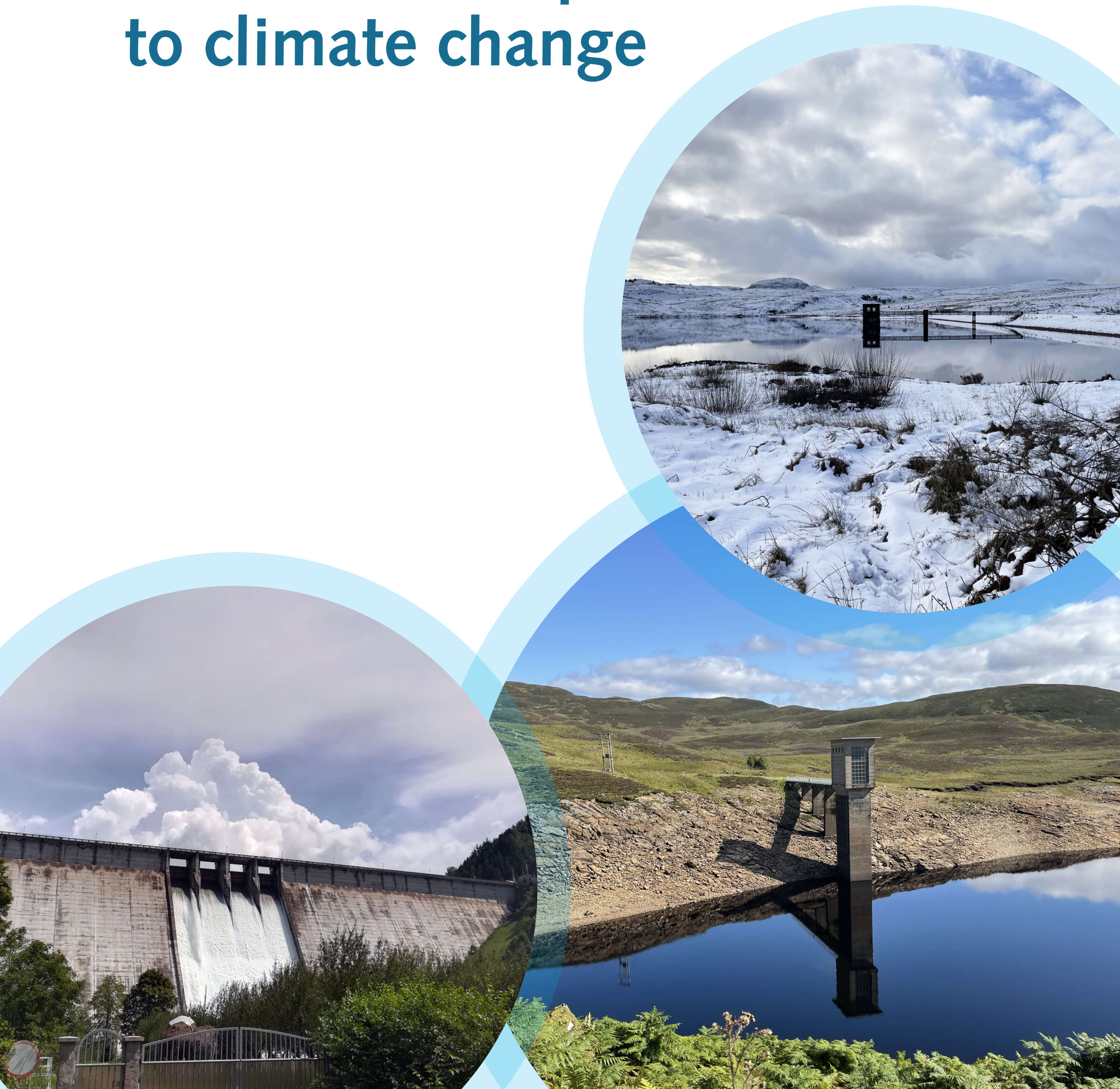
CREW CENTRE OF EXPERTISE FOR WATERS

A review of the risks to water resources in Scotland in response to climate change



CREW CENTRE OF EXPERTISE FOR WATERS

A review of the risks to water resources in Scotland in response to climate change

Ana-Diana Boca, Christopher J. White, Douglas Bertram

University of Strathclyde Engineering
Hydro Nation International Centre
The James Hutton Institute
Scottish Government Riaghaltas na h-Alba gov.scot

CREW CENTRE OF EXPERTISE FOR WATERS

Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes and Research Institutes supported by MASTS. The Centre is funded by the Scottish Government.

Authors: Ana-Diana Boca, Christopher J. White, Douglas Bertram
Department of Civil and Environmental Engineering, University of Strathclyde

Please reference this report as follows: Boca, A.-D., White, C.J., Bertram, D. (2022), A review of the risks to water resources in Scotland in response to climate change. CD2021_02. Centre of Expertise for Waters (CREW). Available online at: crew.ac.uk/publications.

Acknowledgements: The project team wished to thank Scottish Water and the Scottish Environment Protection Agency for their input and guidance throughout the project.

Project Manager: Katya Dimitrova-Petrova (2021-22), Rachel Helliwell (2021)

ISBN number: 978-1-911706-03-8

Dissemination status: Unrestricted

Cover photographs: Photographs courtesy of Dr Christopher J. White and Dr Douglas Bertram.

Executive summary

Project aim and objectives

This report aims to provide a review of studies that have assessed historical and future river flow and water availability changes in Scotland, and to provide evidence on how climatic, hydrological, and other catchment-based processes may influence water resource availability in the future. This study had the following four objectives:

1. Establish a baseline of evidence relating to past and ongoing climate change impacts to Scotland's water resources, including changes to climate variability, seasonality and extreme events based exclusively on information that is on the public domain;
2. Collate, explore and synthesize the latest international literature about the historical and likely future changes to water availability due to climate change, including methods and approaches that are being used elsewhere that may be relevant/applicable to Scotland;
3. Undertake an initial exploration of peer-reviewed literature to ascertain what information is available on how water demand/customer usage may change due to climate change; and
4. Make recommendations for further research relating to how Scotland monitors, evaluates, prepares for, manages, and communicates risks to its water resources due to climate change.

Key findings

- Outflows increased significantly over the 1961-2010 period in Scotland. Seasonally, in Scotland over the period 1965-2014, there was an increase in mean flows in winter, autumn and summer, with the winter increases being statistically significant. In spring, trends for decreases in the east and increases in the west are detected, although none are statistically significant.
- Future annual flows are not expected to change significantly across the UK in the future. However, future seasonal projections in the UK generally show seasonal reductions in spring and summer flows, a mixed pattern in autumn flows, and small increases in winter flows. These changes are, however, spatially and temporarily variable, with some areas likely to see a flow reduction, especially in eastern and southern Scotland. A geographical split between the east and west of Scotland is clearly visible.
- There is uncertainty regarding future frequency, duration and magnitude of both droughts and floods, including their timing and spatial extent, due to the different methodologies, indices and thresholds used and different types of hazards analysed in the reviewed studies. However, there is a consensus relating to an increase across all metrics (frequency, magnitude and duration) Scotland-wide in a warming climate.
- In the 2050s, irrigation demand, especially in summer, may rise due to an increase in temperatures alongside an increase in potential evapotranspiration. Changes in flows could also affect hydropower production, particularly run of river schemes that lack the storage capacity to buffer seasonal changes.
- Groundwater in Scotland forms a major component (73%) of private water supplies, providing drinking water to many rural areas. It is also of key importance to other industries (e.g., whisky, bottled water). While there is a significant body of research around groundwater *quality*, there is a dearth of research towards groundwater *quantity* and the effects of climate change on groundwater availability.
- While drought is the most studied hazard in connection to water resources, both in Scotland and internationally, other hazards and drivers of change are less explored in this context. In Scotland, compound hydro-hotspots (droughts and floods) are projected to occur across eastern Scotland and the Highlands and Islands, including the Loch Ness and River Tay catchments in the far future.
- There are few examples of studies in the peer-reviewed literature relating to water demand and/or customer usage changes due to climate change in the UK. In England and Wales, water companies have set a series of goals: reduce demand, reduce leakage rates, develop new water supplies, increase water transfers and reduce the use of environmentally damaging drought measures that may be of relevance to Scotland.

Recommendations

Based on the outcomes of this study, we provide ten high-level recommendations:

1. **Historical trend analyses of droughts and floods:** Despite notable drought and flood events in Scotland in recent decades, evidence of trends of increased frequency of drought and flood, or of changes to the seasonality of their driving factors are weak and urgently needs further research.
2. **Evidence of, and planning for, emerging risks:** Dedicated evaluation by research institutions in close collaboration with Scottish Water leading to the optimisation of water demand planning and operation of water resource infrastructure that prepares for changing climatic conditions and uncharacteristic regional hazards is needed.

3. **Combinations of compound events across Scotland:** Scotland-focused compound events analyses are required to accurately represent the complex, interacting risks and impacts to the water resources sector identified in this study, both using observations and future climate projections. Based on expert advice and judgement, these include the following priority compound event pairings:

    a. **Temporal sequences of compound events** (including dry to wet and vice versa, and multiple dry periods) – There is a significant gap in knowledge about event sequencing in Scotland, including the 'see-saw' or 'weather whiplash' temporal succession between compound hazards. We recommend, as a priority, that temporal sequences across multiple compound event types are assessed to calculate how different outcomes might occur within the water resources sector.

    b. **Concurrent hot and dry conditions** – There are potential risks from the combination of dry and hot summer conditions, including water supply disruptions from drought and reduced water quality in the natural environment.

    c. **Snow events and streamflows** – Snow is an important factor to consider in future studies and resilience planning due to its significance to water resources and energy in Scotland.

4. **Cascading impacts and risks to water resources:** A multi-sectoral analysis, conducted as a partnership between universities and the water sector, would provide a better understanding of cascading impacts and the economic consequences of such risks, which could inform adaptation efforts.

5. **Improved regional climate modelling:** We recommend using an ensemble of climate projections for any future analysis. It is apparent that the majority of previous studies have been undertaken using outdated projections (UKCP09) and it is recommended that these studies are revised and updated with the current UKCP18 projections, including the high-resolution convection-permitting models.

6. **Water resource and drought planning:** We recommend a review of water resource and drought planning guidance from England and Wales together with water companies' water management and drought plans for regional assessments of water resources and supply demand balance issued each investment period be undertaken.

7. **Water demand and customer behaviours:** We recommend research that reviews international best-practise in water demand and customer behaviour modelling to inform future Scottish regional planning.

8. **Groundwater research:** We recommend research is undertaken in the area of climate change effects on groundwater quantity.

9. **Integration of infrastructure thresholds and feedbacks**: Using inputs from stakeholders across Scotland's water resource sector could be used to identify indicative thresholds and feedbacks for exposed critical infrastructure. This would enable better representation of their impacts on cascading and interacting risks.

10. **Revised adaptation and resilience approaches**: To better understand the risks to the water resources sector in a changing climate, we recommend that further research could be conducted in collaboration with the water companies/water authorities to develop, apply and test risks against different adaptation and resilience scenarios, including using 'storyline' approaches, moving beyond high-level, descriptive, adaptation scenarios.

Contents

1 Introduction

1.1 Background

There is "irrefutable evidence" that the global climate is changing due to human activities (IPCC, 2021). Even in 'water rich' countries like Scotland, these changes will have implications for the future of water supply. In Scotland, changes in rainfall patterns (spatially, temporally, and seasonally), together with the frequency and magnitude of extreme weather events including flood and drought, may produce significant challenges for Scotland's water sector. Such changes may affect drinking water supply, as well as energy, agriculture, economic activity, and supply chains. Although there are inherent uncertainties surrounding the climate change projections for precipitation at the global scale and what they mean regionally for Scotland, especially in the short-term (e.g., the next 30 years), policymakers increasingly need to compare and balance the evidence relating to changes to Scotland's climate with their medium to long term planning decisions about the way water is stored, managed, and supplied.

While there have been several notable studies in recent years that have looked at various aspects of water availability and water resources in Scotland, including hydropower (Sample et al., 2015), economics (McGrane et al., 2018) and agriculture (Brown et al., 2011), and the likely impacts of climate change to Scotland's rainfall, including lower river flow leading to water scarcity (SEPA, 2014) and drought (Gosling, 2014; Kirkpatrick Baird et al., 2021), these have largely been without a direct focus on Scotland's changing water availability for water planning. This gap was highlighted in 2016 by CIWEM (CIWEM, 2016) who identified the need for "research [in Scotland] that specifically addresses the impacts on water resources during drought events and thereby will improve understanding of the range of uncertainty that needs to be taken into account in water resources planning".

There is standard framework and guidance that has been developed by the Environment Agency/Defra in conjunction with UK Water Industry Research (UKWIR) to help plan for future impacts of climate change on water resources for public water supplies. UK water companies use this approach to produce water resource plans that look ahead to assess and plan for the impacts of climate change. These contributed to the Independent Assessment of Climate Risk for the Third UK Climate Change Risk Assessment (CCRA3) (Climate Change Committee, 2021) that highlighted the UK's "risks to public water supplies from reduced water availability" as a priority action in its advice to Government, amongst many others. Other related studies recently commissioned by CREW (Rivington et al., 2020) and ClimateXChange (Waajen, 2019) have reached similar conclusions, concluding that "half of Scotland's private water supplies are estimated to be within areas of increased vulnerability between now and 2050" and an "increase of water supply system resilience against droughts [is needed in Scotland]" respectively.

Despite these various pieces of evidence and information, to date there has been limited research that *directly* relates both observed and plausible future climatic changes in Scotland to water availability. This makes longer-term decision-making incorporating climate change challenging.

However, the extent of evidence from existing studies across water resources in Scotland in general, combined with the latest peer-reviewed studies and approaches relating to climate change science can be explored and interpreted to form a baseline of evidence and best-practise. This will help identify knowledge and innovation gaps and guide Scottish future water resource planning to increase climate resilience. Areas of interest include:

- regional high-resolution climate projections available from UKCP18,
- climate 'transitions' and shifts,
- interacting hazards and cascading impacts,
- longer-range and impact-based forecasting, improved scenarios, and
- other forms of risk-based communication including 'storytelling' and climate services

1.2 Aim and objectives of this study

This report aims to provide a review of peer-reviewed studies that have assessed historical and future river flow and water availability changes in Scotland, and to provide evidence on how climatic, hydrological, and other catchment-based processes may influence water resource availability in the future. It seeks to identify consensus of climate change information in Scotland, including noting any conflicts and gaps in knowledge, to inform ongoing water resource management requirements for users. This report considers the drivers of change (e.g., precipitation, temperature) and natural hazards (e.g., drought, floods) that can impact water resources in Scotland. In addition, this report provides information about changes in seasonality, sequencing of dry and wet events, the likelihood of successive droughts, the impact of other hazards (e.g., heatwaves) on water resources in Scotland, timeline of climate changes and strength of climate signal. Moreover, this report provides information on best practices for climate modelling and other analytical methods that may be relevant for Scotland's water resource sector.

This study has the following main objectives:

1. Establish a baseline of research evidence relating to past and ongoing climate change impacts to Scotland's water resources, including changes to climate variability, seasonality and extreme events based exclusively on information that is on the public domain;
2. Collate, explore and synthesise the latest international research (focused on peer-reviewed literature) into the historical and likely future changes to water availability due to climate change, including methods and approaches that are being used elsewhere that may be relevant/applicable to Scotland;
3. Undertake an initial exploration of the peer-reviewed literature to ascertain what information is available on how water demand/customer usage may change due to climate change. This will include details of what methods may have been developed elsewhere (e.g., by other UK water companies, and/or internationally) that assess water resource system vulnerabilities that may apply to Scotland; and
4. Make recommendations for further research relating to how Scotland monitors, evaluates, prepares for, manages, and communicates risks to its water resources due to climate change.

1.3 Structure of the report

Section 2 of this report discusses the methods used to review existing literature. Section 3 details general information about climate change modelling and uncertainty. Section 4 presents the results relevant to water resources in Scotland, including past and projected future flows and risks to water availability. Section 5 presents findings from international and UK literature that highlight state of the art methodologies for assessing changes to water resources that may be applicable to Scotland. Section 6 presents water demand and management plans from the UK that may be relevant for Scotland. Section 7 presents a discussion and implications of the previous findings, followed by a set of high high-level recommendations (Section 8) and a general conclusion (Section 9).

2. Methods

The hypothesis of this study is that Scotland's climate is changing and will continue to change due to anthropogenically-driven climate change. This change is altering Scotland's natural water resource through increased variability, including changes to seasonal, spatial and temporal patterns, and to extreme events, leading to increased uncertainty around the timing and magnitude of water availability in the future. This project aims to establish if this hypothesis is supported by published literature and to make recommendations that could be used to increase preparedness and improve climate resilience.

To address the project objectives, a comprehensive literature search was performed using web-based search engines alongside other review methods such as chain searching and backwards author searching. An example summary of the search terms used are presented in Table 2.1 and Table 2.2. The search terms used are at times broad, and some searches came with a plethora of results (e.g., 19,900) that cannot be reviewed in their entirety for this study. To overcome this, results were sorted based on their relevance to the search terms and manually combed through by reading the abstracts until the results were no longer relevant to the search terms. A minimum of five pages (~50 results) were analysed per search term. The total filtered results in the tables include duplicates since the searches often came with similar results.

Where search terms such as 'drought sequencing' mainly produced results from biology and nature topics, alternative terms such as 'dry to wet transition' or 'drought succession' were used to refine the key search term. This resulted in fewer studies which have a focus on hydrology and/or water resources. While the search included 'Scotland' or 'UK', none of the results were found to be relevant to them, suggesting, for example, that very little to no research has been published in the UK on drought sequencing, wet to dry transition or drought succession. Since a small amount of literature was found relevant to the study research questions using computerised search terms, the review methodology was mostly based on chain searching and backwards author searching (i.e., by examining the references or works cited within an article or by a selected author identified in the initial search).

Table 2.1: Summary of search terms used for objectives 1 and 2				
Search term	**Returned results**	**Filtered results**	**Search engine/ database**	**Search date**
wet to dry transition AND ("Scotland" OR "UK" OR "Great Britain") (All fields) (2014-2021)	67	4	Web of Science/ Clarivate	29.11.2021
wet to dry transition OR drought succession AND ("Scotland" OR "UK" OR "Great Britain") (All Fields) and JOURNAL OF HYDROLOGY or JOURNAL OF GEOPHYSICAL RESEARCH ATMOSPHERES or JOURNAL OF CLIMATE or WATER RESOURCES RESEARCH or INTERNATIONAL JOURNAL OF CLIMATOLOGY or HYDROLOGICAL PROCESSES or HYDROLOGY AND EARTH SYSTEM SCIENCES or CLIMATE RESEARCH or JOURNAL OF FOOD ENGINEERING or JOURNAL OF HYDROMETEOROLOGY or CLIMATIC CHANGE or NATURE or WATER or ENVIRONMENTAL RESEARCH LETTERS or JOURNAL OF APPLIED METEOROLOGY AND CLIMATOLOGY or ADVANCES IN WATER RESOURCES or NATURE COMMUNICATIONS or NATURAL HAZARDS or AGRICULTURAL WATER MANAGEMENT (Publication Titles)	359	10	Web of Science/ Clarivate	29.11.2021
wet to dry transition OR drought succession AND ("Scotland" OR "UK" OR "Great Britain") (2014-2021)	17,100	0	Google Scholar	29.11.2021
wet to dry transition OR drought succession AND ("Scotland" OR "UK" OR "Great Britain") (All fields)	22	1	Google Scholar	29.11.2021
wet to dry transition OR drought succession (2014-2021) (All in title)	6,530	0	Google Scholar	29.11.2021
successive dry spells Scotland (2014-2021)	19,900	0	Google Scholar	29.11.2021
"successive dry" spells Scotland water resource (2014-2021)	14,900	3	Google Scholar	29.11.2021
drought sequencing AND ("Scotland" OR "UK" OR "Great Britain") -dna -rna -medicine -health -fungi -genetics -microb* -agriculture -crop* -genes -bacteria* (2014-2021)	33	0	Google Scholar	29.11.2021
drought sequencing AND "water" AND ("Scotland" OR "UK" OR "Great Britain") NOT ("dna" AND "rna" AND "medicine" AND "health" AND "fungi" AND genetic* AND microb* AND "agriculture" AND crop* AND gene* AND bacteria*) (All Fields) and Environmental Sciences or Geosciences Multidisciplinary or Environmental Studies or Engineering Civil or Water Resources or Engineering Multidisciplinary or Engineering Environmental or Soil Science or Agriculture Multidisciplinary or Green Sustainable Science Technology or Agricultural Engineering (Web of Science Categories) and 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 (Publication Years)	285	1	Google Scholar	29.11.2021
"flood" risk AND "Scotland" AND "climate change" (All Fields) and 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 (Publication Years)	9	0	Web of Science/ Clarivate	29.11.2021
"flood" risk AND "Scotland" "climate change" (2014-2021)	6,530	0	Google Scholar	29.11.2021
uncertainty in "climate models" (2014-2021)	24,600	3	Google Scholar	29.11.2021
Total	**90,335**			
Total filtered	**22**			

Table 2.2: Summary of search terms used for objective 3				
Search term	Returned results	Filtered results	Search engine/ database	Search date
Scotland "water demand changes" (2014-2021)	13	2	Google Scholar	14.12.2021
Scotland "water" "demand changes" (2014-2021)	479	6	Google Scholar	14.12.2021
Scotland "water" "demand changes" -building* (2014-2021)	110	5	Google Scholar	14.12.2021
Scotland "water" "demand changes" -building* -health* (2014-2021)	35	3	Google Scholar	14.12.2021
Scotland "water" demand change (All Fields) and 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 (Publication Years)	156	3	Web of Science/ Clarivate	14.12.2021
Total	793			
Total filtered	19			

3. Climate change modelling and uncertainty

UK's natural climate variability makes climate modelling and the detection of changes challenging (Watts et al., 2015). Despite this, climate models are good tools to simulate the possible changes in temperature, precipitation or evapotranspiration which can influence water availability in the UK. They simulate the interaction of climate drivers, such as atmosphere, oceans, land surface, and ice to obtain projections of temperature and other meteorological variables under various assumptions (Smith et al., 2009).

The latest climate projections for the UK, UKCP18, include a new set of observations of weather and climate, include a more recent generation of climate models from around the world and include the results from the latest Met Office global and regional climate models (Lowe et al., 2019). UKCP18 includes high resolution (2.2 km) convection-permitting models that can simulate small scale behaviour seen in the atmosphere, in particular, atmospheric convection. UKCP18 uses different RCP scenarios from its former generation of climate projections, UKCP09. An overview of the latest emission scenarios and their similarities with the previous SRES scenarios is explained in Table 3.1. As a result, they provide information on an hourly scale which is important for small-scale weather features which can affect flooding (Kendon et al., 2019b). The last two generations of UK climate projections (UKCP) from the Met Office Hadley Centre, UKCP09 and UKCP18, have been perturbed physics ensembles (PPEs) and they explore parametric uncertainty in a single climate model through systematic variation of uncertain model parameters. The disadvantage of the PPE is that the estimate of uncertainty is dependent on the structure of the underlying model, leading to potential underestimates of uncertainty (Visser-Quinn et al., 2021).

A significant number of studies reviewed in this report used the previous UK climate projections, UKCP09, to measure future variables such as precipitation and river flows (Christierson et al., 2012; Prudhomme et al., 2012; Sample et al., 2015; Watts et al., 2015). However, there are studies that have used the latest climate projections in the UK. For example, Kay (2021) uses the reprojected 12 km grid monthly precipitation and daily minimum and maximum temperature from the UKCP18 Regional Projections to simulate monthly mean flows until 2080 across Great Britain. In Kay (2021), the precipitation data is bias-corrected, downscaled to 1 km grid using a spatial weighting derived from 1 km standard average annual rainfall patterns and temporally downscaled for input in a grid-based hydrological model. No bias-correction was applied for the temperature as the PPE encompasses monthly observations well. The same downscaling methods as for precipitation were applied for temperature. Potential evaporation was estimated for land grid boxes using the Penman-Monteith formula and spatially and temporally downscaled as for precipitation and temperature. In a separate study, Kay et al. (2020) applied both the UKCP09 and UKCP18 probabilistic projections on 10 catchments in England to measure the differences in median, mean, high and low flows into the 2050s between the distinct projections. The small differences indicated in Kay et al. (2020) between flow changes projected by UKCP18 and UKCP09 suggest that current water management practises remain valid, and that results from UKCP09 remain a useful guide to changes in the next 30 years. Nevertheless, the current practices will need to be revised in the light of UKCP18 to make use of the new information available and to ensure that risks are managed correctly[1]. Yet, for low and mid-range flows, the decreases in flows are smaller using UKCP18, than UKCP09 and for high flows, the increases are greater using UKCP18 than UKCP09. However, the uncertainty ranges of flow changes are greater when utilizing the UKCP18 projections than UKCP09.

Observations for the UK show that the last decade (2008-2017) has been warmer by 0.3°C than 1981-

Table 3.1: Comparison between the RCP scenarios and the previous SRES emission scenarios. Data from Met Office (2018)

RCP	Change in temperature (°C) by 2081-2100 from the pre-industrial period relative to the average between 1850-1900 (range of plausible changes shown in parenthesis)	Most similar SRES scenario (with respect to temperature)
RCP2.6	+1.6 (0.9-2.3)	None
RCP4.5	+2.4 (1.7-3.2)	SRES B1 (low emission scenario in UKCP09)
RCP6.0	+2.8 (2.0-3.7)	SRES B2 (between the low and the medium emission scenarios in UKCP09)
RCP8.5	+4.3 (3.2-5.4)	SRES A1F1 (high emission scenario in UKCP09)

[1]The study showed that under the A1B emission scenario (the A1B storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies with a balance across all energy generation sources, similar to RCP6.0), the central estimate of change for all flows from the UKCP18 projections is similar to that from the UKCP09.

2010, and 0.8°C warmer than 1961-1990 and all the top ten warmest years occurred since 1990, with 2021 being the 6th warmest year on record (Margetta, 2022). Furthermore, in the past few decades the UK annual average rainfall has increased, particularly in Scotland, where the last decade (2008-2017) has been 4% wetter than 1981-2010, and 11% wetter than 1961-1990. However, there are also natural variations over the long-term record. Future projections of temperature and precipitation from UKCP18 show an overall increase in both temperature and precipitation in the UK. However, these changes vary seasonally, by location and depend on the emission scenarios as can be seen in Figure 3.1. The strongest climate signal can be seen in the 2080s and under the higher emission scenario (RCP8.5).

However, climate modelling comes with uncertainties and limitations. Various studies identify several sources of uncertainty in the processes of assessing climate change impacts on meteorological or hydrological variables: the greenhouse gas emissions scenario, global climate model (GCM), natural climate variability, downscaling method and in some cases hydrological model structure and parameters. The largest source of uncertainty, however, is the selection of the climate model used. Additionally, uncertainty from various sources also varies over time and higher greenhouse gas emission pathways (e.g., RCP8.5) have a higher projection uncertainty compared to medium emission pathway (e.g., RCP4.5) (Shen et al., 2018). To overcome some of these issues, the IPCC recommend the use of an ensemble of emission pathways and climate models. There is relatively little difference between different emissions pathways for the next two or three decades, but after then the increase in risks can be considerably higher with high emissions (Arnell et al., 2021). This has three main policy implications for Scotland (Arnell et al., 2021): First, the effects of measures taken now to reduce emissions will not reduce risks in the next couple of decades: their effects will be seen later and there will be some increase in risk even with very large reductions in emissions. It is therefore necessary to both increase resilience to changing risks and reduce emissions. Second, adaptation and resilience strategies for the near term do not need to be tied to specific assumptions about emissions, but a longer-term perspective does need to consider the effects of emissions policy. Third – and most critically – adaptation and resilience strategies based around 'worst case' scenarios need to consider carefully the 'high' emissions scenarios and the more sensitive climate models.

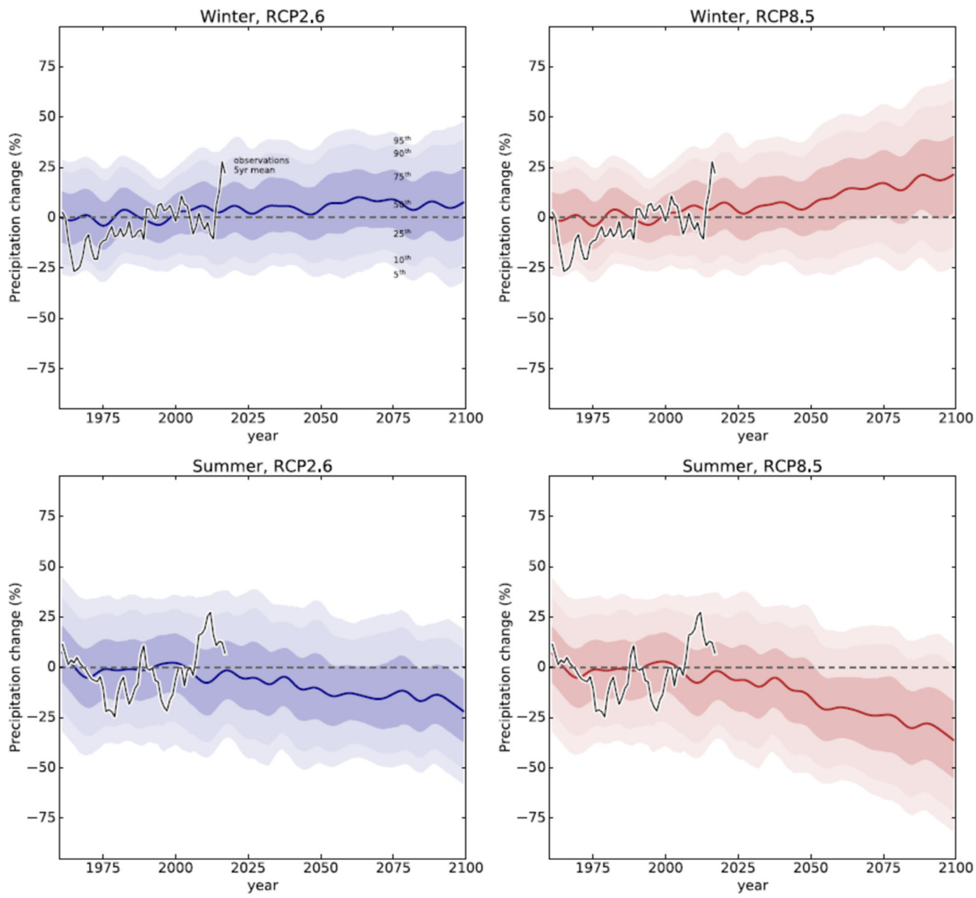


Figure 3.1: Percentage precipitation changes for the lowest emission scenario (RCP2.6, blue) and highest emission scenario (RCP8.5, red). The shading boundaries show the 5th, 10th, 25th, 50th (median, central solid line), 75th, 90th, and 95th percentiles. NCIC observations (https://www.metoffice.gov.uk/climate) are shown as a black line for the historical part of the curves. Values are expressed relative to the 1981-2000 baseline used in UKCP18 projections. Reproduced from Lowe et al. (2019)

4. Results relevant to water resources in Scotland

Scotland has abundant water resources arising from its generally wet climate, but with highly variable spatial and temporal distributions of precipitation comprising a distinct west to east precipitation gradient due to the western uplands' rain shadow influence. Annual and decadal variability in precipitation can be significant: the most recent decade (2009-2018) was on average 7.25% wetter than 1961-1990 (Kendon et al., 2019a). Nonetheless, seasonal deviations from this trend also occur. For example, during the drought of 2018, spring and summer rainfall registered 74% and 83% of the 1981-2010 average respectively (Kendon et al., 2019a), with river flows in the Tweed, Dee, Spey, Deveron and other areas recording less than 40% of the long-term average (CEH, 2018). Met Office precipitation data for 2021, shows that the April-September period in the north and west regions of Scotland was the driest period in 160 years of record (Scottish Water comms).

Scotland is less well served than other parts of the UK in terms of long-term runoff records because river gauging commenced later. Only three Scottish rivers have flow data that extend back to 1930, with the majority of river flow records dating back to the 1960s and 1970s (Werritty, 2002), making long-term trends (generally requiring the standard 30-year period) harder to detect. An important part of Scotland's water resources, especially for private water supplies is groundwater. However, unlike river flows, groundwater bodies are difficult and expensive to monitor, and their records are generally shorter and fewer in number (Ó Dochartaigh et al., 2015). For example, out of approximatively 392 SEPA water level monitor stations, only around 50 are groundwater level sites with varying records of length (SEPA, 2022).

4.1 Observed changes to river flows

Historically, annual mean river flows have increased in the south and west of Scotland in recent decades, especially during the 1970s to mid-1980s as well as an increase in the early 2000s (Harrigan et al., 2018; Werritty, 2002). Since then, during the period of mid-1980s to 2000 mean flows have stabilised in the south and west but have declined in the north and east. Summer flows have generally declined throughout Scotland, but not significantly (Werritty, 2002). There has been a generally sustained increase in the frequency of flood events from the mid-1980s onwards (Werritty, 2002). Outflows increased over the 50-year period 1961-2010 for Scotland, Wales, and Great Britain as a whole, however, only the trend for Scotland is statistically significant over this period (Table 4.1) (Hannaford, 2015).

Table 4.1: Changes in various flow indicators for the total outflow series in Scotland, 1961–2010. Values show the change over the course of the record expressed as a percentage change in the long-term mean. Bold indicates significance at the 95% level (using Mann-Kendall trend test). After Hannaford (2015)

Flow type	Change (%)
Annual runoff	+22.4
Winter	+44.7
Spring	+6.7
Summer	+2.4
Autumn	+16.7
High flows (Q5)	+22.4
Low flows (Q95)	+3.9

Historical climatic changes in river flows are hard to detect in the UK and Scotland because the climate change signal is generally much weaker than background natural decadal climate variability (Harrigan et al., 2018). Additionally, other influences on catchments such as urbanisation, deforestation, dam construction and reservoir operation, and river engineering substantially alter flow regimes thus making trend detection difficult. In a separate study, Gosling (2014) found that gauged flows at Woodend on the River Dee recorded over a long period (1930-2009) showed no clear trend in either winter or summer flows. However, tests on hydrological time series with high natural variability are typically not able to detect weak changes.

Several techniques have been developed to overcome this problem, including using a benchmark river flow dataset which uses 'near-natural' catchments with long and good quality flow records. The Mann-Kendall test is commonly used to detect trends and statistical significance in long time trends in river flows covering the full flow regime (annual low flow: Q95; annual medium flow: Q50, annual mean flow; annual high flow: Q5; seasonal mean flows) for short periods of 30 years (1985-2014) and longer periods of 50 years (1965-2014) (Harrigan et al., 2018). Using this method, for the short period (1985-2014) annual low, medium and high flows show an increase in most locations in Scotland, although few examples are statistically significant. However, spring mean flows show a significant decrease (magnitude ranging from -10% to -50%) and winter mean flows show an increase of +14.3% (ranging from +5.5% to +25.1%) across the UK (Harrigan et al., 2018). For the longer period (1965-2014), similarly, there is an increase in medium flows (Q50, annual mean flow) and high flows (Q5) in most catchments in Scotland. For low flows (Q95), there is a geographical difference between an increasing trend in the northwest and a decreasing trend in the southeast (Harrigan et al., 2018). These changes can be observed in Figure 4.1

Seasonally (Figure 4.2), in Scotland over the period 1965-2014, there is an increase in mean flows in winter, autumn and summer, with the winter increases being statistically significant. In spring, a trend for decreases in the east and increases in the west is detected, although none are statistically significant.

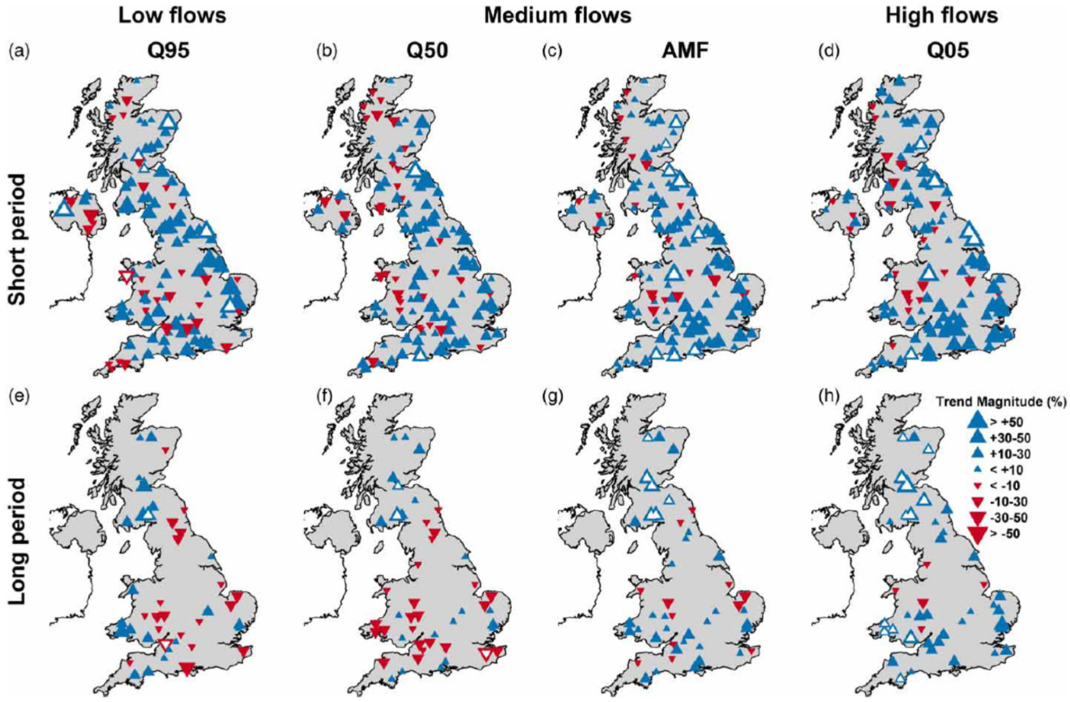


Figure 4.1: Magnitude and direction of trends for the short fixed period (1985–2014) (top row) and long fixed period (1965–2014) (bottom row) for selected low, medium, and high flow indices. Upward-pointing triangles represent increasing trends and downward-pointing decreasing trends, with magnitude proportional to size. Block-bootstrapped significant trends (5% level) shown by white triangles. AMF represents annual mean flow. Reproduced from Harrigan et al. (2018)

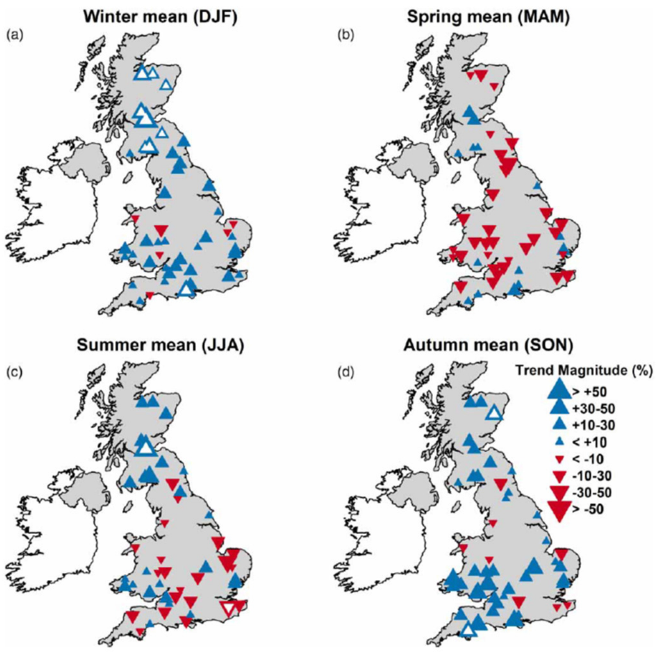


Figure 4.2: Magnitude and direction of trends for the long fixed period (1965–2014) for seasonal mean flow indices. Upward-pointing triangles represent increasing trends and downward-pointing decreasing trends, with magnitude proportional to size. Block-bootstrapped significant trends (5% level) shown by white triangles. Reproduced from Harrigan et al. (2018)

4.2 Future changes to river flows

Future projections of water resources in the UK (detailed in Section 3) generally show seasonal reductions in spring and summer flows, a mixed pattern in autumn flows, and small increases in winter flows, varying with ± 20% (Prudhomme et al., 2012). However, future projections of annual flows are not expected to change significantly across the country (Watts et al., 2015). Annual runoff for four Scottish catchments (Don, Almond, Lyne Water and Nith) is predicted to increase by 8.9-11.6%, while the predicted increase for the whole of Scotland for the 2050s is 5-15%, but this could locally exceed 27% (Werritty, 2002). These changes are, spatially and temporarily variable, with some areas seeing a flow reduction, especially in eastern and southern Scotland. Additionally, a geographical split between the east and west of Scotland (and the UK generally) is apparent (Werritty, 2002). It should also be noted that this study is now ~20 years old, so these results should be treated with caution.

More recent studies indicate western UK areas are projected to experience an increase in winter flows (Christierson et al., 2012, HR Wallingford 2020), whereas for the remainder of the UK, HR Wallingford (2020) indicates that generally the Q95 flows will see 0-20% reductions in flow. Seasonal future flow changes in Scotland, however, vary, both spatially and by study. Winter flows are likely to be more variable in the future but without a clear consensus (Prudhomme et al., 2012; Watts et al., 2015). Spring flows show an overall decrease (Kay, 2021), with more pronounced summer flow decreases (Kay, 2021). Future autumn flows are mixed (Kay, 2021). In the most significant scenarios, basins such as the Tweed could be affected by 30% flow reduction (HR Wallingford, 2020). A summary of these changes for the UK, including Scotland where possible, can be found in Table 4.2. A graphical summary can be found in Table A.1.

Kay et al. (2021) measured the possible changes in low and high flows in Great Britain using the UKCP18 climate projections – the only known study in the UK to do so – and the RCP8.5 emission scenario into the future (30-year time slices up to December 2100). In the future, high flows (both 5- and 20-year return-periods) typically show an increase across Great Britain, while low flows (both 5- and 20-year return periods) mostly display a decrease, with some clusters in the north Scottish regions indicating no change.

4.3 The influence of droughts and floods

4.3.1 Drought in Scotland

Drought is a complex phenomenon with significant impacts. In Scotland, the overall losses to agriculture from the 2018 drought, coupled with heavy snowfall in winter 2017/18, were estimated to be £161 million (Visser-Quinn et al., 2021). Drought can be defined in several ways using a variety of indices and metrics, including:

- **Meteorological drought** – a prolonged period of precipitation deficit compared to a long-term average, possibly combined with increased potential evapotranspiration, extending over a large area, and spanning an extensive period
- **Agricultural drought (soil moisture drought)** – a deficit of soil moisture, reducing the supply of moisture to vegetation, often precedes hydrological drought
- **Hydrological drought** – this is a broad term that refers to surface water and/or river flow deficits compared to long-term averages, which are usually out of phase with the occurrence of meteorological and soil moisture droughts as it takes longer for precipitation deficits to become evident in streamflow, groundwater and reservoir levels
- **Socio-economic drought** – this is the least understood and studied type of drought, associated with the above-mentioned droughts and occurs when water demand is not met

The identification of hydrological drought may be the best metric for measuring risks to water resources, however, meteorological drought may also be a key indicator since reduced precipitation is a key driver of hydrological drought (Brown et al., 2011; Gosling, 2014). A wide range of indices and thresholds are used to define drought. While indices can help measure regional anomalies in a standardised way, they generally require an appropriate statistical distribution to be identified. Threshold methods, in comparison, do not require fitting a distribution to the data. However, there is no standard definition of the threshold level, which makes regional comparison difficult. Whereas indices such as the Standardized Precipitation Index (SPI), the Standardized Precipitation Evaporation Index (SPEI), normalised precipitation index (NPI), available water capacity (AWC) or potential soil moisture deficit (PSMD) can be used to estimate meteorological drought, the focus of this study is explicitly on water resources that are more directly linked to hydrological drought. To this end, studies that focus on hydrological drought are more directly linked to water resource scarcity, but meteorological drought can play an important role in the propagation of hydrological drought, thus they are also discussed here.

While most peer-reviewed publications (e.g., Brown et al., 2011; Collet et al., 2018; Gosling, 2014; Kirkpatrick Baird et al., 2021; McGrane et al., 2018; Rudd et al., 2019; Sample et al., 2015; Visser-Quinn et al., 2021; Werritty, 2002) suggest a future trend towards warmer and drier summers, and warmer, wetter winters in Scotland, the

Table 4.2: Summary of projected future flows. A graphical summary can be found in Appendix A in Table A.1. Details of climate change modelling and scenarios can be found in Section 3

Flow type	Study region	Future projected changes	Timeline	Baseline	Climate model	Reference
Annual	Scotland	Annual runoff for four Scottish catchments (Braemar, Edinburgh, Stornoway, and Dumfries) is projected to increase between +8.9% to +11.6%, with the range +5% to +15%, locally exceeding 27%	2050s	1970-1996	UKCP09, A1B emission scenario	Werritty (2002)
Annual	UK	Limited UK spatial consistency across projections of mean annual flow with most catchments exhibiting changes with a non-null probability ranging from – 10% to +10%	2020s (2011-2040)	1960-1991	(1) UKCP09, A1B emission scenario (2) the UKWIR06 projections derived for the national-scale assessment of water resources	Christierson et al. (2012)
Winter	GB	Winter flows in Scotland shows limited future changes but with increased variability, although this is generally within 20%, but with changes in the east of Scotland reaching up to +40%	2040-2069	1961-1990	UKCP09, A1B emission scenario	Prudhomme et al. (2012)
Winter	GB	Seasonal mean flow changes across GB show increases in the north and west including Scotland (GB median change +9%, range –42% to +51% for 2050-2080)	2020-2050 2050-2080	1980-2010	UKCP18, RCP8.5 emission scenario	Kay (2021)
Winter	UK	Central estimates (50th percent quartile) show a small increase in flows (from November to March) in the near-term (2020s) over western parts of the UK, including Scotland	2020s (2011-2040)	1960-1991	(1) UKCP09, A1B emission scenario (2) the UKWIR06 projections derived for the national-scale assessment of water resources	Christierson et al. (2012)
Spring	GB	Decreases of up to 40% in spring flows across GB	2040-2069	1961-1990	UKCP09, A1B emission scenario	Prudhomme et al. (2012)
Spring	GB	Changes in flows are typically generally negative across Scotland but with some small positive increases in the west by 2050-2080 (median –6%, range –29% to +15%).	2020-2050 2050-2080	1980-2010	UKCP18, RCP8.5 emission scenario	Kay (2021)
Summer	GB	Scenarios predominantly show decreases in runoff across GB but range from +20% to -80% for 2040-2069; 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%)	2040-2069	1961-1990	UKCP09, A1B emission scenario	Prudhomme et al. (2012)
Summer	GB	Summer flows show large decreases across GB by 2050-2080 (GB median –45%, range –66% to –5%)	2020-2050 2050-2080	1980-2010	UKCP18, RCP8.5 emission scenario	Kay (2021)
Summer	UK	Central estimates (50th percent quartile) show a marked seasonal cycle, with large notable reductions in summer flows; all catchments show a decrease in river flows all year round, except for the western part of the UK.	2020s (2011-2040)	1960-1991	(1) UKCP09, A1B emission scenario (2) the UKWIR06 projections derived for the national-scale assessment of water resources.	Christierson et al. (2012)
Autumn	GB	Changes in autumn flows are mixed across GB, but mostly negative indicating decreases in flows, notably in south and east GB (median –29%, range –59% to +22%)	2040-2069	1961-1990	UKCP09, A1B emission scenario	Prudhomme et al. (2012)
Autumn	GB	Mixed patterns across GB, but mostly indicating decreases in flows, notably in south and east GB (median –29%, range –59% to +22%)	2020-2050 2050-2080	1980-2010	UKCP18, RCP8.5 emission scenario	Kay (2021)

methodologies used and therefore the results of these studies differ somewhat, presenting a complex picture. Depending on the indices, thresholds, climate models and future climate scenarios used, their findings are varied. For example, Kirkpatrick Baird et al. (2021) suggest an increase in extreme meteorological drought frequency across Scotland in the near-future (2021-2040) throughout the year, indicating that while the west coast may become wetter, both western and eastern areas of Scotland are also likely to suffer from periods of water scarcity. The largest increases in drought duration are projected to be in autumn, while spring shows limited change. However, Kirkpatrick Baird et al. (2021) used a high emission scenario (RCP8.5) and UKCP18 regional projection for the 2030s indicating a worst-case scenario future. The results from this study are similar to Collet et al. (2018) which used a threshold method to define drought, showing a modest increase of both drought and flood hotspots in a few locations in Scotland during autumn in the 2080s. However, Collet et al. (2018) also determine that while floods are concentrated in the winter months, droughts are more spread out across the year, indicating a greater heterogeneity. Nevertheless, this differs to Gosling (2014) and Visser-Quinn et al. (2021) that show a future increase in summer and spring droughts in Scotland in the near-future. Visser-Quinn et al. (2021), however, used the same RCP8.5 high emission scenario as Kirkpatrick Baird et al. (2021), highlighting the importance of comparing the methods and models used. Another aspect that leads to differing results is the indices used. Brown et al. (2011) calculated future changes in drought from an agricultural land perspective (LCA classification) in Scotland using the AWC, PSMD, and other indices to measure the changes in agricultural drought frequency and the changes to prime agricultural land in the 2050s. Brown et al. (2011) used UKCP09 climate projections with the HadRM3 regional climate model under a medium emission scenario. While this study used indices focused mostly on agricultural drought, the results show that while more land may become available for agricultural purposes in the future in Scotland, such an area of land may require irrigation, adding additional pressures to water resource availability. The PSMD index suggests a trend towards drier summers in Scotland in the 2050s. These results may indicate a future stressor on water resources that may lead to socio-economic droughts. In addition, agricultural abstractions are primarily located in the east of Scotland where rainfall is lower, potentially adding to the pressures to water supplies.

Similar to Collet et al. (2018), Visser-Quinn et al. (2021) analysed possible drought 'hotspots' for water scarcity in Scotland considering water abstractions in the near future (2020-2049). They considered drought event frequency and duration, where a drought event is defined as an event where flow falls below Q95 for more than 30 days. While the methodology used estimates hydrological drought, the defined threshold method cannot be compared to other studies which used standardised meteorological drought indices. Visser-Quinn et al. (2021) used two climate ensembles: the multi-model ensemble (MME) from the EDgE project (5 km grid) and the Perturbed parameter ensemble (PPE) from the MaRIUS project (25 km grid) to reduce climate model uncertainty (see Section 5). This study also used multiple scenarios, including a scenario that considers both climate change and (aggregated) abstractions (agriculture, aquaculture, hydropower and whisky), and a scenario that includes both consumptive and non-consumptive usage, driven by RCP8.5. Across Scotland, Visser-Quinn et al. (2021) show that in the near future (2020-2049), there may be up to 11 distinct hotspots of drought and abstraction pressure, with rivers Spey and Tay being drought hotspots. Additionally, these results indicate a greater prevalence of summer drought, particularly when assessed as hydrological drought using an index based on flow anomalies. This contrasts with the findings of HR Wallingford (2020) that identifies the Spey and Tay catchments as having notable high natural water resource availability. Looking across the studies, it is likely that there will be significant local variability across the catchments in terms of available water resources and prevalence drought conditions.

Rudd et al. (2019) investigated the potential future changes in river flow and soil moisture droughts across Great Britain using UKCP09 climate projection and the HadRM3 regional climate model. They consider a business-as-usual emission scenario, with projections for the near (2020-2049) and far future (2070-2099). However, the threshold used was derived using an observation-driven G2G (Grid 2 Grid) hydrological run. Additionally, this study did not take into account adaptation to climate change and additional water abstraction pressures from population growth or land-use change. The results suggest that the areas of Great Britain currently most susceptible for both river flow and soil moisture droughts are projected to increase in surface into the future. Northern and western areas, which are water abundant, may increasingly be affected by droughts. While moderate-threshold river flow droughts have occurred historically in October to December in Great Britain, in the future projections, there is a clear shift towards droughts occurring from August to December across GB. Additionally, major-threshold river flow droughts, which previously peaked in late winter and early spring are projected to peak in November and December in the future in Britain. These results contrast with Visser-Quinn et al. (2021) who suggest droughts are likely to increase in summer in the near future, and with Collet et al. (2018) who indicate drought prevalence is heterogenous and may spread throughout the year in the future.

In an earlier study, Gosling (2014) used two indices to measure future changes in drought for a medium-term future (2041-2070) in Scotland: the normalised precipitation index (NPI) (1-month and 3-month) and the normalised flow index (NFI) (1-month and 3-month). This study uses the UKCP09 climate projections and the HadRM3-PPE regional climate model. While no distinction is made in terms of the seasonality of the precipitation anomaly, future drought frequency is largely unchanged in most areas under climate change scenarios for the 2050s in Scotland. These results can be explained by the fact that there is little overall projected change in mean annual precipitation projected in Scotland for the 2050s (Gosling, 2014). The intricacies of low summer rainfall and its connection to drought in Scotland, however, requires further research, including drivers, modelling for propagation, severity and recovery, and what constitutes a 'normal' baselevel from which to measure the context of climate change (Rivington et al., 2020). Where a distinction is made between seasons, an increase in the frequency of spring and summer droughts is evident at many parts of Scotland, whereas marked decreases in 1-month precipitation deficit frequency are likely to occur in autumn and winter in the 2050s. The pattern of higher summer and lower winter drought frequency mirrors the general picture of wetter winters and drier summers projected for Scotland by UKCP09. This pattern is relevant to locations where water storage is sufficient to allow any projected enhanced precipitation in one season to offset reductions in another.

Kirkpatrick Baird et al. (2021) and Vidal and Wade (2008) both used a similar index to measure changes in drought in the future although different inputs, baselines, climate models and future time slices were used. Crucially, these findings highlight the uncertainties that occur in climate modelling. The results from Kirkpatrick Baird et al. (2021) indicate that while the west coast will likely remain wetter than the east, both areas are likely to experience increases in droughts, with different implications for different areas based on habitat types and land use. For public water supplies, these implications are dependent on their resilience in the system (for example, the existence of storage reservoirs or water transfer between systems). However, while drought increases along the west coast are less substantial in scale, there is still potential for negative impacts on important ecosystems in these regions. Kirkpatrick Baird et al. (2021) used the UKCP18 climate projections with a high emission scenario (RCP8.5) to detect changes in drought in the near future (2021-2040), based on the SPEI index on a 6-month time step. Observed extreme drought during a baseline (1981-2001) period was relatively low, with a maximum number of 4 extreme droughts per grid cell (12km x 12km) in Scotland and a maximum duration of seven months of extreme drought per cell throughout the period. The median observed (1981-2001) return frequency of extreme drought events across all grid cells was one event every 20 years, up to one every 5 years in the driest areas (e.g., western Scotland). In contrast, in the future projections (2021-2040), the median return frequency of drought is projected to be one every 3 years, and up to one every 1.7 years in the driest areas. Increases are likely across Scotland, with every grid cell showing an increase from the number of events modelled in the near future. Smaller increases are projected along the Western Isles, with the highest increases concentrated in Shetland, Orkney, Caithness, Aberdeenshire, and the Borders. Additionally, dividing drought duration into seasons highlights the seasonality of drought occurrence. For example, the largest increases in drought duration for 2021-2040 is likely to be in autumn, with increases of up to 9.5 months in Aberdeenshire. This contrasts with spring, in which increases are projected to peak at 5.5 months. Spring also shows the greatest number of locations with no change.

Vidal and Wade (2008) used the SPI index on 3-, 6-, 12-, and 24-month time steps and six climate models to assess future characteristics of meteorological droughts across the UK for the 2020s, 2050s, 2080s. Two catchments are analysed in detail including Lochalsh in the western Highlands. The results for the Lochalsh catchment show a future decrease in drought frequency in nearly all cases in the 2080s, with the notable exception of the increase of 3- and 6-month low-frequency droughts under the A2 emission scenario. Results for the Lochalsh catchment also show a small upward trend in 3-month drought frequency, but the frequency of 12- and 24-month extreme droughts appears to decrease similar to moderate and severe droughts. In general, this study finds no increase in the 6-month extreme drought frequency, magnitude, or severity in Scotland, unlike Kirkpatrick Baird et al. (2021). Even though both studies used similar indices to measure plausible changes in drought frequency, magnitude/severity, and duration, their results differ. This is likely due to the differences in climate models used, emission scenarios considered and the slight difference in indices. Because SPEI considers evapotranspiration, it is more sensitive to changes in drought, therefore, unlike the SPI, the SPEI captures the main impact of increased temperatures on water demand.

Snow melt significantly contributes to streamflows in many Scottish catchments (Gosling et al., 2002). Therefore, reduced winter snowfall and cover from milder, wetter conditions could increase water scarcity risks from diminishing streamflow and groundwater recharge (Bell et al., 2016). This is more important for upland catchments rather than low elevation areas that are not predominately governed by snowmelt processes; however, low-flow effects can be felt in lowland rivers with the combination of rising temperatures and declining precipitation in warmer months (Capell et al., 2014).

4.3.2 Floods in Scotland

There are multiple ways to define a flood, but most studies describe it as a ‘flow exceedance’, usually such as a flow higher than the one expected on average once every 100 years ($Q_{1\%}$) or once in 10 years ($Q_{10\%}$) (Arnell et al., 2021; Collet et al., 2018). Additionally, floods are not always disruptive: depending on the area that is flooded, the damage can be minimal and sometimes floods can also have positive effects (such as making the soil more fertile and providing nutrients where it is deficient). There are six main types of flooding:

- **Riverine (fluvial) flooding** – river flooding (also known as fluvial flooding) is where a river’s flow exceeds riverbanks and/or defences to cause inundation, damage or obstruction to the surrounding area
- **Coastal inundation** – affects communities and environments situated along the coastal fringe or along estuaries and tidal rivers, with water topping coastal defences, which can cause significant damage. Sea level rise also presents increased risk of saline intrusion into surface and groundwater resources
- **Surface water (pluvial) flooding** – occurs after periods of intense or prolonged heavy rainfall where excess water cannot drain away, most notably in urban areas
- **Flash flooding** – is typically unexpected or sudden flooding, caused by intense rainfall and runoff, often caused by rainfalls on saturated or parched soils
- **Groundwater flooding** – occurs when the water table rises through a slope and exceeds the ground level
- **Sewer flooding** – usually caused by a blocked combined sewage pipe(s)
- **Reservoir spilling** – causes very fast flowing water to flow down the natural water channel in large quantities; however, this is very rare in the UK due to strict reservoir operations regulations

The most relevant types of flooding for water resource management in the UK are riverine flooding and reservoir spilling. There have been several notable floods in the UK in recent years, with the UK Government estimating that annual flooding costs the economy approximatively £1.1bn each year (Beevers et al., 2020). This cost is expected to increase by up to 50% in a 2°C world, 150% in a 4°C world and 600% in an extremely low probability, high impact future scenario (Sayers et al., 2016). However, while historical records show an increase in extreme precipitation in the past 50-60 years across the UK (Collet et al., 2018), including an increase in river flows across western Britain, no significant trends have been detected in observed flood magnitude (Collet et al., 2018).

Similar to drought studies (discussed above), projections of future floods have typically used a variety of methodologies and definitions, leading to differing results. However, in general, future flood projections mostly agree that the frequency of floods may increase in Scotland by the 2050s despite the different methodologies, indexes, baselines, and timelines used (Arnell et al., 2021; Collet et al., 2018; Werritty, 2002). For example, Collet et al. (2018) measure the future hydro-hazard hotspots in Great Britain based on the changes in flood (and drought) characteristics (frequency, magnitude, duration, and time of the year) for the 2080s. The study used daily flows from the Future Flows Hydro (FFH) database as inputs and UKCP09 using the HadRM3 regional model, and the A1B medium emission scenario. The results indicate an increase of one up to two flood events per year on average by the 2080s. This includes an increase in flood magnitude (most locations in Great Britain increasing by 5-20%) and an increase in flood duration (by one to five days per year in the future). Floods are mostly projected to occur in winter (December or January) in Great Britain, while in Scotland, there are a few hotspots that show an increase in both flood and drought occurrences in autumn (see Figure 8 in Collet et al. (2018) for further information). Additionally, the western part of the Great Britain shows an increase in flood hazards in the 2080s compared to the baseline. These results are similar to Speight and Krupska (2021) who suggest the chance of riverine flooding due to climate change in western Scotland may increase by up to 40% by 2100.

Using the same threshold method as Collet et al. (2018), an earlier study by Werritty (2002) used different future time slices (30-year periods centred on the 2020s, 2050s and 2080s), an older climate model and a medium-high emission scenario. Despite the differing models and time periods, the results are broadly similar to the more recent Collet et al. (2018) with an increased future frequency of riverine floods in Scotland by the 2050s.

In contrast, a recent study by Arnell et al. (2021) project flood magnitude changes for the long-term future (2071-2100) using CMIP5 and three emission scenarios (RCP2.6, RCP6.0, and RCP8.5). Their results indicate that the biggest increases in river flood risk are in the north and west of the UK. The indicator used was the likelihood of experiencing a flood greater than the reference period 10-year flood. However, most communities and infrastructure are protected to a higher level, so this is more a measure for the occurrence of flood events rather than the occurrence of flood loss. Nonetheless, the proportional change in likelihood of the 10-year event is a good approximation to the change in likelihood of damaging events.

Winter flows in Scotland may increase due to more precipitation falling as rain, increasing the risk from flooding as soils become saturated and rivers burst banks, especially if rain falls on existing snow, such as the 1993 flooding event in Perth (Capell et al., 2014; Gosling et al.,

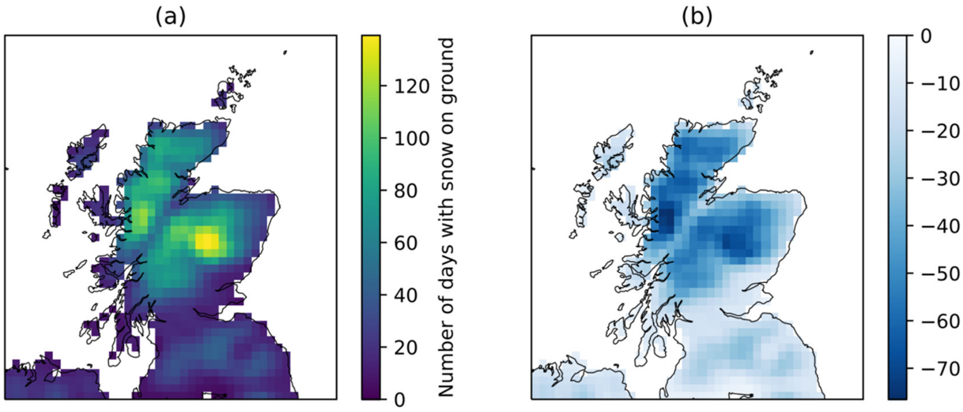


Figure 4.3: Number of days with snow on the ground (a) for the baseline period (1981-2010), and (b) as a relative change in the future (2031-2060) using UKCP18 projections under the RCP8.5 emission scenario. Reproduced from Simmonds et al. (2022)

2002). Bell et al. (2016) also assess the possible impacts of climate change on future snow and peak flows considering changes in number of days with lying snow and peak flows using UKCP09 and the HadRM3 regional model under the A1B medium emission scenario. The results indicate a reduction in the number of snow days by 2100 which, for the northern regions of Great Britain, would lead to a tendency for peak river flows to occur earlier in the water year (October/November in the north-west; November/December in the north-east), either because of less snow or earlier snowmelt. In a separate study, by the 2040s, under the RCP8.5 emission scenario, Simmonds et al. (2022) find that most areas of Scotland, especially the north-west are projected to have significantly fewer days with lying snow (Figure 4.3).

4.3.3 Summary of flood and drought hotspots in Scotland

A summary of combined future flood and drought hotspots across Great Britain from Collet et al. (2018) is presented in Figure 4.4. By the 2080s, droughts are projected to increase in magnitude up to 100% to 150% in Scotland, while floods changes in magnitude are of the order of 20% to 50%. Although there is uncertainty regarding future frequency, duration and magnitude of both droughts and floods because of the different methodologies and indices used (e.g., SPI (Kirkpatrick Baird et al., 2021; Vidal and Wade, 2008), different thresholds for drought and flood and different types of hazards analysed (e.g., meteorological drought

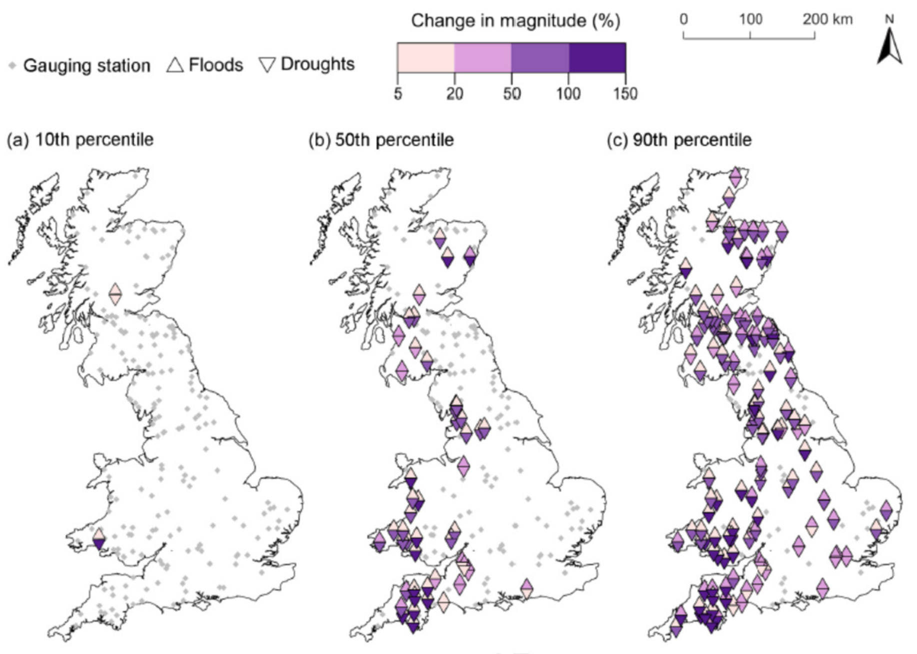


Figure 4.4: Changes in magnitude of the hydro-hazards for the hot-spots in Great Britain for the (a) 10th, (b) 50th, and (c) 90th percentiles by the 2080s. Reproduced from Collet et al. (2018)

(Kirkpatrick Baird et al., 2021; Visser-Quinn et al., 2021) or hydrological drought (Gosling, 2014), and indeed their timing and spatial extent, there is a general consensus relating to an increase across all metrics across Scotland in a warming climate. The future occurrence of these hazards alongside other change may adversely affect drinking water availability, irrigation demand and hydropower production.

4.4 Future changes to water resources

According to the Third UK Climate Change Risk Assessment (Climate Change Committee, 2021), Scotland is likely to maintain a surplus between supply and demand. Catchments in western Scotland, however, where the reductions in low flows tend to be the largest, are at risk of not meeting the volume of environmental flow in the late century in a 4°C world. However, under a high population growth and no additional adaptation measures scenario, deficits could also occur across Scotland by 2100 (HR Wallingford, 2020). A solution to the decreased summer flows, which would likely occur in the eastern parts of Scotland by the 2050s, could be water transfer between the water abundant western and northern regions of the country to the east. However, the infrastructure required would most likely be cost prohibitive. Scottish Water is continuing to review and updating its supply demand resilience through water resource planning.

While flows may increase during the autumn and/or winter seasons in the 2050s, irrigation demand, especially in summer, may also rise due to an increase in temperatures alongside an increase in potential evapotranspiration (PET) (Brown et al., 2011; Christierson et al., 2012). Additionally, reductions in water supply due to an increase in soil moisture deficit could lead to additional pressures from the increased water demand due to agricultural expansion and intensification (Brown et al., 2011). While the risk in Scotland is lower than for the rest of the UK, the impact could be significant, especially if sub-surface and surface abstractions were not regulated (Werritty, 2002). However, since 2011, water abstractions, are now regulated under Water Environment (Controlled Activities) (Scotland) by SEPA, who can also temporarily suspend abstractions for certain sectors during prolonged periods of water scarcity (SEPA, 2020). Given the significance of groundwater resources for private water supply (73% of supply), and limited public supply, impact on sub-surface abstraction from climate change cannot be ignored (see Section 4.5).

Environmental flows (Q95) are, in general, projected to decrease by between 0 and 20% by 2050s across Scotland in line with a 2°C increase in temperature (HR Wallingford, 2020). The exception to this is the western Highlands where flows are projected to increase. However, in a scenario of a 4°C future world, Q95 flows are expected to decrease throughout the UK with decreases up to 50% (Figure 4.5) (HR Wallingford, 2020).

Changes in flows could also affect hydropower production, especially run of river (ROR) schemes (e.g., Williams et al., 2022) that lack the storage capacity to buffer seasonal changes. For example, in the summer months, capacity could decrease by 15-40% by the 2050s in Scotland due to lack of precipitation and lower flows (Sample et al., 2015). In the winter months, flows are projected to increase in Scotland by mid-century (Kay, 2021); however, the installed turbines may not be able to take advantage of the higher flows (Sample et al., 2015).

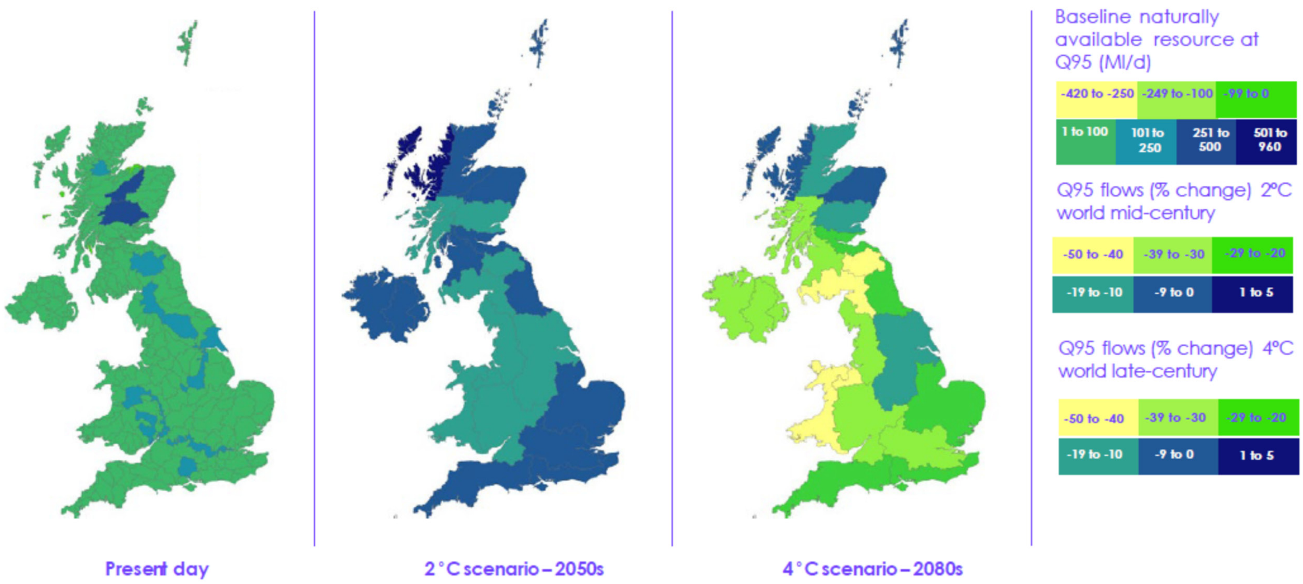


Figure 4.5: Maps of changes in low flows (Q95 indicator) for the present day, and then % change in the 2050s (2°C scenario- approx. RCP2.6) and 2080s (4°C scenario- approx. RCP8.5). Reproduced from Climate Change Committee (2021)

Even if the flows remain largely unchanged annually, seasonal variation may mean a lower energy output from hydropower installations that lack storage (Sample et al., 2015). However, in the UK (and in Scotland in particular), the gross hydropower potential is likely to increase by 7% by the 2070s (Lehner et al., 2005). ROR schemes could take advantage of this potential increase in winter flows if they are designed for higher winter flows.

4.5 Groundwater resources

The volume of groundwater in Scotland is larger than that of rivers and lochs combined (Ó Dochartaigh et al., 2015). It forms a major component (73%) of private water supplies (Rivington et al., 2020), providing drinking water to many rural areas. It is also of key importance to the bottled water, whisky and brewing industries, as well as agricultural and recreational (including golf courses) irrigation. Groundwater provides important environmental functions, supplying at least 30% of river flows and maintaining numerous ecosystems. Groundwater use in Scotland is estimated at 720 Ml/day (Ó Dochartaigh et al., 2015). This is small in contrast to the total volume of licensed abstractions for agriculture, aquaculture, hydropower, and whisky industries from river channels, which is estimated to be 129,120 Ml/day per day (Visser-Quinn et al., 2021).

Globally, groundwater resources are expected to be less affected than rivers and lakes by climate change, and it is understood that they may be used as adaptation measures against increasingly variable rainfall patterns (Howard et al., 2016). Nonetheless, reduced snowfall might affect the groundwater recharge in some areas, which can have an impact on water resources. Additionally, private water supplies in Scotland that extract from shallow aquifers are likely to be increasingly impacted by changes in rainfall variability, such as the 2018 drought (Holdsworth, 2019; Rivington et al., 2020).

The impact of climate change on aquifers is highly dependent on aquifer characteristics and should be assessed accordingly. However, in general, published research in this area is lacking. While there is a significant body of research around groundwater *quality*, there is a dearth of research towards groundwater *quantity* and the effects of climate change on groundwater availability.

5. Other factors influencing water resources in Scotland

While drought is the most studied hazard in connection to water resources, both in Scotland and internationally, other hazards and drivers of change are less explored in this context. In this section, we review emerging areas of research, including event sequencing (e.g., wet to dry, or consecutive dry periods) as well as the influence of other hazards on future changes to water resources in the Scottish context.

5.1 Multi-hazards and compound events

Combinations of multiple hazards is an emerging area of global research. Although natural hazards are typically considered individually, most are caused by a combination of contributing and interacting weather-related and physical processes, such as flooding initiated by successive rainfall episodes (e.g., Bokwa, 2013). While our knowledge of individual hazards has improved greatly in recent decades; the understanding of the processes and mechanisms of multiple, interacting hazards, especially those spanning many temporal and spatial scales, is in its infancy.

Temporal and spatial combinations of events – referred to as compound events – have been the cause of (or have contributed to) many natural disasters, such as the record-breaking wildfire outbreaks, drought and heatwaves that were observed in the USA, Canada and Australia in 2021 (White, 2021; Zscheischler and Fischer, 2020). The terms 'compound event' and 'multi-hazard' are near synonymous, defined as simultaneous, cascading, and cumulative hazards, with Zscheischler et al. (2020) asserting that compound events are those comprised of a mixture of processes, climate drivers and hazards and impacts across spatial and temporal scales.

Specifically, the International Panel on Climate Change (IPCC, 2021) defines compound events as:

"Two or more extreme events occurring simultaneously or successively, combinations of events that are not extreme in themselves but lead to an extreme event or impact of the events when combined, or combinations of extreme events with underlying conditions that amplify the impact of the events".

Obtaining a better understanding of compound events in Scotland may allow for potential risks to water resources, typically overlooked in individual hazard analyses, to be assessed (Zscheischler et al., 2020). For example, rapid change from dry to wet (and vice versa) conditions is encompassed by the phrase 'weather whiplash' (Parry, 2021) or the 'drought-pluvial seesaw' (He and Sheffield, 2020). The wet conditions associated with drought terminations often culminate in high flow and flooding events, therefore making it an important hazard to consider, especially in a warming climate (Parry et al., 2016; Visser-Quinn et al., 2019). While droughts and floods can have clearly identified adverse effects on water resources, a sequencing of dry and wet periods (or indeed, the sequencing of several dry periods) can have even more negative impacts (Wang et al., 2018).

In the UK and Scotland, compound events are a relatively new phenomenon, and have not been studied extensively. Of the studies that exist, Visser-Quinn et al. (2019) identified compound hydro-hazards across the UK, including spatially compound, temporally compound and spatio-temporally compound events. They analysed 239 catchments across the UK using daily flow projections to indicate the mean change signal from a baseline (1971-2000) to the far-future (2071-2099) for the frequency, magnitude, and duration metrics. A multi-model ensemble of Global Circulation Models (GCMs) and Hydrological Models (HMs) were used to capture the uncertainty in the modelling process, under the RCP8.5 emission scenario. In their framework, a compound hydro-hazard is the concurrent increase in the mean annual frequency, magnitude and duration of flood and drought events (six metrics). The results show that in Scotland, compound hydro-hotspots are located across eastern Scotland and the Highlands and Islands, including the Loch Ness and River Tay catchments (Figure 5.1). Drought is projected

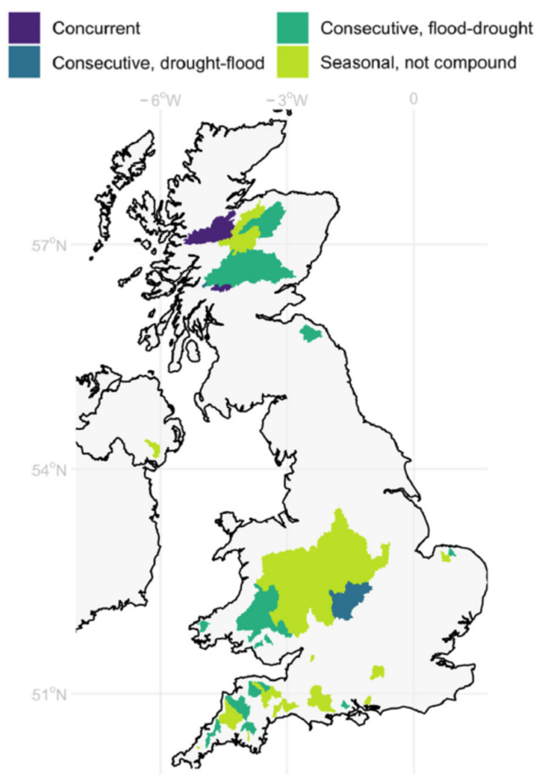


Figure 5.1: Temporal clustering across the compound hydro-hazard hotspots. Reproduced from Visser-Quinn et al. (2019)

to occur in the summer in this hotspot region in the far-future (2071–2099), increasing the pressures there due to the presence of two concurrent hotspots.

In contrast, there are several international studies that research dry to wet changes and their driving factors, although mainly in China (Fang et al., 2019; Huang et al., 2020, 2014; Montaseri et al., 2019; Shan et al., 2018; Shi et al., 2021, 2020; Wang et al., 2018). These studies generally use the SPI to characterise both dry and wet conditions, coupled with trend tests such as Mann-Kendall and/or copula functions to detect trends in hydrological or meteorological time series. Additionally, results from these studies provide some important hints that large-scale climatic drivers may have a major impact on dry to wet sequences. While their impact is limited in Scotland due to its natural climatic variability, these methodologies could be replicated using known drivers of UK weather.

Other indices (e.g., long-cycle drought-flood abrupt transition index, dry to wet abrupt alteration index) could be used alongside the SPI in Scotland to identify dry to wet abrupt alterations. For example, Shi et al. (2021) use the long-cycle drought-flood abrupt transition index (LDFAI) which can be calculated using the standardised precipitation during the months of interest and the drought or flood intensity during those months. The latter is a simple way of calculating the appearance of drought to flood transition. However, the approach has some limitations: firstly, the magnitude of the LDFAI is defined within 4 months, including 2 months for the dry spell and 2 months for the wet spell. Therefore, the turning point from the dry spell to the wet spell is usually fixed at the end of June or the beginning of July. Dry to wet abrupt alterations may occur at *any* time. If the event occurred during the period from May to June, the antecedent precipitation could be considered as normal. This is due to the average effect of the precipitation in the dry and wet spells, which would inevitably lead to the omission of some dry to wet abrupt alteration events. Secondly, the LDFAI only reflects the difference between mean precipitation in the two stages without explicitly considering the alternation duration from a dry spell to a wet spell, therefore not differentiating the two dry-wet abrupt alternation (DWAA) events from identical mean precipitation values during dry-wet spells but with different temporal distributions of precipitation in each spell. To overcome this, Shan et al. (2018) propose an alternate index, dry-wet abrupt alteration index (DWAAI), which uses the standardized precipitation anomalies of the pre-phase and post-phase of an event. DWAAI is an index that represents both the alternation degree and the urgency degree of DWAA events. Specifically, the events with DWAAI values over 15 are defined as DWAA events, and the larger the DWAAI, the more serious the DWAA event. Events with the DWAAI values between 20 and 23 are defined as moderate DWAA events, while those under 20 and over 23 are defined as mild and severe DWAA events, respectively. Moderate and severe DWAA events with DWAAI larger than 20 are considered as high-intensity DWAA events.

Aside from dry to wet sequencing, coupled high temperature and low precipitation events (i.e., concurrent hot and dry events), whose combined effects can surpass the severity of that of the individual component, are increasingly one of the most studied multi-hazard occurrences in the global context (e.g.,Moftakhari and Aghakouchak, 2019; Ridder et al., 2020; Wu et al., 2021; Zscheischler et al., 2021). Higher temperatures are often linked with lower precipitation, a joint occurrence which will be further exacerbated by increasing feedbacks due to anthropogenic climate change, resulting in more extreme hot-dry seasons (Zscheischler and Seneviratne, 2017). A rise in the occurrence of concurrent hot and dry events in Europe is reported to be primarily governed by increasing temperatures attributed to global warming, rather than a lack of precipitation (Manning et al., 2019; Vogel et al., 2021). Heatwaves have increased in frequency and severity globally (Perkins-Kirkpatrick and Lewis, 2020) and in the UK (Hanlon et al., 2021; Sanderson et al., 2017) due to climate change (Sutanto et al., 2020). In Scotland, in the 2040s, compound hot and dry days may increase by up to 400% as it can be seen in Figure 5.2, equating to an increase of approximately 3 to 12 days per year (Simmonds et al., 2022). Studies in Europe (Ionita et al., 2021; Sutanto et al., 2020) have assessed the spatiotemporal variability of compounding low precipitation (including drought) and heatwave events during summer. They estimated that compounding dry and hot events in the summer months (June, July, August) have occurred across Europe, including the UK. Moreover, Ionita et al. (2021) find that the correlation between summer heatwaves co-occurring with dry summer is significant in the UK over the 1950-2020 period and that the decadal frequency of compound dry and hot events has increased in Europe in the last decade. In the future, an increase in concurrent hot and dry events is likely due to their link with the increase in temperature associated with climate change.

The lack of studies evidencing compound hot and dry events in Scotland does not equate to an immunity to multi-hazards. Climate projections indicate increased probabilities of higher temperatures and drier periods in Scotland in the near future (Lowe et al., 2019), which could impact water resources and agriculture. Higher water temperatures may reduce the efficiency of cooling for the whisky industry, with droughts influencing regulations in water use that may prohibit abstractions for other processes (The Independent, 2021; The Whiskey Wash, 2017). Revisiting a notable drought period affecting various locations in Scotland through a multi-hazard lens, such as the 2018 Northern European drought and high temperatures for example, may elucidate the compound nature of the underpinning factors of these types of events. Studies from the UK and Europe, when used in conjunction with weather and climate data for Scotland, may also allow for a multi-hazard understanding of hot and dry compound events to be developed.

5.2 Cascading impacts

Hazards can cascade across space and time, interacting with primary event(s), including complex compound events, to produce unanticipated feedbacks and impacts through complex causal chains (Aghakouchak et al., 2020). This makes modelling cascading impacts challenging. The scales of the associated risks to water resources in the UK from cascading impacts are therefore largely unknown. However, risks are often systemic and can cascade across and between sectors, amplifying the scale and range of impacts, leading to system failures. For example, disruption on one infrastructure network can quickly cascade onto other infrastructure networks (such as water, transport or energy). This can include impacts from single events or from more complex, compound hazards that can prevent the operation of critical infrastructure.

In Scotland, despite the notion of being a 'water rich' nation, recent studies have projected an increase in the frequency (a two or threefold increase) and duration of water scarcity events (Arnell et al., 2021; Gosling, 2014; Visser-Quinn et al., 2021) caused by the impacts of increased summer dry and hot conditions. This is in line with UKCP18 climate change projections that show a spatially varied reductions in total annual precipitation, but with higher summer temperatures resulting in greater evaporative demand and reduced winter snow cover replenishment of streams and groundwater storage in the future (Rivington et al., 2020). The combined effects of dry and hot conditions, especially if observed during prologued periods, can lead to increased evapotranspiration rates and relatively drier soils. This may affect the succession from agricultural to hydrological drought. This will also affect the persistence of drought events as more rainfall will be required to balance soil moisture deficits. Moreover, heat induced increases in evapotranspiration can create a drier overall state and intensify temperature extremes through the reduced evaporative cooling capacity of dry soils (Manning et al., 2019; Mueller and Seneviratne, 2012). More frequent dry and hot events can also precondition the soil and result in multi-year droughts.

Similarly, the 'see-saw' or 'weather whiplash' temporal succession between compound hazards, such as dry to wet conditions or multiple years of low rainfall, can result in significant socio-economic losses (including water resources). This can occur through the exhaustion of recovery resources dealing with the immediate and cascading impacts (De Luca et al., 2020). The cumulative impacts of the dry and wet conditions can surpass those of the individual hazards by the potentially increased vulnerability and exposure to human and environmental systems (He and Sheffield, 2020), thereby challenging long-term resilience. To date, however, there are limited studies in the UK context in this area, highlighting a notable gap in knowledge.

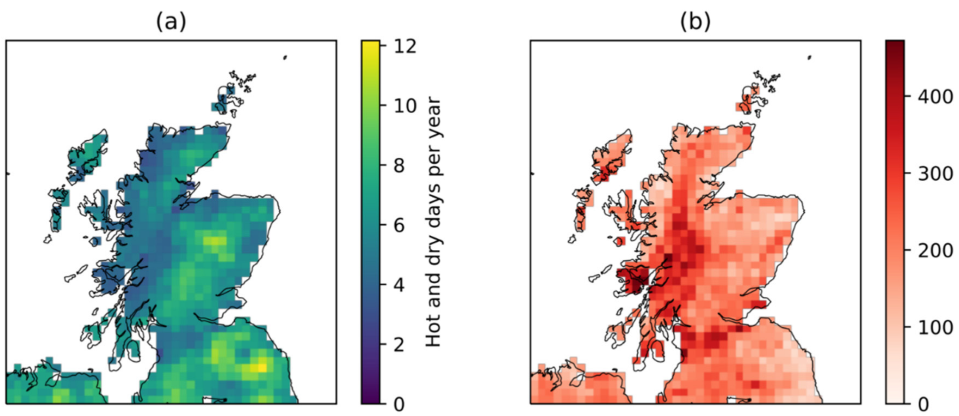


Figure 5.2: (a) Hot and dry days per year averaged over the baseline 1981-2010, (b) Percentage change in hot and dry days per year projected for the near future (2031-2060) using UKCP18 projections under RCP8.5 emission scenario. A hot day is considered a day with mean temperature higher than the 90th percentile during the reference period; a dry day is considered a dry day during a dry month and a dry month has less precipitation than the 10th percentile during the reference period. Reproduced from Simmonds et al. (2022)

6. UK water demand and resource management plans

There are no examples of studies in the peer-reviewed literature relating to water demand and/or customer usage changes due to climate change in the UK. However, there are some publications in the public domain relating to water resource management plans assessing different scenarios which lead to different outcomes in water availability. While not extensive, in this section, we review these publications in the Scottish context.

In Scotland, Scottish Water has no regulatory requirement to produce a water resource plan but does so as best practice, including looking ahead to assess and plan for climate change impacts. These plans include sustainability of the water, meeting the demand for water during periods of dry weather and adaptability to climate change estimates, and ensuring a reliable supply demand balance for a 25 year planning horizon with no long-term supply interruptions (Scottish Water, 2014). The Third UK Climate Change Risk Assessment (HR Wallingford, 2020; Climate Change Committee, 2021) reports that the UK maintains a water demand surplus of approximately 950 Ml/day, although at a regional scale some deficits already exist in water companies baseline plans (National Audit Office, 2020). However, changes in water supply due to climate change alongside changes in demand due to population growth may lead to water deficits in the future (HR Wallingford, 2020). By the 2050s, across all population growth and adaptation scenarios, projections for future supply-demand balances range from – 2,740 Ml/day to +4,620 Ml/day, with between 200-470 Ml/day of impact attributed to climate change under the 2°C and 4°C world scenarios, with the largest reductions likely to be in England (HR Wallingford, 2020). However, under a central population growth and demand-side adaptation scenario, in a 2°C and 4°C future world, all UK regions (except for Water Resources South East in a 4°C world) are projected to have a supply-demand surplus of 1,860 Ml/day to 2120 Ml/day (HR Wallingford, 2020). By 2100, projections for future UK supply-demand balances range from a deficit of 5,570 Ml/day to a surplus of 3,200 Ml/day, with approx. 210-1,890 Ml/day attributed to climate change (2°C and 4°C world). Wales, Northern Ireland, and Scotland all maintain a surplus under these scenarios, however, across the UK as a whole, it is insufficient to compensate for the deficits in England. Additionally, Scotland, Wales and Northern Ireland may see a deficit in water availability under a high population growth and no demand-side adaptation (Figure 6.1).

These findings highlight that demand-side adaptation actions alone are unlikely to be sufficient to tackle the water deficits across the UK and that future adaptation programmes are likely to require a combination of demand-side measures, supply-side measures, and potentially some water transfers. These challenges are highlighted by the UK Water Industry Research (UKWIR) in the 12 'big questions' (HR Wallingford, 2020). These help to define a strategic research programme to address the key challenges facing the water sector, now and in the future, including 'BQ3: How do we achieve zero interruptions to water supplies by 2050?'.

In England, water supply resilience will be increased to withstand a 1 in 500- year drought event that will have implications for the next round of water company plans that are due in 2024 (Climate Change Committee, 2021). In England and Wales, regional plans inform water companies' Water Resources Management Plans (Environment Agency, 2020).

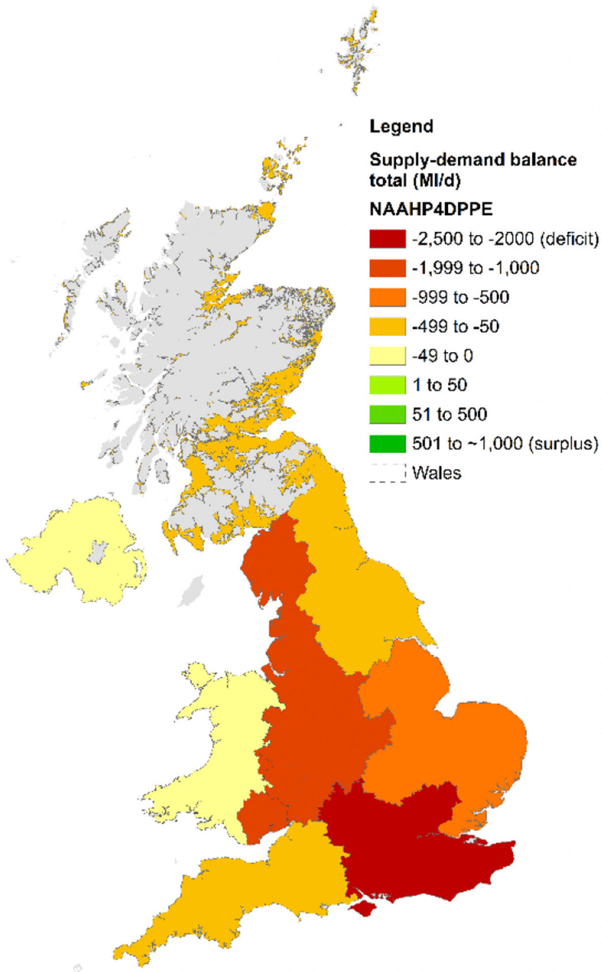


Figure 6.1: Supply-demand balance in the late-century (50th percentile value of only simulations using the UKCP18 Global projections based on the latest Met Office Hadley Centre model) for a 4°C world, high population projection and assuming no additional adaptation action scenario. Reproduced from HR Wallingford (2020)

They have set a series of goals including:

- Reduce demand to 110 litres per day per person by 2050
- Reduce the leakage rates by 50% by 2050
- Develop new water supplies (reservoirs, water reuse schemes, etc.)
- Increase water transfers
- Reduce the use environmentally damaging drought measures

These Water Resources Management Plans will be used to inform a National Framework and establish regional measures across England and Wales. The final regional plans are set to be published in September 2022; however, some draft plans were made available in August 2021. As an example, Water Resources East (2022) draft plans for the near future are presented in Table 6.1 and Table 6.2.

Table 6.1: Draft demand-side strategy for Water Resources East (2022)

Demand-side strategy		
Now to 2025	2025 to 2030	2030 onwards
Water company delivery (e.g., demand management such as current regional average daily water used per person (PCC), leakage reduction)	Significant focus on household and non-household water efficiency and demand management, particularly smart metering, leakage reduction	Continued focus on water efficiency and delivery of a long-term approach
	Innovation around tariffs	
Identification of multi-sector, non-household exemplars, and development of a collaborative strategy	Focus on water sharing/trading opportunities using international learning	
	Delivery of multi-sector, non-household water efficiency approaches	
	Delivery of a long-term approach and trajectory	

Table 6.2: Draft supply-side strategy for Water Resources East (2022)

Supply-side strategy		
Now to 2025	2025 to 2030	2030 onwards
Focus on immediate abstraction hotspots around chalk streams and the Broads	Strategic reservoir system construction	Strategic reservoir systems into supply
	Intermediate solutions (e.g., Anglian Water to Cambridge Water transfers)	Wider re-use and next generation desalination options, including for public water supply
'Next generation' desalination research and development	First re-use schemes and next generation desalination, linked to green hydrogen pilots	
	Aquifer storage and recover (ASR) pilot (Sherwood sandstone)	Aquifer storage and recover ASR implementation
Strategic reservoir design and planning	Local multi-sector infrastructure delivery*	Wider green hydrogen implementation
	Catchment investigations and planning linked to environmental vision	Significant delivery of further multi-sector local infrastructure linked to catchment plans
Local infrastructure studies	Development of further strategic storage options and potential transfers through Regional and National planning	

*Green infrastructure refers to natural systems including forests, floodplains, wetlands and soils that provide additional benefits for human well-being, such as flood protection and climate regulation. Grey infrastructure refers to structures such as dams, seawalls, roads, pipes or water treatment plants.

7. Discussion

7.1 General discussion

This report provides a review of studies that have assessed historical and future river flow and water availability changes in Scotland, and has detailed evidence on how climatic, hydrological, and other catchment-based processes may influence water resource availability in the future. It establishes a baseline of evidence relating to past and ongoing climate change impacts to Scotland's water resources, including changes to climate variability, seasonality and extreme events based exclusively on information that is on the public domain. It collates, explores and synthesizes the latest peer-reviewed literature that is relevant/applicable to Scotland. The report does not, however, take account of the activities that are underway across Scottish Water as much of these are ongoing and/or unpublished.

Taken together, the results presented here suggest that the water sector in Scotland will have to continue to re-evaluate, prepare for, manage, and adapt to climate change to ensure the continuity of water availability. Ongoing and further analysis is therefore necessary to develop a better understanding of impacts and risks.

In establishing the evidence baseline, outflows are found to have increased significantly over the 1961-2010 period in Scotland. Seasonally, in Scotland over the period 1965-2014, there was an increase in mean flows in winter, autumn and summer, with the winter increases being statistically significant. In spring, trends for decreases in the east and increases in the west are detected, although none are statistically significant.

There is a clear indication from this review that both droughts (Gosling, 2014; Visser-Quinn et al., 2021) and floods (Beevers et al., 2020; Collet et al., 2018) across Scotland are likely to increase in frequency, duration, and magnitude in the future due to climate change. While there is uncertainty regarding future droughts and floods because of different methodologies and indices used across studies, by the 2080s, droughts are projected to increase in magnitude up to 100% to 150%, and changes in flood magnitude are of the order of 20% to 50% at selected 'hotspots' (Collet et al., 2018). Despite that there are a number of studies on the prevalence of droughts in the future UK climate, their definition of drought and results differ making comparisons challenging. However, there is a general consensus relating to an increase across all metrics across Scotland in a warming climate. Therefore, the future occurrence of these hazards alongside other changes may adversely affect drinking water availability, irrigation demand and hydropower production.

Comparatively, other hazards and influences such as compound events and cascading impacts are far less studied in Scotland. Nevertheless, Visser-Quinn et al. (2019) suggests that concurrent drought and flood events may occur more frequently in Scotland in the future, with hotspots in the Loch Ness and River Tay catchments. There is a notable lack of knowledge in compound events in Scotland. There are very few studies evidencing compound events, including hot and dry concurrent events or temporally sequencing between events such as dry to wet events. This lack of knowledge compromises the immunity to multi-hazards in Scotland and highlights the need for research in this area (see Section 8).

Climate change is likely to have an impact on Scotland's water resources. Climate projections indicate increased probabilities of higher temperatures and drier periods in Scotland in the near future (Lowe et al., 2019), which could impact water resources, freshwater ecosystems, agriculture, whisky industry and private water supplies. Studies from the UK and Europe, when used in conjunction with weather and climate data for Scotland, may also allow for a multi-hazard understanding of hot and dry compound events to be developed, adopting suitable approaches used elsewhere. Increases in the number of hot and dry days indicates the need for specific research and optimisation of planning and resources to prepare for 'emerging' hazards uncharacteristic of regions that could be especially vulnerable to water scarcity.

Studies of future streamflows in Scotland were found to generally show seasonal reductions in spring and summer flows, mixed patterns in autumn flows, and small increases in winter flows (Prudhomme et al., 2012). These changes are, however, spatially and temporarily variable, with some areas likely to see a flow reduction in some seasons, especially in eastern and southern Scotland. Western areas are projected to experience an increase in winter flows (Christierson et al., 2012), however seasonal future flow changes in Scotland vary both spatially and by study. Longer-term, catchments in western Scotland are at risk of not meeting environmental flows in the late century in a 4°C world, while the rest of Scotland is likely to maintain a surplus between supply and demand (HR Wallingford, 2020). Although, under a high population growth and no additional adaptation measures scenario, deficits could also occur across Scotland by 2100 (HR Wallingford, 2020).

From the perspective of methods and data, Kay et al. (2021) measured the possible future changes in low and high flows in Great Britain using the latest UKCP18 climate projections – the only known study in the UK to do so – and the RCP8.5 emission scenario. The small differences indicated by Kay et al. (2020) between flow changes projected by UKCP18 and UKCP09 suggest that current water management guidance and allowances remain valid, and results from UKCP09 remain a useful guide to changes in the next 30 years. Nevertheless, the current practices will need to be revised in the light of UKCP18 to make use of the latest information available and to ensure that risks are managed correctly in the horizons beyond 2050. Similarly, although the majority of studies reviewed use a high emission pathway such as RCP8.5 (which contains notable uncertainties and assumptions), this is still valid for the near-term future (e.g., the next 20 years).

The present study highlights the risks that climate change presents to Scotland's water resources, supported by evidence from the peer-reviewed literature. The recently published Third UK Climate Change Risk Assessment (CCRA3) (Climate Change Committee, 2021; HM Government, 2022) identified 61 risks and opportunities for each country (Sniffer, 2021) – aligning with many of the findings from this review – of which the following risks are closely related to water resources:

- *I1*. Infrastructure networks
- *I2*. Infrastructure services: river and surface water flooding
- *I6*. Hydroelectric generation: low or high river flows
- *I7*. Subterranean and surface infrastructure: subsidence
- *I8*. Public water supplies: reduced water availability
- *I9*. Energy generation: reduced water availability
- *H3*. People, communities, and buildings: flooding
- *H10*. Health: poor water quality and household water supply
- *B1*. Flooding of business sites: increase in flood risks
- *B3*. Business production processes: water scarcity

where *I* refers to infrastructure risks, *H* refers to health, communities and the built environment risks, and B refers to business and industry risks. Of these, *I1, I2, I6, I7, H3, H10, B1* and *B3* are identified as priority areas where 'more action' and/or 'further research' is needed, while the others are for a 'watching brief' or 'sustain current action'. Climate change will therefore likely lead to increased risks across many of Scotland's sectors, including water resources.

Despite the evidence presented here, the findings of this report are, however, somewhat limited by the lack of published literature in certain areas (e.g., climate change impacts on groundwater, event sequencing, compounding events, limited flood and drought trend information, and water demand/costumer changes due to climate change). The gaps in literature focused on customer usage and demand changes associated with climate change, in particular, create difficulties in forecasting future water demands and changes in behavioural patterns. However, this suggests that these areas are an important issue for further research.

7.2 Other projects and initiatives

While the focus of this project has been on evidence in the published literature, primarily peer-reviewed, we acknowledge that there are several projects and initiatives underway around Scotland and the UK that may, in part, start to address some of the research gaps and priorities (see Section 8) identified in this study.

The *IMPRESS – Approaches to IMProve flood and drought forecasting and warning in catchments influenced by REServoirS* project is a 'sister' project to this one, also supported by CREW, and due for completion in early 2022. Led by UKCEH, it aims to advise the Scottish Government and stakeholders on opportunities for improving flood and drought forecasting and warning where catchments are influenced by reservoir operation, with forecasts over time-scales of hours, weeks and months.

The ongoing eFLaG: Enhanced Future Flows and Groundwater project, led by UKCEH, aims to develop a prototype climate service that will enhance the resilience of the water sector to drought events. Specifically, it will provide nationally-consistent hydrological projections to enable robust assessment of drought risk. The core deliverable of the project is the eFLaG dataset of nationally-consistent climatological and hydrological projections based on UKCP18, which can be used by the water industry for water resources and drought planning. This involves the £5m CS-N0W programme that is building on the eFLaG climate projections and combining them with projections of future demand. There are also ongoing efforts to document observed hydrological trends across the UK, mainly using the National River Flow Archive (NRFA) (e.g., (Hannaford et al., 2021).

There is also progress being made in the compound events and cascading impacts topic. Simmonds et al. (2022) reviews the latest science in interacting weather-driven hazards and cascading impacts across Scotland, funded through the National Centre for Resilience and led by the University of Strathclyde.

Another CREW funded project, *Evaluating evidence-based changes in management strategy to steer adaptive responses for mitigating climate change impacts on water quality in Scottish standing waters*, is currently looking at the effect climate change may be having on freshwater lochs, led by UKCEH. This project includes model outputs of effective rainfall that are being produced using 1 km grid squares across Scotland to support loch residence time estimations.

More broadly, with more an international focus, a new multi-hazard focused project called *EMERGE – Multi-hazards and emergent risks in Northern Europe's remote and vulnerable regions*, is bringing together experts to explore weather-driven hazards – primarily extreme rainfall, landslides and floods – and their emergent and compounding risks across the UK, Norway and Iceland. The project is funded by the Natural Environment Research Council (NERC) and led by Dr Christopher White from the University of Strathclyde, formed by a new partnership with the Icelandic Meteorological Office, the Norwegian Water Resources and Energy Directorate, the British Geological Survey (BGS), Newcastle University, and the Scottish Environment Protection Agency (SEPA). The two-year *EMERGE* project (2021-2023) aims to bring together researchers that work in similar climatic zones to foster collaboration and create novel, cutting-edge science that is beneficial to the UK and its near neighbours. Closely related and starting in April 2022, a NERC multi-centre initiative *CANARI* will look at future North Atlantic and Arctic changes on future UK Climate, including hydrology. A new EU Horizon 2020 funded PerfectSTORM project, led by Dr Anne Van Loon and colleagues has also recently launched. This project is studying the risks of cascading hazards of flooding after drought, focusing on hydro-social feedbacks. This multi-year project aims to provide guidance on future management of drought-to-flood events.

8. Recommendations

Based on the outcomes of this study, here we provide ten high-level recommendations that could be undertaken to better understand how climate change is and will continue to impact the water resources sector across Scotland:

1. **Historical trend analyses of droughts and floods**: Despite notable drought and flood events in Scotland in recent decades, evidence of trends of increased frequency of drought and flood, or of changes to the seasonality of their driving factors (e.g., high or low precipitation), are weak and urgently needs further research. This may include and expand upon existing drought inventories, such as the historic drought inventory 1890-2015 (https://reshare.ukdataservice.ac.uk/853673/).
2. **Evidence of, and planning for, emerging risks**: Dedicated research leading to the optimisation of water demand planning.
3. **Combinations of compound events across Scotland**: Scotland-focused compound events analyses are required to accurately represent the complex, interacting risks and impacts to the water resources sector identified in this study, both using observations and future climate projections. Not doing so could underestimate these risks if they are considered using an individual hazard focus. Based on expert advice and judgement, these include the following priority compound event pairings:
    a. **Temporal sequences of compound event**s (including dry to wet and vice versa, and multiple dry periods) – Current approaches typically assess linear pathways of singular hazards. There is a significant gap in knowledge about event sequencing in Scotland, including the 'see-saw' or 'weather whiplash' temporal succession between compound hazards. In order to better understand the impact of multiple or sequences of events (such as rapid dry to wet conditions, or multiple years of low precipitation), further modelling is required. We recommend, as a priority, that temporal sequences across multiple compound event types are assessed to calculate how different outcomes might occur within the water resources sector.
    b. **Concurrent hot and dry conditions** – There are potential risks from the combination of dry and hot summer conditions, including water supply disruptions from drought and reduced water quality in the natural environment. However, few studies exist in Scotland to support adaptation actions; and

c. **Snow events and streamflows** –
Uncertainties remain in the likely future changes to the amount and timing of snow cover and the interplay with streamflows, especially in spring and summer run-off. Snow is an important factor to consider in future studies and resilience planning due to its significance to water resources and energy in Scotland.

4. **Cascading impacts and risks to water resources**:
The UK-wide CCRA3 risk mapping does not recognise the national (Scottish) or location-specificity of risks and impacts. This is an issue that affects the water resources sector, including critical infrastructure. A multi-sectoral analysis (renewable energy, drinking water availability, natural environment) would provide a better understanding of cascading impacts and the economic consequences of such risks, which could inform adaptation efforts.

5. **Improved regional climate modelling**:
To overcome the inherent uncertainties from climate modelling and projections, we recommend using an ensemble of climate projections for any future analysis (i.e., including recommendations 2-4). It is apparent through this review that the majority of previous studies have been undertaken using now outdated projections (UKCP09) and it is recommended that these studies are revised and updated with the current UKCP18 projections. Exploration of the UKCP18 high resolution (2.2 km) convection-permitting models should be a priority.

6. **Water resource and drought planning**:
We recommend a review of water resource and drought planning guidance from England and Wales together with water companies' water management and drought plans for regional assessments of water resources and supply demand balance issued each investment period be undertaken.

7. **Water demand and customer behaviours**:
There are few examples of studies in the UK peer-reviewed literature relating to water demand and/or customer usage changes due to climate change in the UK. This including socio-economic drought, which is poorly understood and the least studied type of drought. We recommend research that reviews international best-practise in water demand and customer behaviour modelling to inform future Scottish regional planning.

8. **Groundwater data collation and research**:
Groundwater represents a relatively small, yet strategic, share of Scotland's water supply – both public and private – and it may be the only source of water in remote areas where surface water supplies are unavailable. While there is significant research around groundwater *quality* in Scotland, the research is more limited around groundwater *quantity*, and the effects of climate change on groundwater availability. Moreover, while the Scottish Government has requested that Local Authority Public Health Officers keep weekly records of impacted private water supplies, there remains no process in place to keep track of recovery. The scale of this issue is not widely understood in Scotland since groundwater is mostly used in private water supplies, whereas surface water impact on public supply is clearer. Therefore, we recommend research is undertaken in the area climate change effects on groundwater quantity.

9. **Integration of infrastructure thresholds and feedbacks**: Using inputs from stakeholders across Scotland's water resource sector could be used to identify some indicative thresholds and feedbacks for critical water infrastructure. It would be particularly beneficial to formally identify the scope of these to find a way to model their effects, such as through indicators or other approaches. This would enable better representation of their impacts on cascading and interacting risks.

10. **Revised adaptation and resilience approaches**:
Build on the ongoing work by water companies to better understand the risks to the water resources sector in a changing climate. We recommend that further research could be conducted to develop, apply and test risks against different adaptation and resilience scenarios, including using 'storyline' approaches. Moving beyond high-level, descriptive, adaptation scenarios to sector/sub-sector specific plans may act as a lens through which the benefits of adaptation (and, inherently, urgency of action) may be better understood.

9. Conclusions

The purpose of this study was to determine whether the hypothesis that climate change is impacting (and will continue to impact) the quantity and availability of water in Scotland, and to provide evidence on how climatic, hydrological, and other catchment-based processes may alter Scotland's water resources in the future.

This report identifies recent peer-reviewed literature indicating that Scotland's water resources have changed and may continue to change in the future. Evidence of drivers of change, such as increases in air temperature, snow cover and run-off, and changes to rainfall patterns, extremes and variability, are identified. These may affect Scotland's water resources in the future through increased frequencies or magnitudes of hazards like droughts, sequencing of events, and concurrent dry and hot events. There is, however, a significant gap in knowledge about climatic event sequencing in Scotland. Despite this, current evidence suggests that annually river flows may not change significantly in the future, however seasonal changes (e.g., decreases in summer flows) might occur which may affect Scotland's water resources.

While Scotland may be thought of as a 'water rich' country, water scarcity – especially for private water supplies and water-dependent industries (e.g., whisky) – may become an issue in the near-future, particularly where these industries are groundwater-dependent. There is a lack of research on climate change related impacts to this resource. Similarly, there are few examples of studies relating to water demand and/or customer usage changes due to climate change in the UK. This including socio-economic drought, which is poorly understood.

In conclusion, this report provides a deeper insight into the risks for water resources in Scotland and the drivers behind them. It showcases emerging risks, such as the sequencing of dry periods and the compounding of hazards and gaps in the literature about them, alongside lack of research in Scotland about groundwater quantity and changes in water demand/costumer usage due to climate change.

References

Aghakouchak, A., Chiang, F., Huning, L.S., Love, C.A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S.M., Ragno, E., Sadegh, M., 2020. Climate Extremes and Compound Hazards in a Warming World. Annu. Rev. Earth Planet. Sci. 48, 519–548. https://doi.org/10.1146/annurev-earth-071719-055228

Arnell, N.W., Kay, A.L., Freeman, A., Rudd, A.C., Lowe, J.A., 2021. Changing climate risk in the UK: A multi-sectoral analysis using policy-relevant indicators. Clim. Risk Manag. 31, 100265. https://doi.org/10.1016/j.crm.2020.100265

Beevers, L., Collet, L., Aitken, G., Maravat, C., Visser, A., 2020. The influence of climate model uncertainty on fluvial flood hazard estimation. Nat. Hazards 104, 2489–2510. https://doi.org/10.1007/s11069-020-04282-4

Bell, V.A., Kay, A.L., Davies, H.N., Jones, R.G., 2016. An assessment of the possible impacts of climate change on snow and peak river flows across Britain. Clim. Change 136, 539–553. https://doi.org/10.1007/s10584-016-1637-x

Bokwa, A., 2013. Natural Hazard. Encycl. Earth Sci. Ser. 711–718. https://doi.org/10.1007/978-1-4020-4399-4_248

Brown, I., Poggio, L., Gimona, A., Castellazzi, M., 2011. Climate change, drought risk and land capability for agriculture: Implications for land use in Scotland. Reg. Environ. Chang. 11, 503–518. https://doi.org/10.1007/s10113-010-0163-z

Capell, R., Tetzlaff, D., Essery, R., Soulsby, C., 2014. Projecting climate change impacts on stream flow regimes with tracer-aided runoff models - preliminary assessment of heterogeneity at the mesoscale. Hydrol. Process. 28, 545–558. https://doi.org/10.1002/HYP.9612

CEH, 2018. UK Hydrological Status Update - early August 2018 | UK Centre for Ecology & Hydrology. https://www.ceh.ac.uk/news-and-media/blogs/uk-hydrological-status-update-early-august-2018 (accessed 29 November 2021).

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

CIWEM, 2016. Regulation of Water Resources Planning in Scotland 1043409. https://www.ciwem.org/assets/pdf/Policy/Policy%20Position%20Statement/Regulation-of-Water-Resources-Planning-in-Scotland.pdf (accessed April 2021)

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. https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/ (accessed April 2021)

Collet, L., Harrigan, S., Prudhomme, C., Formetta, G., Beevers, L., 2018. Future hot-spots for hydro-hazards in Great Britain: A probabilistic assessment. Hydrol. Earth Syst. Sci. 22, 5387–5401. https://doi.org/10.5194/hess-22-5387-2018

De Luca, P., Messori, G., Wilby, R.L., Mazzoleni, M., Di Baldassarre, G., 2020. Concurrent wet and dry hydrological extremes at the global scale. Earth Syst. Dyn. 11, 251–266. https://doi.org/10.5194/ESD-11-251-2020

Environment Agency, 2020. Meeting our future water needs: a national framework for water resources 91. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/873100/National_Framework_for_water_resources_summary.pdf (accessed April 2022)

Fang, W., Huang, S., Huang, G., Huang, Q., Wang, H., Wang, L., Zhang, Y., Li, P., Ma, L., 2019. Copulas-based risk analysis for inter-seasonal combinations of wet and dry conditions under a changing climate. Int. J. Climatol. 39, 2005–2021. https://doi.org/10.1002/JOC.5929

Fosser, C.G., Murphy, J., Chan, S., Clark, R., Harris, G., Lock, A., Lowe, J., Martin, G., Pirret, J., Roberts, N., Sanderson, M., Tucker, S., Kendon, E.J., Fosser, G., Murphy, J., Chan, S., Clark, R., Harris, G., Lock, A., Lowe, J., Martin, G., Pirret, J., others, 2019. UKCP Convection-permitting model projections: Science report 1–153. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP-Convection-permitting-model-projections-report.pdf (accessed April 2022)

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

Gosling, R.D., Black, A.R., Brock, B.W., 2002. High snow melt rates in the Cairngorns. BHS 8th Natl. Symp. https://discovery.dundee.ac.uk/ws/portalfiles/portal/49775088/Gosling_et_al_2002.pdf (accessed April 2022)

Hanlon, H.M., Bernie, D., Carigi, G., Lowe, J.A., 2021. Future changes to high impact weather in the UK. Clim. Change 166, 1–23. https://doi.org/10.1007/s10584-021-03100-5

Hannaford, J., 2015. Climate-driven changes in UK river flows: A review of the evidence. Prog. Phys. Geogr. 39, 29–48. https://doi.org/10.1177/0309133314536755

Hannaford, J., Mastrantonas, N., Vesuviano, G., Turner, S., 2021. An updated national-scale assessment of trends in UK peak river flow data: how robust are observed increases in flooding? Hydrol. Res. 52, 699–718. https://doi.org/10.2166/NH.2021.156

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

He, X., Sheffield, J., 2020. Lagged Compound Occurrence of Droughts and Pluvials Globally Over the Past Seven Decades. Geophys. Res. Lett. 47. https://doi.org/10.1029/2020GL087924

HM Government, 2022. 'Third UK Climate Change Risk Assessment (CCRA3). https://www.gov.uk/government/publications/uk-climate-change-risk-assessment-2022 (accessed 17 February 2022).

Holdsworth, C., 2019. Private Water Supplies in a changing climate: Insights from 2018 16. https://www.climatexchange.org.uk/media/3676/cxc-private-water-supplies-in-a-changing-climate-insights-from-2018.pdf (accessed April 2022)

Howard, G., Calow, R., Macdonald, A., Bartram, J., 2016. Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action. Annu. Rev. Environ. Resour. 41, 253–276. https://doi.org/10.1146/annurev-environ-110615-085856

HR Wallingford, 2020. Updated projections of future water availability for the third UK Climate Change Risk Assessment. https://www.ukclimaterisk.org/wp-content/uploads/2020/07/Updated-projections-of-future-water-availability_HRW.pdf (accessed April 2022)

Huang, H., Zhang, B., Cui, Y., Ma, S., 2020. Analysis on the characteristics of dry and wet periods in the yangtze river basin. Water (Switzerland) 12, 1–22. https://doi.org/10.3390/w12112960

Huang, S., Hou, B., Chang, J., Huang, Q., Chen, Y., 2014. Copulas-based probabilistic characterization of the combination of dry and wet conditions in the Guanzhong Plain, China. J. Hydrol. 519, 3204–3213. https://doi.org/10.1016/j.jhydrol.2014.10.039

Ionita, M., Caldarescu, D.E., Nagavciuc, V., 2021. Compound Hot and Dry Events in Europe: Variability and Large-Scale Drivers. Front. Clim. 3, 1–19. https://doi.org/10.3389/fclim.2021.688991

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen,. Cambridge Univ. Press 3949. https://www.ipcc.ch/report/ar6/wg1/

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., Griffin, A., Rudd, A.C., Chapman, R.M., Bell, V.A., Arnell, N.W., 2021. 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., 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

Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A., Legg, T., 2019. State of the UK climate 2018. Int. J. Climatol. 39, 1–55. https://doi.org/10.1002/joc.6213

Kirkpatrick Baird, F., Stubbs Partridge, J., Spray, D., 2021. Anticipating and mitigating projected climate-driven increases in extreme drought in Scotland , 2021-2040. NatureScot Res. Rep. No.1228. 2021–2040. https://www.nature.scot/sites/default/files/2021-02/Publication 2021 - NatureScot Research Report 1228 - Anticipating and mitigating projected climate-driven increases in extreme drought in Scotland 2021-2040.pdf (accessed April 2022)

Lehner, B., Czisch, G., Vassolo, S., 2005. The impact of global change on the hydropower potential of Europe: A model-based analysis. Energy Policy 33, 839–855. https://doi.org/10.1016/j.enpol.2003.10.018

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., 2019. UKCP18 Science Overview Report 2018, 1–73. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf (accessed April 2022)

Manning, C., Widmann, M., Bevacqua, E., Van Loon, A.F., Maraun, D., Vrac, M., 2019. Increased probability of compound long-duration dry and hot events in Europe during summer (1950-2013). Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab23bf

Margetta, R., 2022. 2021 Tied for 6th Warmest Year in Continued Trend, NASA Analysis Shows. https://www.nasa.gov/press-release/2021-tied-for-6th-warmest-year-in-continued-trend-nasa-analysis-shows/ (accessed April 2022)

McGrane, S.J., Allan, G.J., Roy, G., 2018. Water as an economic resource and the impacts of climate change on the hydrosphere, regional economies and Scotland. Fraser Allander Econ. Comment. 42, 53–74. https://pureportal.strath.ac.uk/en/publications/water-as-an-economic-resource-and-the-impacts-of-climate-change-o (accessed April 2022)

Met Office, 2018. What are RCPs?. https://doi.org/10.1175/JCLI-D-12-00577.1

Moftakhari, H., Aghakouchak, A., 2019. Increasing exposure of energy infrastructure to compound hazards: Cascading wildfires and extreme rainfall. Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab41a6

Montaseri, M., Amirataee, B., Yasi, M., 2019. Long-term probability of drought characteristics based on Monte Carlo simulation approach. Int. J. Climatol. 39, 544–557. https://doi.org/10.1002/joc.5827

Mueller, B., Seneviratne, S.I., 2012. Hot days induced by precipitation deficits at the global scale. Proc. Natl. Acad. Sci. U. S. A. 109, 12398–12403. https://doi.org/10.1073/pnas.1204330109

National Audit Office, 2020. Water supply and demand management. Dep. Environ. Food Rural Aff. https://www.nao.org.uk/report/water-supply-and-demand-management/ (accessed April 2022)

Ó Dochartaigh, B.É., MacDonald, A.M., Fitzsimons, V., Ward, R., 2015. Scotland's aquifers and groundwater bodies. Br. Geol. Surv. Open Report, OR/15/028 76pp. https://nora.nerc.ac.uk/id/eprint/511413/1/OR15028.pdf (accessed April 2022)

Parry, S., 2021. A weather whiplash? Assessing the abrupt swing from dry to wet in Spring 2021 | UK Centre for Ecology & Hydrology. https://www.ceh.ac.uk/cy/node/24255 (accessed 16 February 2022).

Parry, S., Prudhomme, C., Wilby, R.L., Wood, P.J., 2016. Drought termination: Concept and characterisation. Prog. Phys. Geogr. 40, 743–767. https://doi.org/10.1177/0309133316652801

Perkins-Kirkpatrick, S.E., Lewis, S.C., 2020. Increasing trends in regional heatwaves. Nat. Commun. 11, 1–8. https://doi.org/10.1038/s41467-020-16970-7

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

Ridder, N.N., Pitman, A.J., Westra, S., Ukkola, A., Hong, X. Do, Bador, M., Hirsch, A.L., Evans, J.P., Di Luca, A., Zscheischler, J., 2020. Global hotspots for the occurrence of compound events. Nat. Commun. 11, 1–10. https://doi.org/10.1038/s41467-020-19639-3

Rivington, M., Akoumianaki, I., Coull, M., 2020. Private Water Supplies and Climate Change The likely impacts of climate change (amount, frequency and distribution of precipitation), and the resilience of private water supplies. CRW2018_05. Scotland's Centre of Expertise for Waters (CREW). CREW. https://www.crew.ac.uk/sites/www.crew.ac.uk/files/publication/CRW2018_05_report_FINAL.pdf (accessed April 2022)

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

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

Sanderson, M.G., Economou, T., Salmon, K.H., Jones, S.E.O., 2017. Historical trends and variability in heat waves in the United Kingdom. Atmosphere (Basel). 8. https://doi.org/10.3390/atmos8100191

Sayers, P., Horritt, M., Penning-Rowsell, E., McKenzie, A., Thompson, D., 2016. The analysis of future flood risk in the UK using the Future Flood Explorer. E3S Web Conf. 7, 1–9. https://doi.org/10.1051/e3sconf/20160721005

SEPA, 2022. Water levels | Scottish Environment Protection Agency (SEPA). https://www.sepa.org.uk/environment/water/water-levels/ (accessed 28 Feburary 2022).

SEPA, 2020. Scotland's National Water Scarcity Plan 51. https://www.sepa.org.uk/media/219302/scotlands-national-water-scarcity-plan.pdf (accessed April 2022)

SEPA, 2014. The impact of climate change on water scarcity 7–24. https://doi.org/10.4324/9781315884394-12

Scottish Water, 2014. 'Water Resource Plan 2015 (Summary Report) Water Service Strategy Version 0.2.

Shan, L., Zhang, L., Song, J., Zhang, Y., She, D., Xia, J., 2018. Characteristics of dry-wet abrupt alternation events in the middle and lower reaches of the Yangtze River Basin and the relationship with ENSO. J. Geogr. Sci. 28, 1039–1058. https://doi.org/10.1007/s11442-018-1540-7

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

Shi, W., Huang, S., Liu, D., Huang, Q., Han, Z., Leng, G., Wang, H., Liang, H., Li, P., Wei, X., Shi, W., Huang, S., Liu, D., Huang, Q., Han, Z., Leng, G., Wang, H., Liang, H., Li, P., Wei, X., 2021. Drought-flood abrupt alternation dynamics and their potential driving forces in a changing environment. J. Hydrol. 597, 126179. https://doi.org/10.1016/j.jhydrol.2021.126179

Shi, W., Huang, S., Liu, D., Huang, Q., Leng, G., Wang, H., Fang, W., Han, Z., 2020. Dry and wet combination dynamics and their possible driving forces in a changing environment. J. Hydrol. 589, 125211. https://doi.org/10.1016/j.jhydrol.2020.125211

Simmonds, R., White, C.J., Douglas, J., Sauter, C., Brett, L., 2022. A review of interacting natural hazards and cascading impacts in Scotland.

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

Sniffer, 2021. Summary for Scotland Summary of climate risks and opportunities for Scotland. CCRA-Evidence-Report-Scotland-Summary-Final-1.pdf (ukclimaterisk.org)

Speight, L., Krupska, K., 2021. Understanding the impact of climate change on inland flood risk in the UK. Weather 76, 330–331. https://doi.org/10.1002/wea.4079

Sutanto, S.J., Vitolo, C., Di Napoli, C., D'Andrea, M., Van Lanen, H.A.J., 2020. Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale. Environ. Int. 134. https://doi.org/10.1016/j.envint.2019.105276

The Independent, 2021. Climate crisis: Temperature changes could halt whisky production in Scotland by 2080, report warns. https://www.msn.com/en-gb/news/world/climate-crisis-temperature-changes-could-halt-whisky-production-in-scotland-by-2080-report-warns/ar-AAPQUgC (accessed 24 February 2022).

The Whiskey Wash, 2017. Hot Scotch: The Impact of Climate Change on your Whisky - The Whiskey Wash. https://thewhiskeywash.com/lifestyle/hot-scotch-impact-climate-change-whisky/ (accessed 24 February 2022).

UKWIR (2022) Water Industry Big Questions. https://ukwir.org/big-questions-facing-uk-water-industry (accessed 25 March 2022).

Vidal, J.-P., Wade, S., 2008. A multimodel assessment of future climatological droughts in the United Kingdom. Int. J. Climatol. 2029, 2011–2029. https://doi.org/10.1002/joc

Williams, R.D., Downs, P.W., Moir, H.J. and Lavarini, C. (2022), Sediment continuity through run-of-river hydropower schemes. CRW2019_02. Centre of Expertise for Waters (CREW). Available online at: crew.ac.uk/publications

Visser-Quinn, A., Beevers, L., Collet, L., Formetta, G., Smith, K., Wanders, N., Thober, S., Pan, M., Kumar, R., 2019. Spatio-temporal analysis of compound hydro-hazard extremes across the UK. Adv. Water Resour. 130, 77–90. https://doi.org/10.1016/j.advwatres.2019.05.019

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

Vogel, J., Paton, E., Aich, V., Bronstert, A., 2021. Increasing compound warm spells and droughts in the Mediterranean Basin. Weather Clim. Extrem. 32, 100312. https://doi.org/10.1016/j.wace.2021.100312

Waajen, A.C., 2019. The increased risk of water scarcity in Scotland due to climate change and the influence of land use on water scarcity: issues and solutions. https://www.climatexchange.org.uk/media/3680/cxc-water-scarcity-climate-change-and-land-use-options.pdf (accessed April 2022)

Wang, J., Horne, A., Nathan, R., Peel, M., Neave, I., 2018. Vulnerability of Ecological Condition to the Sequencing of Wet and Dry Spells Prior to and during the Murray-Darling Basin Millennium Drought. J. Water Resour. Plan. Manag. 144, 04018049. https://doi.org/10.1061/(asce)wr.1943-5452.0000963

Water Resources East, 2022. The Emerging Water Resources Regional Plan for Eastern England. https://wre.org.uk/projects/the-regional-plan/ (accessed April 2022)

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

White, C.J., 2021. How summer 2021 has changed our understanding of extreme weather. https://theconversation.com/how-summer-2021-has-changed-our-understanding-of-extreme-weather-165268 (accessed 16 February 2022).

Wu, X., Hao, Z., Tang, Q., Singh, V.P., Zhang, X., Hao, F., 2021. Projected increase in compound dry and hot events over global land areas. Int. J. Climatol. 41, 393–403. https://doi.org/10.1002/joc.6626

Zscheischler, J., Fischer, E.M., 2020. The record-breaking compound hot and dry 2018 growing season in Germany. Weather Clim. Extrem. 29, 100270. https://doi.org/10.1016/j.wace.2020.100270

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W., Vignotto, E., 2020. A typology of compound weather and climate events. Nat. Rev. Earth Environ. 1, 333–347. https://doi.org/10.1038/s43017-020-0060-z

Zscheischler, J., Seneviratne, S.I., 2017. Dependence of drivers affects risks associated with compound events. Sci. Adv. 3. https://doi.org/10.1126/SCIADV.1700263/SUPPL_FILE/1700263_SM.PDF

Zscheischler, J., Sillmann, J., Alexander, L., 2021. Introduction to the special issue: Compound weather and climate events. Weather Clim. Extrem. 100381. https://doi.org/10.1016/J.WACE.2021.100381

CREW
CENTRE OF EXPERTISE FOR WATERS

CREW Facilitation Team

Hydro Nation International Centre

James Hutton Institute

Craigiebuckler

Aberdeen AB15 8QH

Scotland UK

Tel: +44 (0)344 928 5428

Email: enquiries@crew.ac.uk

www.crew.ac.uk

Hydro Nation International Centre

The James Hutton Institute

Scottish Government
Riaghaltas na h-Alba
gov.scot

CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes and Research Institutes. The Centre is funded by the Scottish Government.