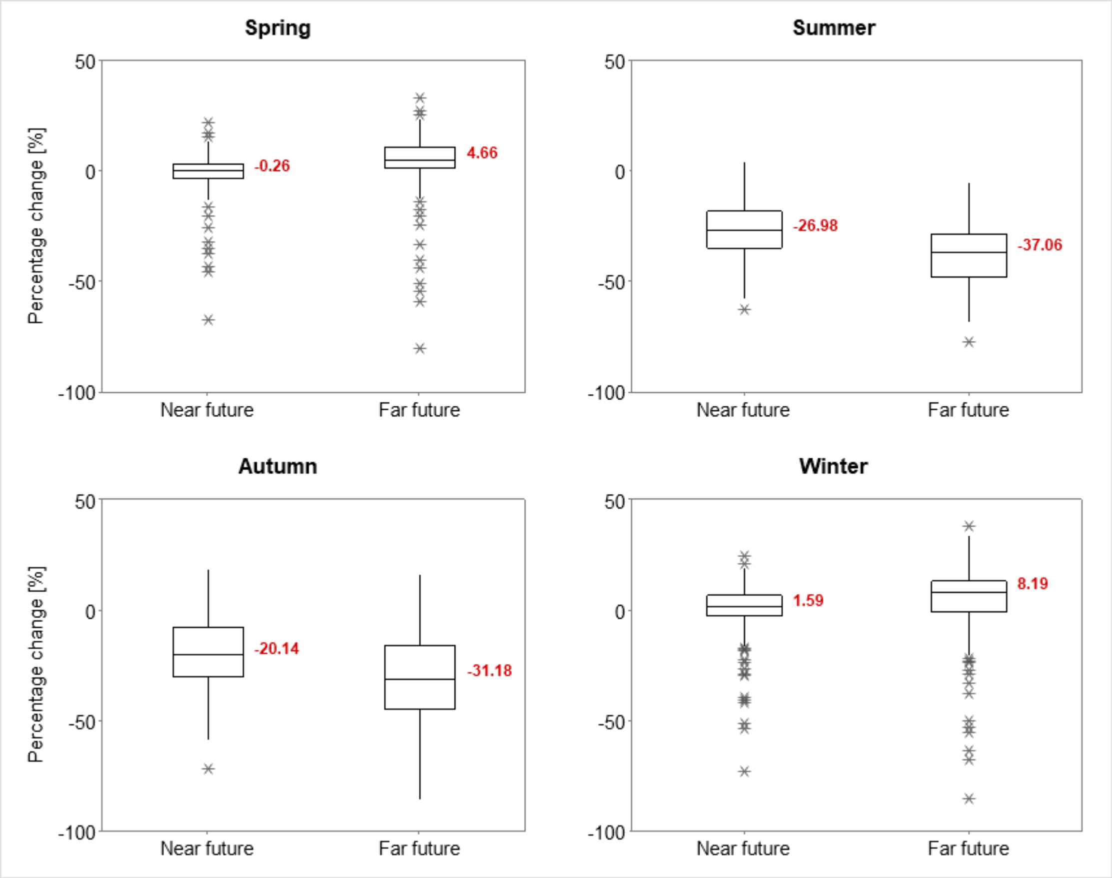

Figure S2 2: Seasonal changes in river flows in the near (2030-2059) and far future (2050-2079) from the baseline (1980-2009) for all eFLaG gauges

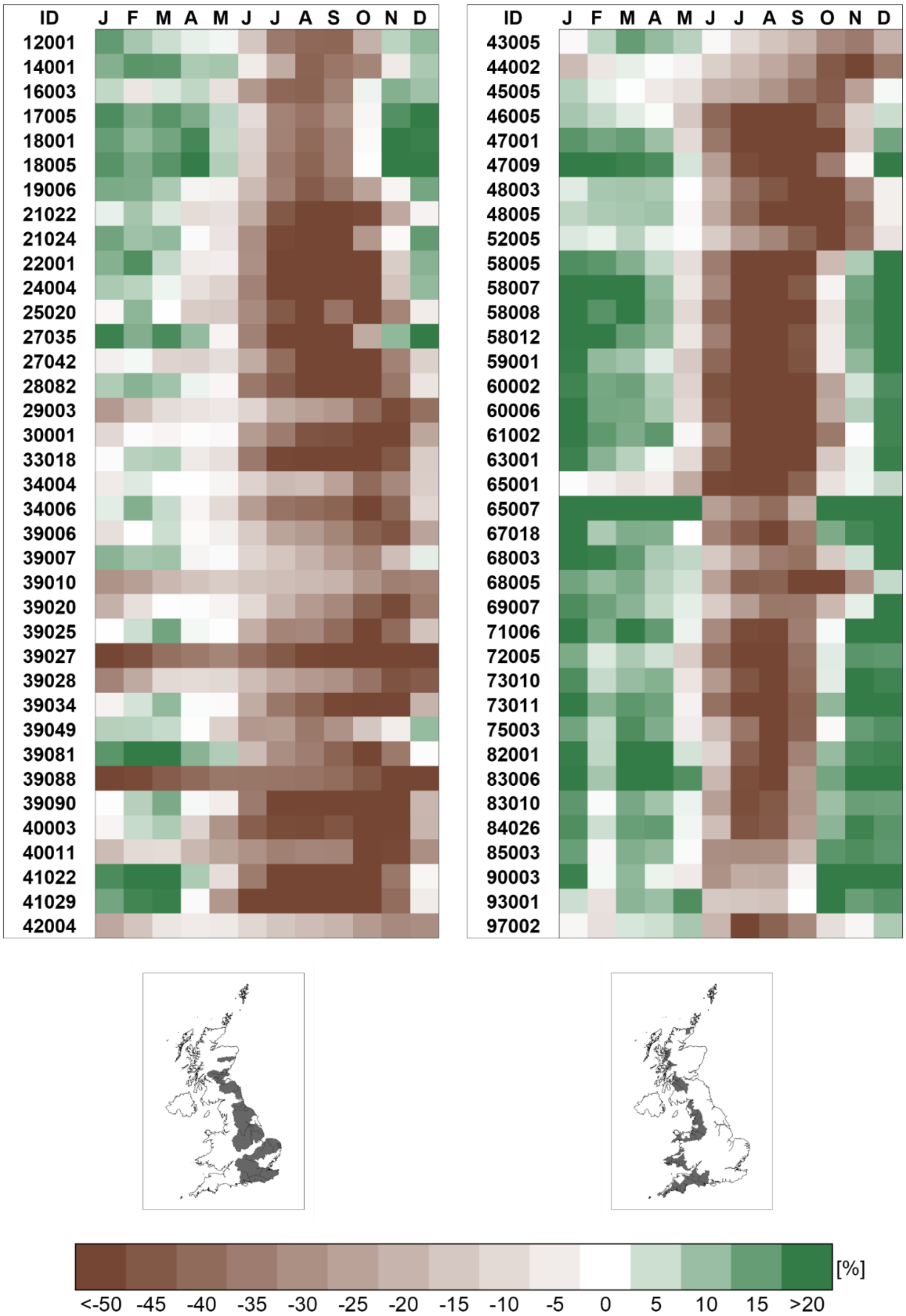

Figure S2 3: Monthly changes in river flows in the far future (2050-2079) from the baseline (1980-2009) at eFLaG gauges near RoR stations

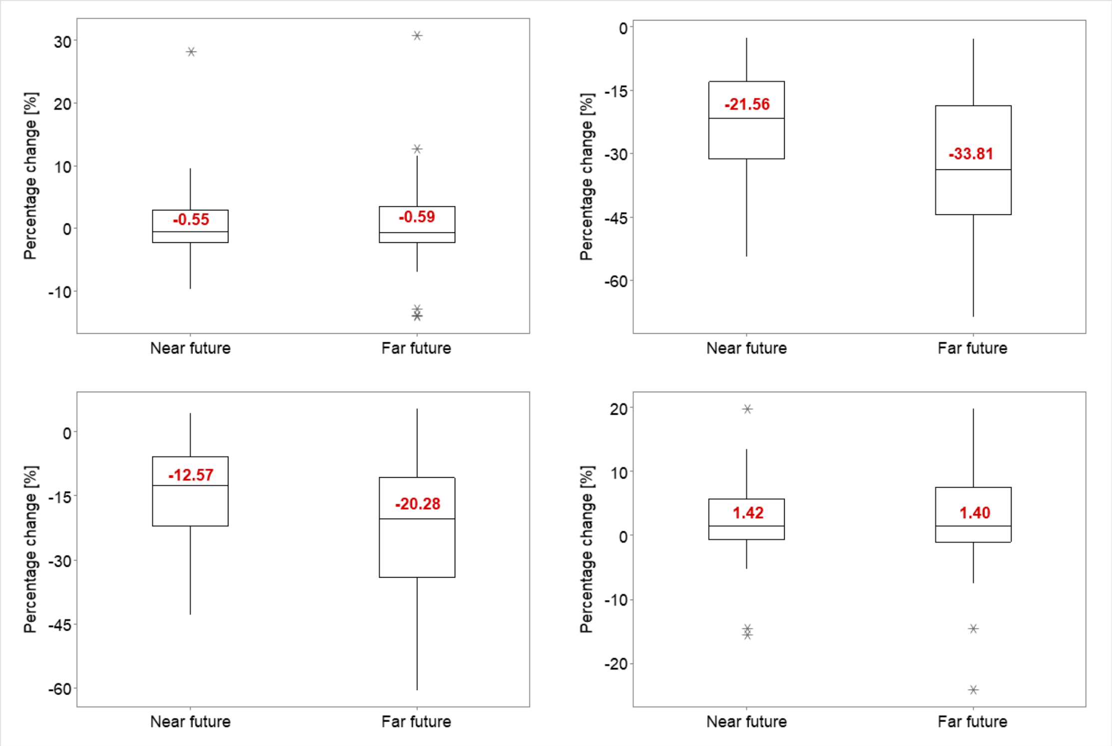

Figure S2 4: Percentage changes in seasonal total energy output in the near future (2030-2059) and the far future (2050-2079) from the baseline (1980-2009) at all the RoR schemes analysed in this study.

Table S2 1: Median changes in the future (near future – 2030-2059; far future – 2050-2079) from the baseline (1980-2009) in different metrics for all eFLaG gauges in the dataset

Metric	**Change from the baseline**	
	Near future	**Far future**
Annual mean flow	-5.65%	-6.78%
Spring mean flow	-0.26%	4.66%
Summer mean flow	-26.98%	-37.06%
Autumn mean flow	-20.14%	-31.18%
Winter mean flow	1.59%	8.19%
Design flow (Q_{40})	-2.80%	-5.70%
Environmental flow (Q_{95})	-16.40%	-23.30%
Days with flow below Q_{40}	+3 days/year	+6 days/year
Days with flow below Q_{95}	+22 days/year	+36 days/year

Table S2 2: Changes in total energy generated in the near future (2030-2059) from the baseline (1980-2009)

No.	Intake ID	Type	Spring change near future	Summer change near future	Autumn change near future	Winter change near future	Annual change near future
1	22350	Pico	-1.21	-28.17	-28.39	0.52	-11.62
2	26433	Pico	-5.38	-36.55	-27.24	1.95	-10.27
3	108693	Pico	-9.57	-12.92	-21.92	-15.57	-13.83
4	115426	Pico	-2.64	-12.66	-4.36	1.80	-4.75
5	2190	Micro	-1.75	-13.46	-9.71	0.36	-5.43
6	4698	Micro	28.19	-18.20	4.39	19.80	12.42
7	5872	Micro	-2.45	-8.94	3.65	2.50	-0.79
8	7126	Micro	-1.94	-5.66	-16.76	-2.30	-6.10
9	8876	Micro	3.47	-21.53	-3.88	8.99	-1.45
10	11592	Micro	4.69	-22.90	-3.14	7.09	-0.68
11	14619	Micro	-2.20	-2.48	-2.41	-0.57	-1.92
12	17098	Micro	0.62	-13.26	-14.04	-0.67	-6.03
13	17975	Micro	-3.49	-13.97	-15.90	-1.59	-8.57
14	21114	Micro	0.20	-33.04	-17.98	1.39	-9.89
15	22243	Micro	0.88	-32.00	-27.51	1.05	-10.27
16	22477	Micro	2.29	-27.07	-11.45	3.57	-6.86
17	24048	Micro	-3.80	-32.12	-30.00	-0.99	-13.57
18	27390	Micro	1.85	-32.41	-14.80	3.75	-8.62
19	28249	Micro	-1.96	-5.70	-19.52	-4.83	-7.45
20	30764	Micro	7.96	-20.61	-6.82	6.89	-2.15
21	30912	Micro	-1.67	-6.52	-10.91	-1.46	-4.87
22	37423	Micro	-2.48	-18.92	-30.97	-1.51	-11.23
23	42834	Micro	-1.67	-14.39	-22.07	-0.36	-8.21
24	43958	Micro	-0.51	-27.24	-21.57	0.47	-9.47
25	46202	Micro	-2.17	-54.29	-41.38	1.11	-16.87
26	50701	Micro	1.47	-21.61	-21.94	0.09	-8.28
27	51679	Micro	-5.64	-13.90	-16.07	0.20	-8.07
28	53056	Micro	-1.21	-14.40	-26.25	-3.31	-10.07
29	54007	Micro	-3.14	-9.63	-26.42	-4.67	-9.77
30	55023	Micro	2.56	-27.18	-5.69	11.47	-3.00
31	58075	Micro	-3.64	-12.44	-25.96	-2.38	-9.62
32	59803	Micro	-0.34	-15.54	-19.81	-1.35	-7.81
33	60966	Micro	-3.26	-9.65	-10.89	-0.51	-5.95
34	76933	Micro	-9.27	-14.00	-22.62	-14.55	-14.96
35	83774	Micro	-0.42	-12.89	-22.90	0.41	-7.37

No.	Intake ID	Type	Spring change near future	Summer change near future	Autumn change near future	Winter change near future	Annual change near future
36	85083	Micro	-1.10	-36.85	-42.88	-1.25	-15.56
37	99121	Micro	-1.33	-17.57	-7.30	4.79	-4.75
38	101092	Micro	-2.32	-27.01	-29.20	-1.56	-12.71
39	106546	Micro	-2.27	-3.84	-5.87	-1.40	-3.33
40	131120	Micro	-8.85	-23.48	-35.81	-14.61	-20.02
41	154321	Micro	-2.99	-8.90	-18.63	-4.59	-8.57
42	160647	Micro	-1.19	-19.16	-26.61	0.59	-8.76
43	166579	Micro	-1.86	-6.26	-7.81	-0.25	-3.98
44	209114	Micro	-0.84	-23.30	-21.63	-1.04	-10.33
45	4084	Mini	-1.87	-9.33	-8.20	-0.05	-4.47
46	4453	Mini	-2.45	-8.88	3.62	2.50	-0.80
47	4570	Mini	-0.68	-39.90	-14.78	5.97	-9.42
48	7071	Mini	-1.98	-5.13	-15.43	-2.20	-5.75
49	7940	Mini	2.17	-23.33	-3.08	3.71	-3.32
50	8170	Mini	9.14	-24.04	-2.44	13.25	1.73
51	9359	Mini	5.39	-37.26	-13.15	7.05	-6.51
52	10792	Mini	2.46	-39.48	-21.74	3.69	-10.61
53	12523	Mini	-1.88	-12.30	-11.99	-0.23	-5.81
54	12770	Mini	4.48	-22.38	-3.21	6.63	-0.90
55	16018	Mini	-1.41	-20.97	-18.75	-0.11	-8.71
56	17815	Mini	0.85	-39.71	-8.88	10.74	-5.00
57	18458	Mini	2.10	-25.41	-10.09	5.25	-5.82
58	19856	Mini	1.17	-12.15	-9.01	1.13	-3.91
59	21194	Mini	-0.71	-30.25	-33.49	-0.99	-12.54
60	21998	Mini	2.94	-16.74	-6.06	2.12	-3.18
61	22118	Mini	-3.32	-13.06	-26.20	-5.26	-11.13
62	23125	Mini	0.30	-33.47	-18.09	1.59	-9.85
63	23467	Mini	3.02	-24.45	-17.47	1.91	-7.11
64	23993	Mini	-3.82	-31.86	-9.93	7.90	-8.17
65	24111	Mini	4.42	-29.97	-11.98	4.21	-6.62
66	24333	Mini	6.34	-24.70	-3.76	11.11	-0.51
67	25410	Mini	3.04	-32.59	-22.25	2.04	-7.79
68	28224	Mini	9.71	-20.41	-5.10	4.18	-0.52
69	32402	Mini	4.61	-48.31	-14.44	6.29	-8.00
70	34073	Mini	8.14	-20.76	-6.81	7.10	-2.06
71	35184	Mini	3.86	-12.51	-5.34	3.04	-1.62
72	45222	Mini	-1.58	-15.08	-22.76	-0.15	-8.26

No.	Intake ID	Type	Spring change near future	Summer change near future	Autumn change near future	Winter change near future	Annual change near future
73	47749	Mini	-2.49	-20.38	-32.59	-1.35	-11.47
74	49626	Mini	4.46	-24.16	-24.84	0.34	-7.42
75	53277	Mini	-1.11	-14.63	-26.64	-3.36	-10.14
76	54422	Mini	4.41	-27.92	-4.96	13.47	-1.68
77	57212	Mini	-3.46	-10.37	-11.62	-0.52	-6.33
78	63923	Mini	-0.78	-26.97	-28.75	-0.08	-11.65
79	107208	Mini	-0.46	-22.17	-11.92	0.78	-6.72
80	113697	Mini	-2.19	-3.45	-4.73	-1.17	-2.88
81	189463	Mini	5.87	-26.31	-11.78	5.57	-3.89
82	2078	Small	4.35	-15.20	-0.29	5.49	-0.37
83	2509	Small	9.43	-30.80	-1.50	10.32	0.69
84	5831	Small	4.44	-8.41	3.43	2.76	1.24
85	8564	Small	-2.21	-32.52	-6.87	12.87	-4.08
86	9988	Small	-3.02	-41.58	-7.83	4.00	-6.51
87	10911	Small	-0.58	-46.80	-15.70	6.82	-9.97
88	11448	Small	6.23	-29.09	-3.24	8.12	-0.29
89	18667	Small	-2.17	-2.85	-1.27	-0.30	-1.65
90	18896	Small	-0.39	-31.34	-10.99	7.49	-6.93
91	18944	Small	-0.10	-34.39	-3.78	1.45	-4.04
92	20693	Small	8.55	-24.01	-5.72	9.82	-0.22
93	22277	Small	4.46	-33.05	-21.24	2.57	-8.16
94	25548	Small	6.68	-8.40	2.28	6.48	2.50
95	27404	Small	-2.18	-33.70	-7.23	9.15	-5.12
96	30466	Small	1.98	-50.42	-15.56	5.74	-9.62
97	33633	Small	1.70	-14.58	-5.93	2.21	-3.01
98	34822	Small	2.05	-49.12	-26.49	2.62	-11.69
99	44301	Small	2.57	-50.61	-17.45	6.86	-9.79
100	59684	Small	-0.02	-14.24	-10.25	0.63	-5.27

Table S2 3: Changes in total energy generated in the far future (2050-2079) from the baseline (1980-2009)

No.	Intake ID	Type	Spring change far future	Summer change far future	Autumn change far future	Winter change far future	Annual change far future
1	22350	Pico	-1.53	-36.52	-43.56	-0.77	-16.64
2	26433	Pico	-6.85	-45.03	-37.80	1.54	-14.57
3	108693	Pico	-13.92	-18.89	-31.82	-24.16	-21.07

No.	Intake ID	Type	Spring change far future	Summer change far future	Autumn change far future	Winter change far future	Annual change far future
4	115426	Pico	-1.91	-18.82	-9.96	2.15	-7.14
5	2190	Micro	-0.99	-19.19	-14.40	0.36	-7.50
6	4698	Micro	30.84	-40.09	-6.03	19.80	7.43
7	5872	Micro	-2.89	-18.53	4.57	2.50	-0.65
8	7126	Micro	-1.96	-7.18	-23.75	-2.30	-8.29
9	8876	Micro	5.30	-33.36	-5.49	8.99	-2.75
10	11592	Micro	8.29	-37.15	-6.88	7.09	-2.36
11	14619	Micro	-2.23	-2.65	-3.21	-0.57	-2.25
12	17098	Micro	0.55	-18.50	-20.60	-0.67	-9.05
13	17975	Micro	-3.98	-16.98	-20.73	-1.59	-10.82
14	21114	Micro	0.33	-44.00	-28.29	1.39	-14.34
15	22243	Micro	-0.68	-41.08	-38.02	1.05	-14.57
16	22477	Micro	3.26	-39.08	-18.63	3.57	-10.70
17	24048	Micro	-5.04	-39.12	-38.65	-0.99	-17.42
18	27390	Micro	2.31	-46.01	-24.26	3.75	-13.41
19	28249	Micro	-2.83	-9.38	-29.88	-4.83	-12.21
20	30764	Micro	9.94	-34.26	-11.18	6.89	-5.08
21	30912	Micro	-2.01	-10.72	-18.60	-1.46	-8.04
22	37423	Micro	-3.00	-24.57	-44.06	-1.51	-15.76
23	42834	Micro	-2.64	-20.33	-33.99	-0.36	-12.45
24	43958	Micro	-1.25	-40.68	-34.67	0.47	-15.01
25	46202	Micro	-3.41	-67.07	-52.45	1.11	-21.72
26	50701	Micro	0.83	-30.39	-34.46	0.09	-13.06
27	51679	Micro	-5.29	-15.14	-20.37	0.20	-9.42
28	53056	Micro	-2.11	-21.46	-38.99	-3.31	-15.29
29	54007	Micro	-3.40	-13.02	-37.58	-4.67	-13.75
30	55023	Micro	3.60	-43.08	-11.21	11.47	-6.60
31	58075	Micro	-3.66	-15.99	-36.31	-2.38	-13.10
32	59803	Micro	-1.48	-24.63	-30.54	-1.35	-12.62
33	60966	Micro	-3.43	-11.01	-14.68	-0.51	-7.30
34	76933	Micro	-14.05	-20.36	-32.94	-14.55	-22.56
35	83774	Micro	-0.80	-18.10	-35.32	0.41	-11.31
36	85083	Micro	-2.59	-49.01	-60.44	-1.25	-22.21
37	99121	Micro	-0.49	-23.91	-13.15	4.79	-7.25
38	101092	Micro	-3.11	-34.42	-43.34	-1.56	-17.81
39	106546	Micro	-2.36	-4.52	-8.79	-1.40	-4.58
40	131120	Micro	-12.87	-32.64	-49.00	-14.61	-28.74

No.	Intake ID	Type	Spring change far future	Summer change far future	Autumn change far future	Winter change far future	Annual change far future
41	154321	Micro	-3.22	-11.49	-25.39	-4.59	-11.55
42	160647	Micro	-1.65	-24.91	-36.68	0.59	-12.21
43	166579	Micro	-1.89	-7.47	-10.74	-0.25	-4.99
44	209114	Micro	-1.74	-30.59	-32.43	-1.04	-14.76
45	4084	Mini	-1.43	-14.95	-12.69	0.00	-6.60
46	4453	Mini	-2.89	-18.45	4.52	9.75	-0.67
47	4570	Mini	0.55	-54.69	-23.25	7.26	-13.68
48	7071	Mini	-2.01	-6.41	-21.95	-3.21	-7.77
49	7940	Mini	2.08	-35.46	-5.34	8.70	-4.61
50	8170	Mini	11.60	-40.07	-4.24	16.66	0.30
51	9359	Mini	5.86	-55.64	-22.08	8.17	-11.67
52	10792	Mini	0.85	-55.68	-32.94	3.87	-16.66
53	12523	Mini	-1.32	-16.40	-16.66	-0.11	-7.51
54	12770	Mini	7.89	-36.37	-6.96	8.16	-2.68
55	16018	Mini	-1.08	-28.92	-26.99	-1.01	-12.32
56	17815	Mini	5.43	-57.36	-14.28	13.52	-7.34
57	18458	Mini	2.67	-37.52	-16.54	6.31	-9.54
58	19856	Mini	2.15	-17.09	-15.07	1.09	-6.11
59	21194	Mini	-0.96	-39.86	-47.96	-1.88	-17.56
60	21998	Mini	3.31	-26.30	-9.44	3.41	-5.28
61	22118	Mini	-3.38	-14.88	-34.03	-7.47	-13.87
62	23125	Mini	0.47	-44.46	-28.44	1.88	-14.28
63	23467	Mini	3.24	-34.46	-27.92	1.41	-11.50
64	23993	Mini	-2.25	-43.85	-13.44	11.51	-10.31
65	24111	Mini	5.52	-44.38	-19.95	5.17	-10.96
66	24333	Mini	10.77	-37.98	-5.79	13.72	-1.62
67	25410	Mini	3.15	-48.11	-35.24	1.74	-12.90
68	28224	Mini	10.23	-35.33	-9.48	5.80	-3.18
69	32402	Mini	5.13	-66.19	-26.46	7.38	-13.48
70	34073	Mini	10.18	-34.50	-11.18	9.03	-4.97
71	35184	Mini	5.66	-24.24	-9.57	3.55	-4.09
72	45222	Mini	-2.68	-21.25	-35.04	-0.90	-12.64
73	47749	Mini	-2.99	-26.49	-46.03	-3.56	-16.13
74	49626	Mini	3.64	-37.58	-40.96	-0.55	-13.41
75	53277	Mini	-2.04	-21.84	-39.47	-5.87	-15.43
76	54422	Mini	5.54	-45.22	-10.73	16.44	-5.43
77	57212	Mini	-3.66	-11.86	-15.67	-0.78	-7.78

No.	Intake ID	Type	Spring change far future	Summer change far future	Autumn change far future	Winter change far future	Annual change far future
78	63923	Mini	-0.75	-36.90	-43.15	-1.13	-17.05
79	107208	Mini	0.28	-31.09	-19.84	0.83	-10.04
80	113697	Mini	-2.27	-3.93	-7.06	-2.19	-3.85
81	189463	Mini	7.11	-42.72	-20.20	6.39	-8.09
82	2078	Small	4.89	-27.53	-0.29	13.30	-0.33
83	2509	Small	12.70	-46.71	-5.41	12.69	-1.23
84	5831	Small	6.60	-16.07	5.39	10.02	3.02
85	8564	Small	1.36	-50.47	-11.06	16.69	-6.35
86	9988	Small	-0.71	-47.63	-10.92	4.92	-7.22
87	10911	Small	0.90	-63.28	-24.42	8.21	-14.31
88	11448	Small	10.62	-46.04	-7.24	9.96	-1.92
89	18667	Small	-2.17	-3.57	-2.10	-0.30	-2.04
90	18896	Small	-0.35	-45.51	-17.07	9.31	-10.77
91	18944	Small	-1.33	-58.08	-13.70	7.52	-7.17
92	20693	Small	11.13	-44.38	-11.32	11.67	-3.81
93	22277	Small	4.78	-46.37	-33.82	1.96	-13.37
94	25548	Small	7.71	-20.88	2.29	13.34	2.37
95	27404	Small	2.69	-50.61	-12.22	11.90	-7.26
96	30466	Small	2.55	-67.48	-27.40	6.86	-14.96
97	33633	Small	3.28	-25.46	-10.00	2.61	-5.47
98	34822	Small	0.81	-64.93	-40.13	2.71	-17.53
99	44301	Small	3.35	-68.59	-28.94	8.20	-15.14
100	59684	Small	0.79	-20.61	-16.16	0.65	-7.82

Appendix 3 – Chapter 5 Appendices

Appendix 3 has been submitted as the Supplementary Information of Chapter 5 submitted as :*Golgojan, A.-D., White, C.J. & Bertram, D. (2024). The effects of climate change on hydropower drought: A run of river case study, International Journal of Energy research, in review*

Appendix 3.1 Supplementary figures

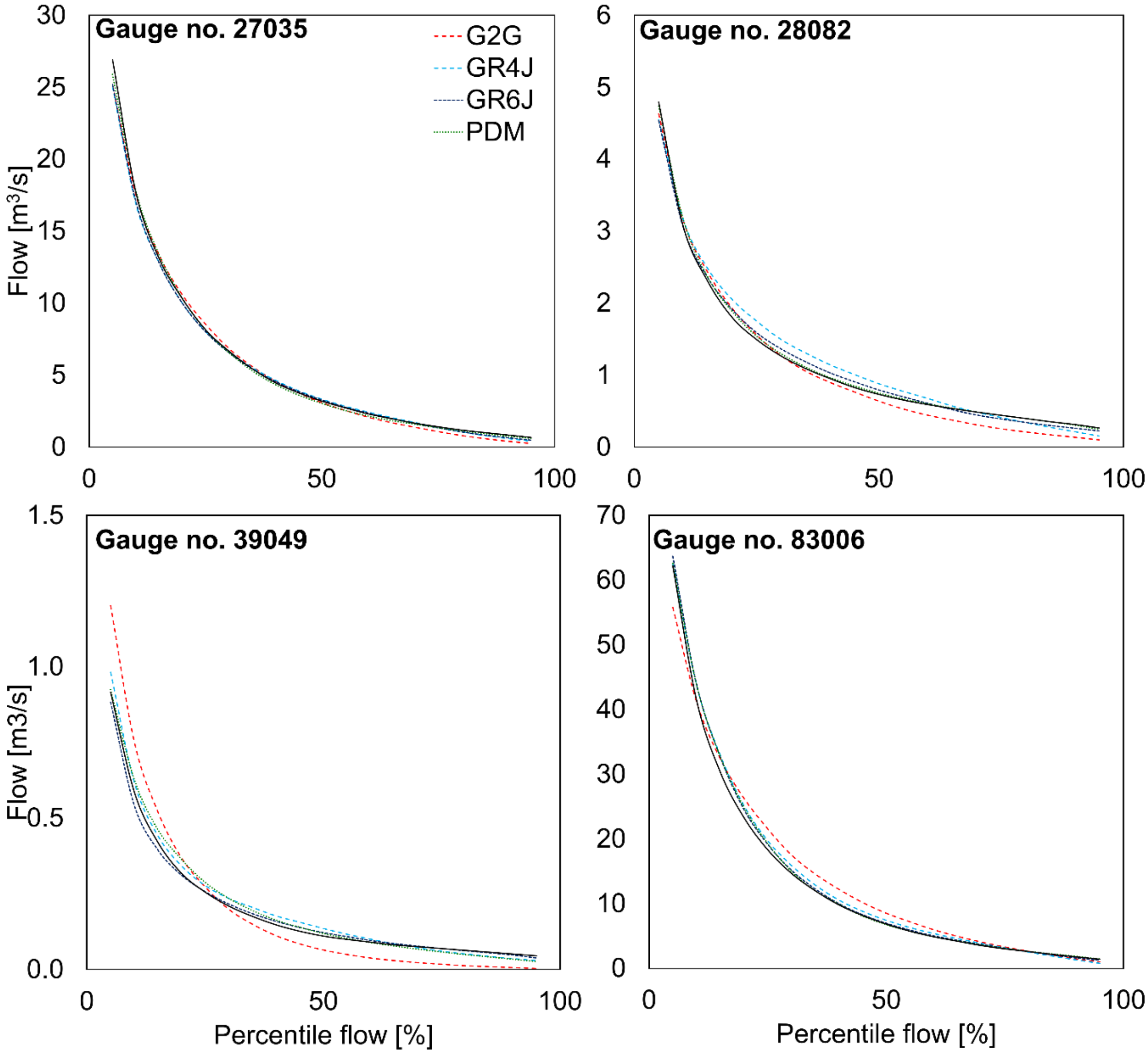

Figure S3 1: Comparison between simulated and observed percentile flows at each gauge near the virtual RoR schemes. The simulated flows are taken from the eFLaG dataset (Hannaford et al., 2022) *and the observed flows are taken from the National River Flow Archive* (NRFA, 2021)

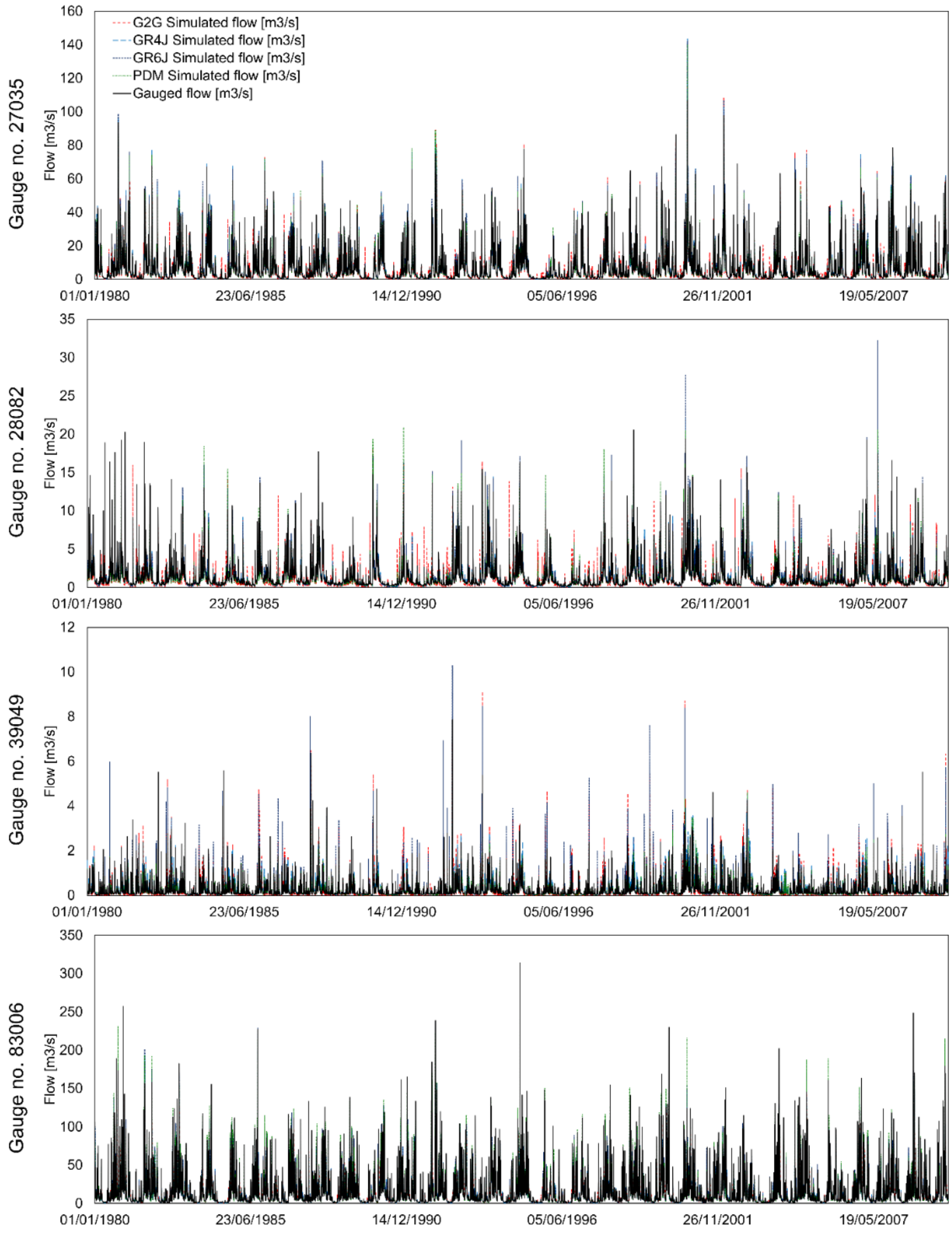

Figure S3 2: Time series of gauged flows vs simulated flows at the eFLaG stations near RoR schemes