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Dallison, Richard; Patil, Sopan

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Impact of climate change on hydropower potential in the UK and Ireland

Richard J.H. Dallison *, Sopan D. Patil

School of Natural Sciences, Bangor University, Bangor, Gwynedd, LL57 2UW, UK

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ABSTRACT

Despite making up a small proportion of total electricity generation in the UK and Ireland, hydropower has an important role in providing resilience to the energy network and contributing to governmental net-zero emissions targets. Run-of-river hydropower schemes are popular in both countries, but are vulnerable to changes in streamflow patterns. In this study, we examine how climate change induced streamflow alterations will affect hydropower in the UK and Ireland. We use EXP-HYDRO hydrological model to simulate future streamflow in 585 catchments under worst-case future climate change (Representative Concentration Pathway 8.5). Within 178 catchments we identify 531 run-of-river hydropower abstractions and analyze the impact of modelled streamflows on hydropower water abstraction characteristics. Results show that by 2080 there will be a reduction in annual hydropower water abstraction in Wales (−2.1%) and Northern Ireland (−1.9%), increased abstraction in England (+3.0%) and Scotland (+12.9%), and no changes in Ireland. For annual average power generation, a 6.2% increase is projected for Great Britain by the 2080s, and a 1.4% decrease for the island of Ireland. Our results suggest that the ability of hydropower schemes to make optimal use of future flows will depend on abstraction license conditions, with implications for overall power grid resilience.

1. Introduction

In the United Kingdom (UK), hydropower (excluding pumped-storage systems) contributed 5% of renewable electricity generation in 2021 [1], while in the Republic of Ireland (hereafter referred to as Ireland), this figure was 6.5% [2]. While these contributions are small in comparison to other renewable energy technologies, such as solar and wind power, hydropower has an important role in ensuring the resilience of the energy grid. In particular, hydropower provides a reliable level of output that is highly predictable and can be used to make up for deficiencies in other renewable energy outputs, and to balance the grid. This is particularly true in winter, when hydropower generation potential is at its highest, and technologies such as solar power may see waning generation. Consequently, hydropower has an important role to play in the context of national renewable energy generation and emissions reduction targets. With climate emergencies having been declared by the governments of the UK, Wales, Scotland, and Ireland in 2019, and Northern Ireland in 2020, obtaining a clear picture of the likely future contribution of different renewable energy technologies is important. This is particularly true in the context of greenhouse gas emissions reduction targets set by national governments too, with the UK, Wales, Northern Ireland, and Ireland targeting net zero emissions by 2050, and Scotland setting a more ambitious timeframe of 2045. However, climate change, combined with changes in the funding for small hydropower schemes, and the curtailment of tariffs paid to operators exporting power to the grid in coming years, may call the viability of some hydropower schemes into question. Given this, and the important contribution that hydropower makes to the diffuse energy production system of the UK and Ireland, understanding the future nature of its contribution, and safeguarding its viability, is important in ensuring resilience of the energy network moving forward, and the successful accomplishment of emission reduction targets.

The impacts of climate change on streamflows in the UK and Ireland have been well researched in recent years. Studies of historical alterations suggest that average streamflows, although remaining mostly stable at an annual perspective, have become more seasonally amplified [3–5], with this being most pronounced in the south of the UK [4]. Indeed, a northeast-southwest divide across Great Britain (England, Wales, and Scotland), and an east-west divide across the island of Ireland (Northern Ireland and Ireland) are commonly observed pattern in studies on the hydrological implications of both historical and future climate change [6–10]. In addition, reviews such as Watts et al. [7], Hannaford [11], and Garner et al. [12] suggest that extreme streamflow events have been trending upwards in terms of frequency and magnitude

* Corresponding author.
E-mail address: r.dallison@bangor.ac.uk (R.J.H. Dallison).

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in particular, with some local variation. Investigations of the impacts of future climate change suggest the continuation, and in some cases exacerbation, of these observed trends, to the end of the 21st century [7, 13–15], with this being linked to corresponding changes in precipitation patterns. A small increase is projected in average precipitation by 2100, compared to the 1986–2005 baseline by the Intergovernmental Panel on Climate Change [16] for the British Isles, with average temperatures also expected to increase. Furthermore, the UK Climate Projections 2018 (UKCP18) Science Overview Report suggests a move towards warmer, wetter winters, and hotter, drier summers, as well as an increase in extreme weather events [17]. These projected changes clearly have implications for annual and seasonal average flows, as well as high and low flows. These projections and links are supported by the likes of Rau et al. [18], who found that in the long-term (2070–2100), hourly precipitation volumes are set to increase by 12%, while Hanlon et al. [19] demonstrate a link between future daily rainfall and increased number of flood days under high and low future emissions scenarios. Furthermore, works by the likes of Kay et al. [20–22], Prudhomme et al. [23–25], and Sanderson et al. [26], support the suggestion that future streamflows will be more seasonally amplified across the British Isles, both in terms of average and extreme flows. These projected future streamflow changes clearly have implications for water users and abstractors (those extracting water from streams), as the timing and quantity of the available water resource is likely to be altered. Such climate induced streamflow alterations are particularly like to effect run-of-river (RoR) hydropower schemes, which are highly dependent on instantaneous flows, and therefore vulnerable, in particular to changes in low flows [27].

The aforementioned studies highlighting the variation in climate forcing and catchment responses across the UK and Ireland, show that the impacts of future climate change will not be felt evenly. Therefore, understanding the nature of these variations in terms of streamflow, and the knock-on implications for RoR hydropower generation potential is important. In addition, environmental regulation varies across the four nations of the UK (England, Wales, Scotland, and Northern Ireland), and between these nations and Ireland. In particular of note here, is the different general standards set for abstraction licenses (regulated and monitored licences controlling the conditions under which it is allowable to extract from a river and the maximum extraction rate at a given moment) across the five nations; key conditions typically relate to hands-off-flow volume, percentage take, and maximum abstraction volume. The combination of uneven climate change forcing across Great Britain and the island of Ireland, as well as differences in abstraction license conditions, gives cause to believe that different areas may see varying impacts on RoR hydropower generation under projected climate change. Different abstraction license conditions across the nations in particular are likely to have an impact on the ability of RoR schemes to make optimal use of future streamflows for the benefit of renewable power generation.

This study aims to first demonstrate the impact of a future worst-case climate change scenario on streamflows across the British Isles (Great Britain and the island of Ireland). This work, using the latest (2018) UK climate projections (UKCP18) from the UK Met Office, will provide insight into regional climate change patterns influence over streamflows, and therefore likely water resource availability. Second, the impact of the modelled streamflow alterations on water abstraction characteristics of RoR hydropower across the British Isles will be quantified, taking account of nation-specific abstraction license conditions for the four nations of the UK, and Ireland. This work allows investigation into the combined impacts of both alterations in streamflows due to climate change, and the impact of nation-specific abstraction license condition, on the availability of water for abstraction for hydropower, and therefore potential power generation implications.

2. Data and methods

2.1. Streamflow modelling

Future daily streamflow at gauging stations in 585 individual catchments has been simulated using the spatially lumped version of the EXP-HYDRO hydrological model [28]. Taking daily precipitation, air temperature, and potential evapotranspiration (PET) as inputs, EXP-HYDRO conceptualizes the catchment as a bucket store, with an additional snowpack storage component. Water balance of the bucket is calculated based on Equation (1):

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

where dS is catchment bucket water storage (mm), P_r is rainfall (mm/day), M is snowmelt (mm/day), ET is evapotranspiration (mm/day), Q_{bucket} is runoff from water stored in the bucket (mm/day), and Q_{spill} is bucket capacity excess runoff (mm/day). Daily streamflow is therefore equal to the sum of Q_{bucket} and Q_{spill}. EXP-HYDRO was selected for use in this study partly due to its computational efficiency, important when considering the large number of catchments to be modelled, in combination with the twelve repeat runs required for each catchment based on the twelve realizations of future climate scenarios (more details below). Furthermore, the model was preferable due to its relatively simple data input requirements (air temperature, precipitation and PET), which were available for all studied catchments, as well as its consideration of snowpack storage, which is important for some of the more northly and mountainous catchments studied. In addition, the model has been used for large scale analysis such as this previously, with Patil and Stieglitz [28] analyzing some 756 catchments across the contiguous United States, with the model performing most successfully in wetter and mountainous catchments, in common with the catchments studied in this research. Much greater detail on EXP-HYDRO, such as underpinning equations for calculation of potential evapotranspiration, snow melt, and bucket runoff generation, can be found in Patil and Stieglitz [28].

For nations in Great Britain, timeseries of historical air temperature, precipitation, PET, and streamflow have been obtained from the CAMELS-GB dataset [29]. This dataset of 671 catchments has been specifically developed for environmental modelling and analysis, with various catchment attributes and meteorological variables provided for each catchment, covering the period 1970–2015 [29]. For both Northern Ireland and Ireland, a comparable dataset to CAMELS-GB is not available. In Northern Ireland a manual selection of catchments with near-natural flow and sufficient record length has been undertaken from the National River Flow Archive dataset [30], this identified 25 catchments before calibration. For Ireland, catchments studied have been identified from the Irish Reference Network of hydrometric stations [6] as well as further suitable stations maintained by the Environmental Protection Agency and Office of Public Works. A total of 36 catchments for Ireland were therefore identified pre-calibration. Historical climate data for both Ireland and Northern Ireland are from the Europe-wide 0.1° gridded Copernicus E-OBS dataset [31]. In order to provide a single timeseries of each of the required meteorological variables for each catchment, the daily mean average of all grid squares within each catchment was taken.

Multi-parameter calibration of the six EXP-HYDRO calibration parameters [28] for the total 732 individual catchment models has been executed using the Particle Swarm Optimization method [32]. Eighteen hydrologic years (1988–2005) were used for calibration, with the two proceedings years used as a warm-up period. The 2006–2015 hydrological years were then used for validation. This total 30-year timespan (1986–2015) of data was the longest complete period available across the required meteorological and streamflow datasets in all nations. Only catchments with Kling-Gupta Efficiency [33] scores greater than 0.6 for both calibration and validation were retained for study.

Of the initial 732 catchments identified, 585 (Great Britain 546, Northern Ireland 18, Ireland 21; Fig. 1) could be calibrated and validated to the set benchmark. Future modelling for these remaining catchments has been completed for 60 hydrological years (2021–2080) using the latest and most comprehensive climate projections for the UK and Ireland, the Met Office Hadley Centre's 2018 UK Climate Projections (UKCP18). Specifically, the 'Regional Projections on a 12 km grid over the UK for 1980–2080' dataset [34] has been used, with its spatial extent covering the full UK and Ireland study area. This dataset is based on a worst-case future climate change scenario using Representative Concentration Pathway 8.5 (RCP8.5) from the Intergovernmental Panel on Climate Change. This pathway represents a pessimistic future, with no downturn in global greenhouse gas emissions, and was selected to enable robust future planning of mitigation measures. The 12 km resolution projections provide an ensemble of twelve regional climate model projections derived, and dynamically downscaled from, twelve of the fifteen members of the 60 km HadGEM3-GC3.05 global coupled model perturbed parameter ensemble [35]. Uncertainty in the global model ensemble members, as well as natural climate variability between them (being based on a range of plausible climate storylines), cause the 12 outputs to differ when downscaled [36]. Using the same method implemented for the aforementioned E-OBS data across the island of Ireland, the mean of all grid squares within a given catchment was taken, in order to provide a single future timeseries of precipitation,

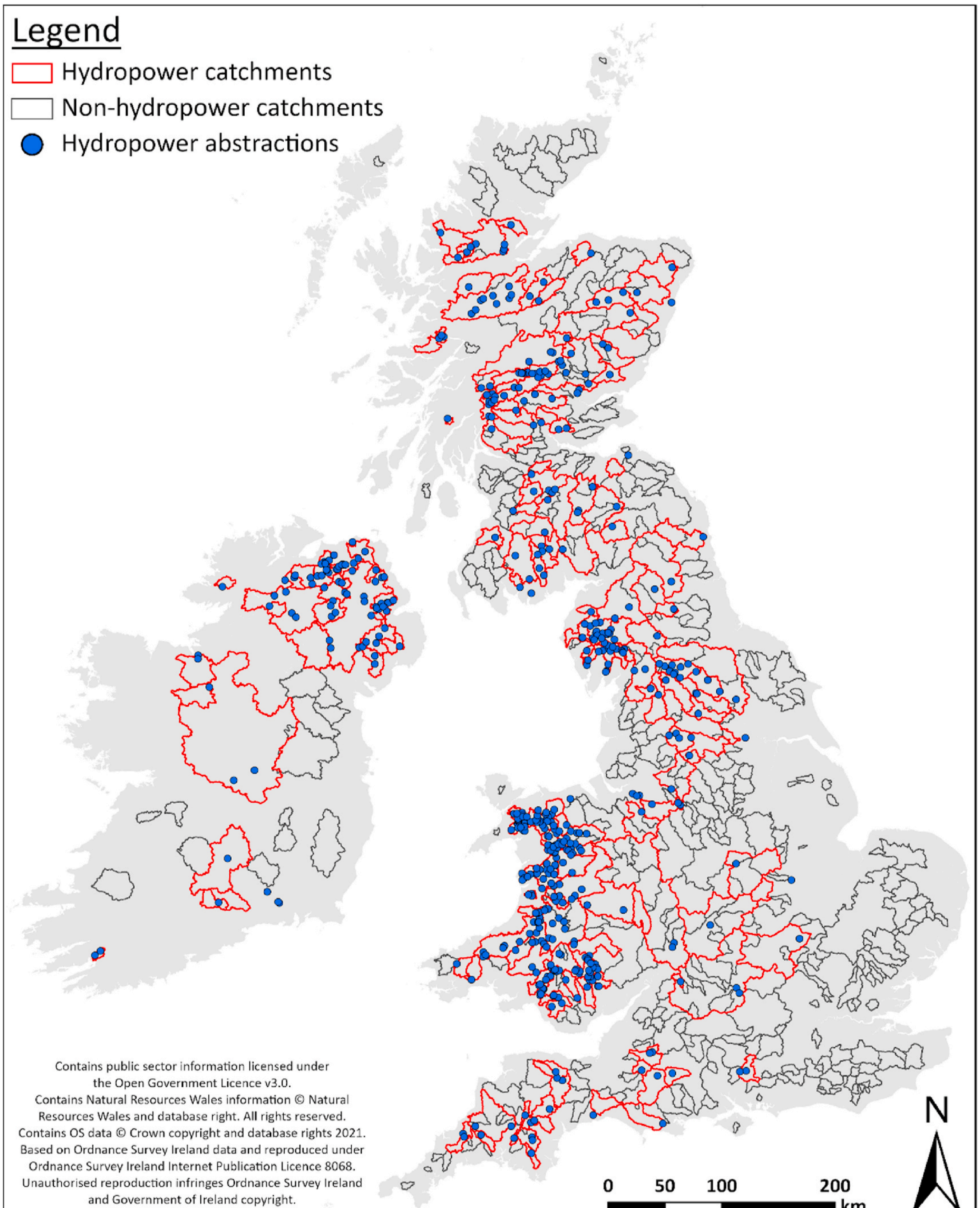

Fig. 1. The 585 modelled catchments, with the 178 catchments containing, or immediately upstream of, one or more studied run-of-river hydropower sites (blue markers), shown in red.

temperature, and PET for each catchment. This process was completed for each of the twelve ensemble members, resulting in twelve future climate scenarios for each catchment, twelve future streamflow timeseries outputs per catchment, and a therefore a total of 7020 60-year daily timestep model runs. It is the mean of the twelve streamflow timeseries for each catchment that has been analysed and presented in this paper. A flow chart depicting the methodological process of calculating the future streamflow projections can be found in Appendix Fig. A1.

2.2. Hydropower water abstraction calculation

In terms of hydropower water abstraction location data, this has been obtained from separate datasets provided by the environmental regulator for each nation [37–40]. These datasets were then filtered so as to only contain water abstraction sites for RoR hydropower schemes which take water from a single source for a single purpose, a total of 808 across the five nations. When cross-referenced, 531 of these sites, 65.7%, were found to be within, or immediately downstream of, one of 178 of the original 585 modelled catchments (Fig. 1); a breakdown of the locations of these by nation is shown in Table 1. We have no reason to believe the hydropower sites studied in this work to not be representative of the unmodelled schemes. For each of these 531 hydropower abstraction sites, a future streamflow timeseries was extrapolated from the 12-member average future streamflow timeseries for the gauge within the corresponding catchment. This extrapolation was conducted using the area discharge method, in conjunction with computed flow accumulation values. The remaining 277 water abstraction sites for hydropower in unmodelled catchments were removed from the study.

The daily abstractable water resource for the hydropower schemes was calculated individually for each abstraction site, using abstraction license conditions as laid out in relevant guidelines by environmental regulators for each nation. While it is likely that variation between sites within a given nation will exist, due to the lack of site/scheme specific details, it has been assumed that standard conditions are used at each scheme. Each nation's regulator sets guidelines, for non-ecologically sensitive surface waters, of likely values for hands-off-flow volumes, maximum abstraction rates, and percentage take, for the protection of low flows, high flows, and flow variability respectively. Table 1 provides the abstraction license conditions that have been used for hydropower schemes in each nation, based on the relevant environmental guidelines [41–44]. These values have been calculated for each hydropower water abstraction site based on historical flow records, with the conditions then applied to the projected future daily streamflow timeseries. Firstly, the surplus amount of water available for abstraction ($Q_{surplus}$) on a given day has been calculated according to Equation (2):

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

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

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

where Q_{take} is the percentage take, A_{start} is the minimum abstraction volume needed to start the turbine for efficient operation, and A_{max} denotes the maximum allowable abstraction volume (see process schematic in Fig. A1). The resulting timeseries represents a record of daily permitted abstractable water resource for each hydropower water abstraction site under the assumption that each scheme takes the maximum allowable water resource each day. In addition, it is assumed that each hydropower scheme is operating with an impulse type turbine, these are the predominant turbine type for small RoR schemes such as those studied [45–47], due to their high efficiency at low percentages (10%–15%) of designed maximum flow [48–50]. For this reason, A_{start} has been set at 15% of A_{max} for each scheme, with A_{max} being the assumed designed maximum flow volume.

The daily abstractable water resource timeseries for each hydropower scheme has then been examined through the calculation of four factors on both a seasonal and annual basis. These four factors are, 1) number of days abstraction is possible (days A_{start} achieved), 2) number of days maximum abstraction (A_{max}) is reached, 3) mean abstraction on days abstraction is possible (mean A_{daily}), and 4) total abstraction (A_{total}). In addition to the trend analysis, detailed in Section 2.4, the seasonal and annual totals have also been summed for each of the five nations, to give a national perspective of any changes.

2.3. Hydropower generation calculation

Due to the impulse type of turbines assumed to be in use, and our focus on RoR schemes, a linear relationship has been implemented between calculated daily total water abstraction and daily total power generation. This assumption has been made due to, as aforementioned, impulse type turbines operating with a high and stable level of efficiency across a wide range of incoming water flows, from 15% to 100% of maximum designed flow [48–50]. Therefore, no disproportionate power generation benefit is provided at higher flows. This assumption is also in line with various previous studies that have equated run-off and streamflow change to changes in hydropower energy production [27, 51–54]. In addition, due to the lack of any hydropower scheme specific details, such as net head, it is not possible to complete a calculation of power implications in terms of actual energy output, only relative change via the abstraction-generation relationship. Both of the islands studied have individual singular power transmission networks, with power production in England, Wales, and Scotland supplying the GB National Grid, and Northern Ireland and Ireland suppling the island of Ireland Single Electricity Market. Therefore, changes in hydropower generation are best thought of collectively for each island, rather than at national levels, as power generated will contribute towards, and have a role to play in balancing and providing resilience to, those systems as a whole. For this reason, calculations of power generation changes under future climate change have been summed, to show net change for the

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

Nation	All modelled catchments	Catchments with 1+ HP abstraction	Modelled HP abstraction sites	Abstraction conditions		
				HoF	A_{max}	Q_{take}
England	323	60	115	Q_{95}	$1.3{*}Q_{mean}$	35%
Wales	64	40	218	Q_{95}	Q_{mean}	70%
Scotland	159	52	113	Q_{95}	$1.5{*}Q_{mean}$	50%
N. Ireland	18	18	72	Q_{80}	Q_{mean}	50%
Ireland	21	8	13	Q_{95}	Q_{mean}	50%
Total	**585**	**178**	**531**			

energy transmission systems of both islands.

2.4. Trend analysis

Mann-Kendall trend analysis [55,56] has been used in the assessment of trends in both the future 12-member mean streamflow projections for all 585 catchments, as well as for each of the four factors analysed for the 531 studied hydropower schemes. This analysis has been conducted annually, based on hydrological years (October–September), and for all four seasons, where winter is December–February, Spring is March–May, Summer is June–August, Autumn in September–November. The Mann-Kendall test is non-parametric and therefore suitable for use here due to the nature of hydrological data, which is usually non-normally distributed, and exhibits seasonality. In addition, the Hamed & Rao method of auto-correlation correction [57] has been applied, in conjunction with Sen's slope estimator [58] to provide further detail on the direction and magnitude of any detected trends. Such analytical method is consistent with hydrological timeseries analysis in similar works [6,59–63], and is a standard method in the field.

3. Results

3.1. Average streamflow trends

The trends observed in seasonal and annual average streamflow across the 60-hydrological year period studied can be seen in Fig. 2. Seasonal trends generally have a larger magnitude of change than is seen annually. In addition, the seasonal trends can be seen as an exacerbation of current seasonal streamflow patterns, particularly for the island of Ireland and western areas of Great Britain. In these areas especially, periods of higher flow presently, winter and spring, are increasing, while present periods of lower flow, summer and autumn, are declining. However, these trends are not spatially uniform, with central and southeastern England seeing declines in winter and spring streamflows, in contradiction to the rest of the study area. At an annual perspective, this leads to an overall decline in average streamflows across much of eastern, central, and southern England, while increases are seen along the west coast of Great Britain. On the island of Ireland however, the predominately negative trends in annual average streamflow are likely caused by the decreases in summer and autumn streamflow being larger in magnitude than winter and spring increases.

In winter, the largest magnitude changes are reserved for the mountainous regions or north Wales, northwest England, and northern Scotland. Trends across the island of Ireland are generally increasing, with the magnitude of these increases being larger in the west, as with Great Britain. Small declines are seen in central and southern England. These trends are replicated in direction and spatial distribution, albeit much lesser in magnitude, in spring streamflows across both islands, with many catchments showing almost no change. In summer, decreasing trends are seen across the study area, with larger decreases seen in western regions, such as the island of Ireland and west coast Great Britain, than in eastern and southern areas of Great Britain. This trend is somewhat reversed in autumn however, where western Great Britain sees small declines in the south, and small to medium increases in the north, while eastern and southern regions see large magnitude declines.

Taking the mean of the first, middle, and final nine years of projected annual streamflows (equivalent to 15% of the timeseries each), and comparing (Table 2), gives perspective on the speed of change between the medium and long term respectively. It can be observed that a decline is present in all nations in the medium term, and that this is most pronounced in England, Northern Ireland, and Ireland, seeing 4.0%, 5.3%, and 3.1% declines respectively. Wales and Scotland experience smaller decreases, 1.0% and 1.2% in turn. These trends are continued into the long term in all nations except Scotland, which sees a reversal, culminating in 1.1% increase when comparing the 2021-29 mean to the 2172-80 mean. In the other four nations the rate of decline clearly slows in the second half the century, in Northern Ireland in particular the rate of change appears to plateau, with the difference from the 2021-29 mean being a 5.3% reduction when compared to both the 2047-54 and 2072-80 means.

3.2. Hydropower water abstraction characteristics

3.2.1. Number of days abstraction is possible

Within each season, similar trends are observed in all nations when looking at the mean number of days per scheme that abstraction for hydropower production is possible (Fig. 3). The least change is generally seen in winter, with all nations except for England essentially continuing with being able to abstract nearly 100% of the time. In England in winter a small decline is seen, driven by hydropower schemes in central and southwestern England (Fig. A2). Few days of abstraction were already possible in summer at the start of the study period, however in all nations this essentially reduces to zero days by 2080. The most variation in trend magnitude between nations is seen in autumn (Fig. 3 and Fig. A5), with Wales seeing the largest magnitude of change, decreases specifically. Contrastingly, in Scotland, hydropower schemes in the northwest experience small increases in the number of days that abstraction is possible (Fig. A5), leading to a more stable picture in that season, as well as annually, when looking at Scotland overall (Fig. 3). In the other four nations the annual analysis shows small declines, with this being most pronounced in Wales, mostly due to the contribution of autumn reductions aforementioned.

3.2.2. Number of days maximum abstraction reached

Little change is seen in the mean number of days that maximum abstraction is reached per scheme in England and Scotland in any season or annually (Fig. 3), with the value essentially not being reached across the study period. In Northern Ireland and Ireland, the maximum abstraction volume is only reached regularly in winter, with small increase being observed over the period to 2080, and a therefore corresponding trend in the annual analysis. In Wales, maximum abstraction is reached in winter, spring, and autumn, as a likely consequence of lower maximum abstraction volume and higher percentage take in the abstraction license conditions. While there is an increase in frequency of maximum abstraction being reached in winter and spring, a minimal decline is seen in the autumn timeseries. At an annual perspective however, there is ~20% increase.

3.2.3. Mean daily abstraction

When considering the mean daily abstraction, for days when abstraction is possible, increases are generally present in all seasons except summer (Fig. 4; Table 3). The largest of these increases in all nations except Wales, is in winter, for Wales similar increases are seen in winter and spring, 6.2% and 6.4% respectively (Table 3). England and Scotland see the largest changes, be they negative or positive, in all seasons. Annually the increases are 12.1% and 15.5% respectively, substantially larger than for Wales, Northern Ireland, and Ireland, at 10.7%, 7.8% and 8.4%. At an individual hydropower scheme level, the trends in mean daily abstraction are arguably the most spatially consistent of all of the four factors studied, showing little variation across the study region (Figs. A2-A6).

3.2.4. Total abstraction

The results of the national level total abstraction analysis once again highlight the increased seasonality of future abstraction (Fig. 4; Table 4). In Scotland in particular, substantial increases are seen in winter (18.0%) and spring (10.5%), with a 53.9% decrease seen in summer; this leads to an overall 12.9% increase in annual abstraction across the 60-year study period. In the other four nations summer declines are greater in magnitude, between 59.0% and 77.8%, while increases in winter and spring total abstraction are smaller than Scotland. Scotland is

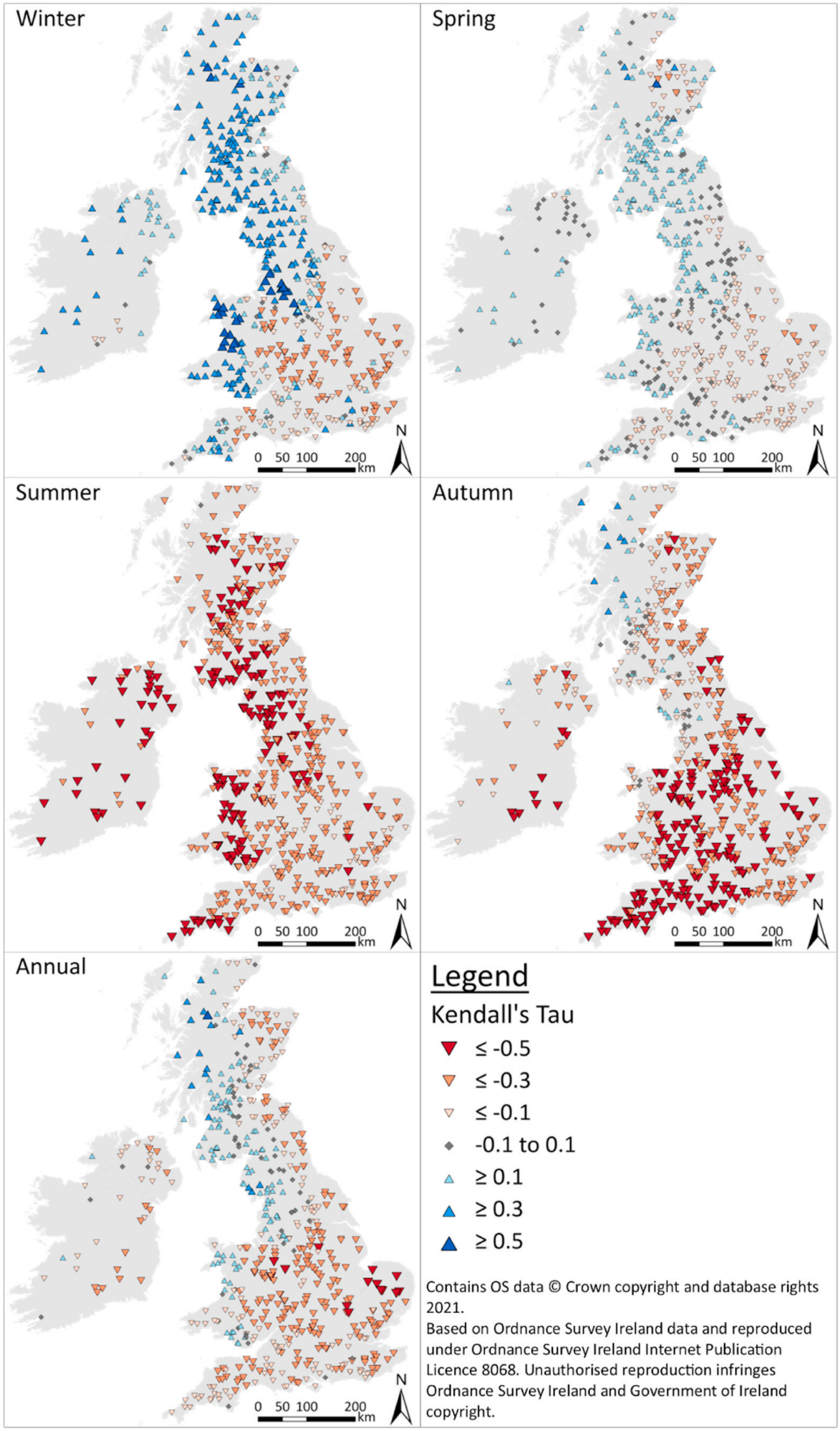

Fig. 2. Mann-Kendall trend analysis results for change in seasonal and annual streamflow (2021–2080).

Table 2
Percentage change in mean annual streamflow of all catchments between the first nine modelled years and the central and last nine modelled years.

Nation	2021-29 to 2047-54	2021-29 to 2072-80
England	−4.0%	−7.2%
Wales	−1.0%	−1.5%
Scotland	−1.2%	+1.1%
N. Ireland	−5.3%	−5.3%
Ireland	−3.1%	−4.7%

also an outlier in autumn, where 12.0%–23.4% decreases are seen in the other nations, while for Scotland the decrease is much smaller at 2.0%. Regardless of the magnitude, across the study area historical observed abstraction patterns can be seen to be exacerbated by future climate change induced streamflow alterations. In terms of the magnitude of annual change, Scotland is once again an outlier from the other four nations, which generally show smaller changes, from a 3.0% increase in England to a 2.1% decrease in Wales; indeed, in Ireland the annual increase is only 0.1% across the six decades (Table 4). Looking at the spatial distribution of trends in individual hydropower schemes (Figs. A2-A6), a similar northeast-southwest divide for Great Britain can

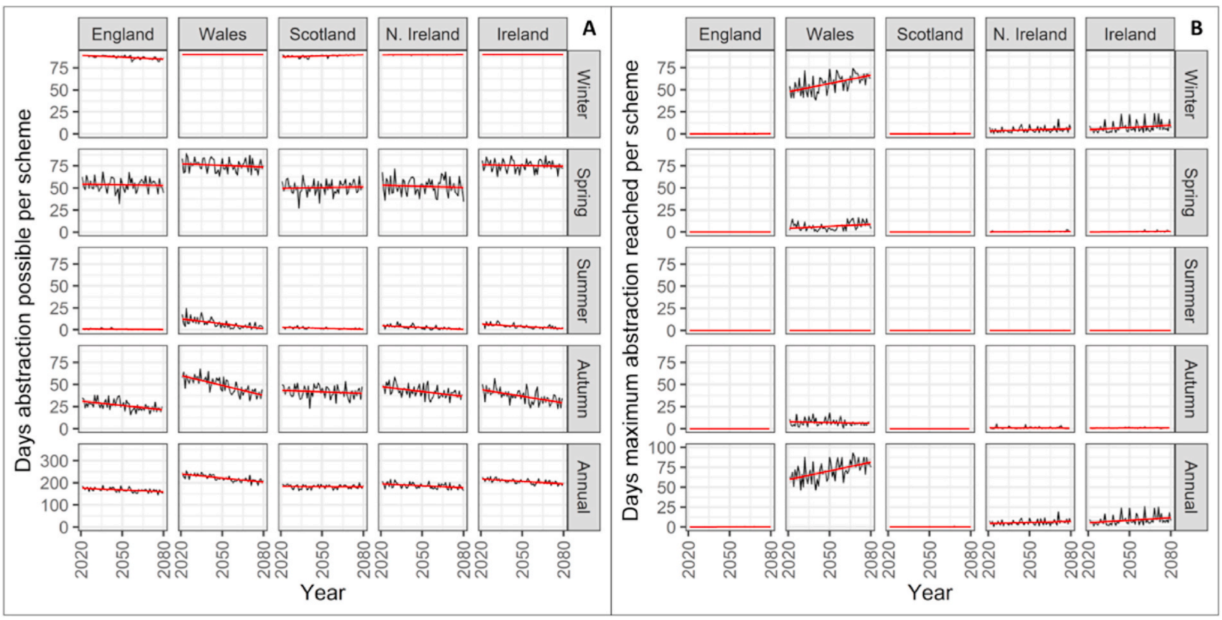

Fig. 3. Seasonal and national timeseries of (**A**) the mean number of days per scheme that streamflow is sufficient to support abstraction for hydropower, and (**B**) the mean number of days per scheme that the maximum abstraction volume is reached per scheme. Red lines show the linear trends across the full 60-year datasets; light grade shading shows trend line 95% confidence range.

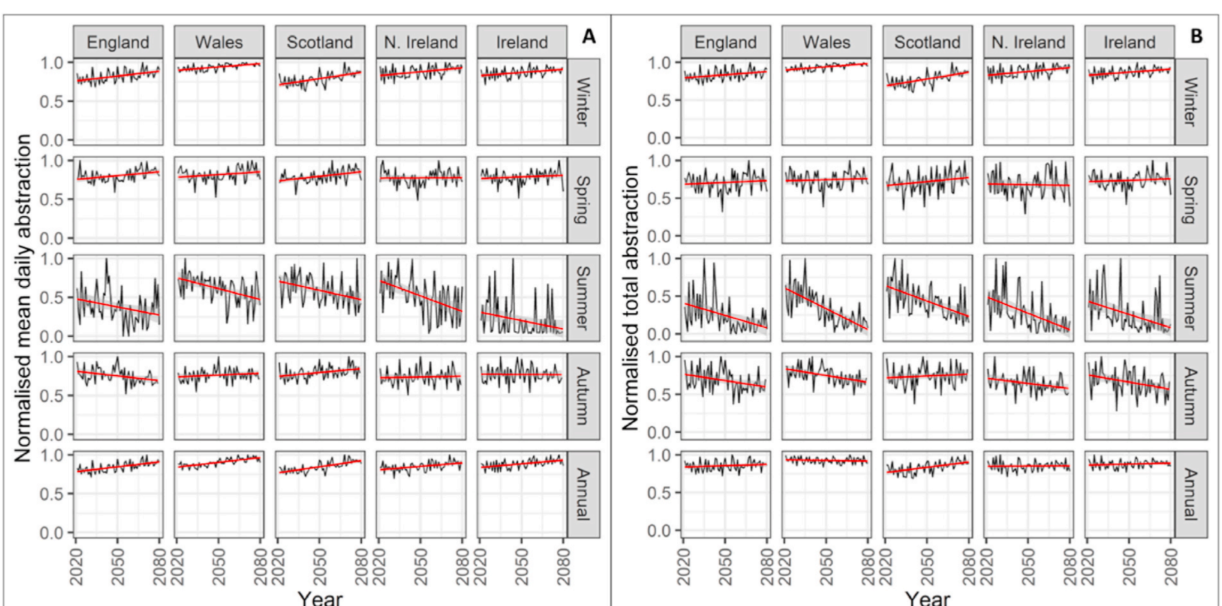

Fig. 4. Seasonal and national timeseries of (**A**) normalized mean daily abstraction volume on days when abstraction is possible, and (**B**) normalized total abstraction volume. Normalization competed by maximum value normalization method. Red lines show the linear trends across the full 60-year datasets; light grade shading shows trend line 95% confidence range.

Table 3
Percentage change in seasonal and annual mean daily water abstraction, on days abstraction is possible, between the 2021-29 and 2072-80 means for each studied nation.

	England	Wales	Scotland	N. Ireland	Ireland
Winter	+12.1%	+6.2%	+16.0%	+9.0%	+7.0%
Spring	+8.8%	+6.4%	+12.6%	−5.6%	+2.2%
Summer	−25.4%	−34.8%	−27.3%	−46.1%	−59.1%
Autumn	−6.6%	+6.2%	+13.5%	+3.0%	+1.1%
Annual	+12.1%	+10.7%	+15.5%	+7.8%	+8.4%

Table 4
Percentage change in seasonal and annual total water abstraction between the 2021-29 and 2072-80 means for each studied nation.

	England	Wales	Scotland	N. Ireland	Ireland
Winter	+7.9%	+6.2%	+18.0%	+9.3%	+7.0%
Spring	+1.6%	+0.4%	+10.5%	−14.4%	−2.5%
Summer	−59.0%	−73.8%	−53.9%	−77.8%	−64.0%
Autumn	−12.0%	−23.4%	−2.0%	−22.3%	−19.0%
Annual	+3.0%	−2.1%	+12.9%	−1.9%	+0.1%

be observed as aforementioned for seasonal and annual streamflow changes. This pattern is somewhat dampened by the impact of abstraction license conditions, however.

3.3. Hydropower generation

Owing to the assumptions made about hydropower operations in this work, as detailed in Sections 2.2 and 2.3, total future power generation for each nation, from the hydropower schemes studied, is assumed to increase or decrease in line with total abstraction. Totals for each nation have been summed to their corresponding island, to give net power generation change over the study period. For Great Britain, an increase is seen in both winter (12.4%) and spring (5.2%) total power generation from the 446 studied hydropower schemes in England, Wales, and Scotland (Table 5). While summer and autumn see decreases, 63.6% and 10.6% respectively, the annual outlook is positive, with an overall 6.2% increase. For the island of Ireland, the 85 hydropower schemes in Northern Ireland and Ireland only see a net increase in power generation in Winter (8.7%). Overall, the decreases in spring, summer, and autumn outweigh this winter increase, leading to a 1.4% reduction in power generation annually by the 2080s (Table 5). The trends seen for Great Britain are strongly influenced by the output of Scottish schemes, which account for ~50% of water abstracted for hydropower, and therefore power generation, in this study; Wales accounts for ~33%, and England the remainder. On the island of Ireland, the majority of abstraction, and therefore power generation contribution, is from Northern Ireland, at ~75% of the total.

Table 5
Projected percentage change in seasonal and annual hydropower generation for Great Britain and the Island of Ireland, when comparing the 2021-29 and 2072-80 means.

Season	Great Britain	Island of Ireland
Winter	+12.4%	+8.7%
Spring	+5.2%	−11.0%
Summer	−63.6%	−76.8%
Autumn	−10.6%	−21.8%
Annual	+6.2%	−1.4%

4. Discussion

4.1. Streamflow

The observed trends in future streamflows show a northeast-southwest divide across Great Britain, in line with the aforementioned results of previous analysis of both historical observations and future projections [7–10]. Prudhomme et al. [23], when comparing mean seasonal flows for 2040–2069 with those for a baseline 1961–1990 period, highlights a decrease in summer mean flow that is particularly pronounced in the west of the UK. Meanwhile, autumn flows are more variable with a larger proportion of the 11 models compared showing a decline, more so for England and Wales than Scotland. Both of these regional scale variations in trends match the observations from this study. Similarly, the findings of Sanderson et al. [26] also show a high degree of correlation with our findings, in particular, summer and autumn flows display decreases for the whole of the UK in summer, and all but the northwest of Scotland in autumn, nearly identical to the results presented here. Our Great Britain results also correspond well spatially with the more contemporary results of Kay et al. [64], from their modelling use the Grid-to-Grid hydrological model. Also using the latest UKCP18 projections under RCP8.5 conditions, a similar distribution in terms of the magnitude and direction of trends across Great Britain is displayed as presented above.

In terms of the island of Ireland, summer streamflow declines are large in magnitude across both nations, with very little change seen in spring flows. However, autumn and winter flows show an east-west divide that has been previously observed, and this carries through to the annual projections. These results relate particularly well to those of Kay et al. [10] in terms of Northern Ireland, who also observe large reductions in summer flows under UKCP18 projections of an RCP8.5 future climate scenario. The east-west divide aforementioned for the island of Ireland is also observed in the results of Kay et al. [10], particularly for autumn and winter flows. With regards Ireland, recent work by Meresa et al. [65] represents the most comprehensive study of future mean flows since Charlton et al. [66], and Steele Dunne et al. [3]. Our observations correspond with those of Meresa et al. [65], especially when comparing their results generated under a worst-case future climate change scenario. Under both models implemented, by the 2080s, increases are shown in winter and spring flows for almost all catchments, with large magnitude decreases seen in summer flows; autumn flows are more variable. Our results also parallel with the RCP8.5 scenario streamflow outputs from the small scale study by Coffey et al. [67], for catchments in the West of Ireland.

4.2. Hydropower water abstraction

As is to be expected, trends in the four hydropower abstraction characteristics studied display similar spatial variation (Figs. A2-A6) as seen in the streamflow analysis. However, it is also clear that differing abstraction license conditions between nations have an impact on the ability of hydropower schemes in some nations to make full use of future streamflows for abstraction. The number of days per year that maximum abstraction volume is reached in Wales, Northern Ireland, and Ireland, for example. Lower maximum abstraction volume limits in these three nations, Q_{mean}, rather than $1.3{*}Q_{mean}$ and $1.5{*}Q_{mean}$, as used in England and Scotland respectively, naturally make it likely that this volume will be reached more frequently. Furthermore, with future streamflows expected to become more seasonally exacerbated, with a greater number of very high flow days in winter and spring in particular, this results in potentially lost abstraction, and therefore also lost power generation. In addition, in Wales, this lower maximum abstraction volume is combined with a higher percentage take, which means the maximum abstraction level is reached sooner even than in Northern Ireland and Ireland. The impact of the maximum abstraction volume and percentage take limits can clearly be seen in the results (Fig. 3). English and Scottish hydropower schemes almost never reach their maximum abstraction volumes, whereas in Wales, the limit is being reached nearly two thirds of the time in winter by the 2070s, up from around half of the time in the 2020s. The increases are more modest in winter in Northern Ireland and Ireland; this being the only season effected for these two nations. For Wales, the impact of abstraction license conditions is still felt into spring, with a small increase in the number of days the maximum volume is reached. The results clearly show therefore that abstraction license conditions are potentially limiting Welsh hydropower schemes in particular from making the best use of future flows.

Conversely, when looking at lower flows and how often hydropower schemes are able to be started, the more stringent HoF volume in Ireland (Q_{80}) compared to the other four nations (Q_{95}), seems to have little impact. The mean number of days per scheme that abstraction is possible is in line with the other four nations for all seasons, and annually (Fig. 3). This lack of impact is likely due to shift in the annual hydrograph while HoF volumes stays static. With future streamflows showing greater seasonality there is likely to be an increase in the frequency of very high and very low flows, and less variation between, this effectively begins to flatten the central section of the flow duration curve, meaning the difference in probability in the future of Q_{80} and Q_{95} flows occurring is reduced. This highlights the need to keep abstraction license conditions under review for current schemes, but also to license future schemes in a manner that takes account of future flows, instead of relying on historical flows only. The outlier in terms of the number of days that abstraction is possible is England, where in winter there is a small decline across the study period. In the other four nations this is stable, with, on average, abstraction being possible ~100% of the time in winter. However, when considering the spatial variation of trends in future streamflow changes (Fig. 2), the decline in the number of abstraction days is unsurprising, with almost all of the observed negative streamflow trends being in English catchments.

When looking at the impact of streamflow changes on water abstraction (Fig. 4; Tables 3 and 4), it is clear that future hydropower abstraction is likely to be concentrated in winter and spring. For England and Scotland, the higher licensed maximum abstraction volumes allow for the increased occurrence of higher flows in these seasons to be taken greater advantage off. This in turn compensates for lower abstraction in summer in both nations, as well as in autumn in England. Due to the fact that in winter and spring abstraction was already possible a large proportion of the time at the start of the study period, few additional days of abstraction have been added, this therefore leads to mean abstraction, on days when generation is possible, increasing. At an annual perspective these seasonal changes lead to fewer days per year when abstraction will take place, but greater abstraction overall, which creates a much more seasonally unbalanced picture in these two nations in particular. While winter and spring flow increases are better able to be utilized in England and Scotland, in Wales, Northern Ireland, and Ireland, increases in mean daily abstraction are also seen when looking annually. These trends are smaller in magnitude than in England and Scotland however, due to the abstraction license conditions in these nations. Indeed, at an annual perspective we see declines in total abstraction potential in Wales and Northern Ireland, and little change in Ireland (Table 4), likely again due to the difference in licensed maximum abstraction volume and percentage take. Scotland, which has the most generous maximum abstraction volume conditions correspondingly sees the largest annual total abstraction potential increase of all nations, 12.9%; this is driven by strong growth in winter (18.0%) and spring (10.5%). Of course, regional variation in future climate forcing also plays a role in the national level differences seen, with Scotland in particular seeing larger increases in annual average flows than other nations. This in turn leads to likely higher water abstraction for hydropower.

4.3. Hydropower generation

Given the changes in future water abstraction characteristics presented, it is clear that alterations to the quantity and timing of hydropower generation will be felt across the UK and Ireland over the next 60 years. Although little work has been completed for the UK and/or Ireland as a whole in this area, larger regional studies covering the area do conclude similar changes to those presented here to be likely. Lenher et al. [54], in a study of hydropower potential in Europe, for example, suggest that for the UK, RoR hydropower potential is likely to increase by around 4% by the 2070s, with this being particularly evident for Scotland, similar to our results. In addition, smaller studies of specific UK nations, such as Carless & Whitehead [52] for Wales, and Sample et al. [51] for Scotland, conclude that currently installed hydropower schemes are not best placed to make optimal use of future streamflows, particularly increased maximum flows in winter. For this reason, annual production levels are shown to likely decrease, due to the summer reductions in production outweighing winter increases. However, these studies use the assumption that maximum abstraction is set at Q_{mean}, while this corresponds to our Welsh assumption, for Scotland, based on the latest advice from the Scottish Environmental Protection Agency, we have assumed a maximum abstraction of $1.5*Q_{mean}$. Given that Scottish hydropower schemes account for roughly half of the power generation potential for Great Britain in our study, the ability of these schemes to make use of these higher flows, negates the reductions seen in overall annual abstraction, and therefore power generation, in Wales. For this reason, this work suggests an overall increase in power generation protentional for Great Britain (Table 5), in agreement with the results of Lehner et al. [54] for the UK. However, the conclusions of Carless & Whitehead [52] and Sample et al. [51] are supported for England, Wales and the island of Ireland, with current abstraction license conductions limiting the ability of schemes to maximize increased winter streamflows for power generation.

5. Conclusions

Future worst-case scenario climate change is likely to bring substantial change to the hydrology of the UK and Ireland, with the likelihood of much larger winter streamflows, and much lower flows in summer. In addition, the impact of climate change will not be evenly felt across the region, with northwest-southeast divide seen across Great Britain, in line with previous works. On the island of Ireland, the magnitude of modelled changes is generally less severe than those in Great Britain. However, as with its neighboring island, there is also an east-west divide, albeit less prominent, in the changes seen, bringing more serious impact for some catchments than others. For hydropower, greater seasonality in abstraction, and therefore generation potential, is likely to be the main impact of a worst-case future climate scenario for both the UK and Ireland. However, at an annual perspective the picture is more stable with only a small decline seen in total water abstraction in Wales (−2.1%) and little change across the island of Ireland (−1.9% to +0.1%). Indeed, England and Scotland in particular seem to benefit in the future from increased winter and spring flows, bringing about abstraction potential increases, especially so in Scotland (+12.9%). These changes in water abstraction timing and quantity have clear implications for corresponding overall power generation from hydropower schemes, especially so for the island of Ireland which sees a decline of 1.4% in projected annual average power generation. These changes potentially limit the ability of the sector to contribute renewable energy to the electricity grid consistently when needed, especially in summer and autumn, bringing implications for emission reduction targets.

The methods presented in this work allow, for the first time, for the direct estimation of power generation from streamflow projections for RoR hydropower schemes on-mass. While these methods have made use of standard abstraction license conditions applied across all schemes in each of the five nations studied, there is scope for the method to be applied at this scale with license conditions for individual schemes, where this data is readily available. Such analysis with additional data would require minimal alteration to the model code, as the methodological processes and equations used in remain applicable across RoR schemes with different abstraction conditions. While the methodology used in this paper likely does miss some nuance in the specific scheme operation characteristics due to the standard abstraction license conditions applied, for a national scale study the assumptions made are justifiable. In addition, the results of this work are highly likely to be representative of other non-modelled RoR schemes within the study area, with some applicability to impoundment-type schemes also, although clearly this latter type of hydropower operation has added resilience to streamflow alterations due to the water storage capability.

Future work should look to fully quantify the power generation output implications of the observed abstraction alterations, to ensure robust planning of the future energy system. In addition, we have shown that abstraction license conditions have the potential to hamper the optimal use of future flows for hydropower generation. Therefore, further investigation into the impacts of abstraction license conditions based on historical flow conditions, on the future operations of existing and planned hydropower schemes is needed. Despite the results presented, it is clear that hydropower has a continued and important future role to play in a more sustainable future energy generation system in the UK and Ireland. The hydropower sector still has the ability to add resilience to the energy networks of the UK and Ireland over the next 60 years, especially in winter months, when such added resilience is most required; this also aids in moving towards the successful accomplishment of government net-zero emissions targets.

Appendix

CRediT authorship contribution statement

Richard J.H. Dallison: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Sopan D. Patil:** Conceptualization, Software, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Richard Dallison reports financial support was provided by European Regional Development Fund. Sopan Patil reports financial support was provided by European Regional Development Fund.

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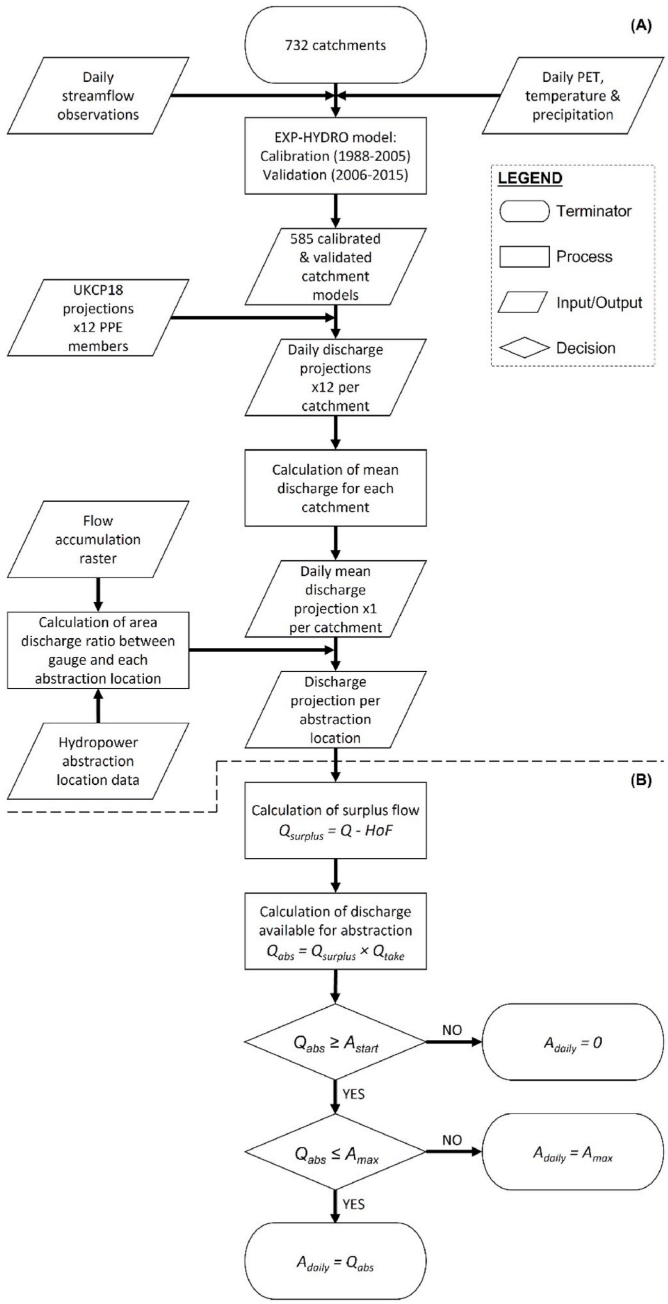

Fig. A1. Methodological process and data inputs for the calculation of **(A)** future daily streamflow timeseries, and subsequently **(B)** daily abstractable water volume.

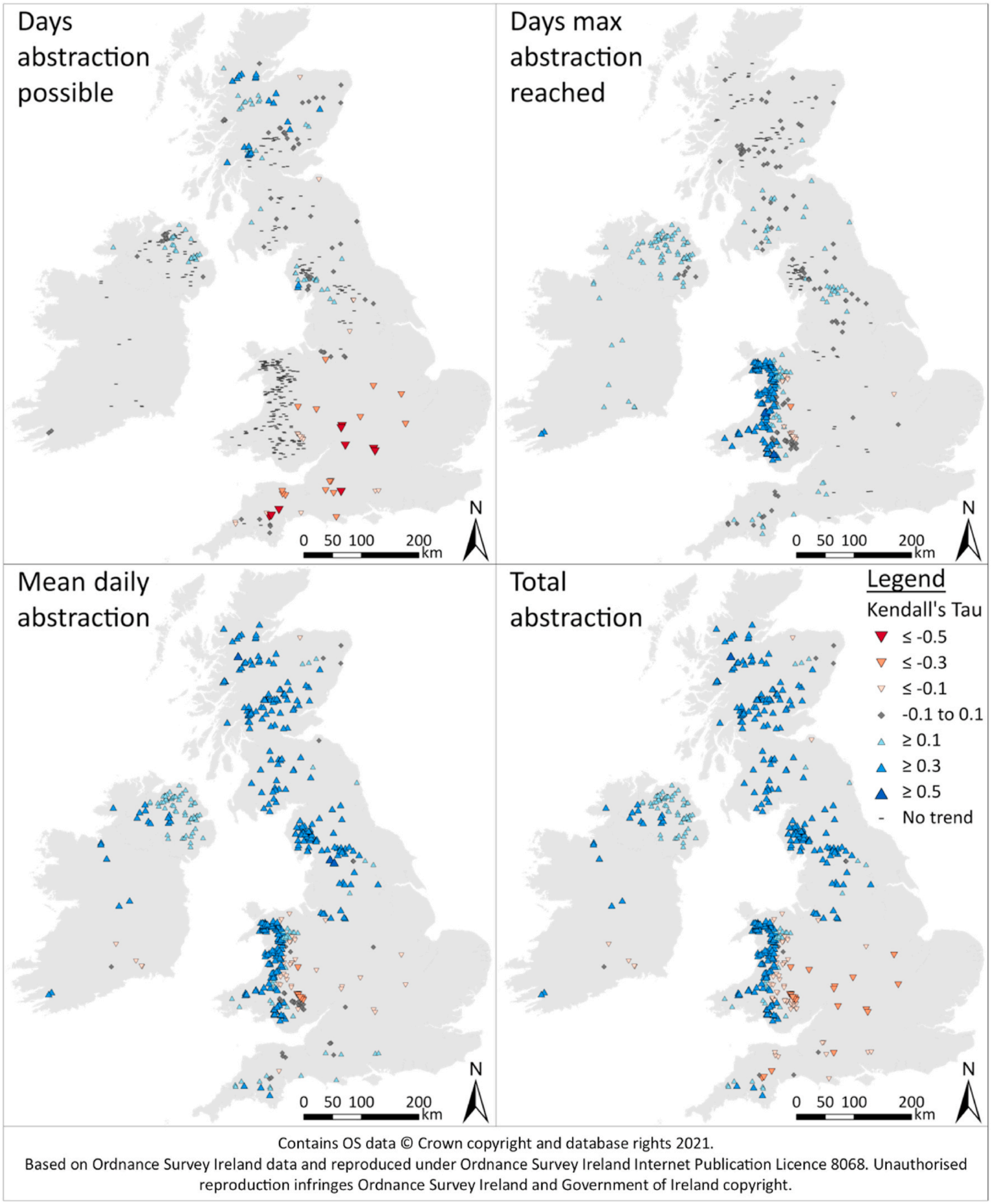

Fig. A2. Winter (December–February) Mann-Kendall trend analysis results for change in water abstraction characteristics (2021–2080).

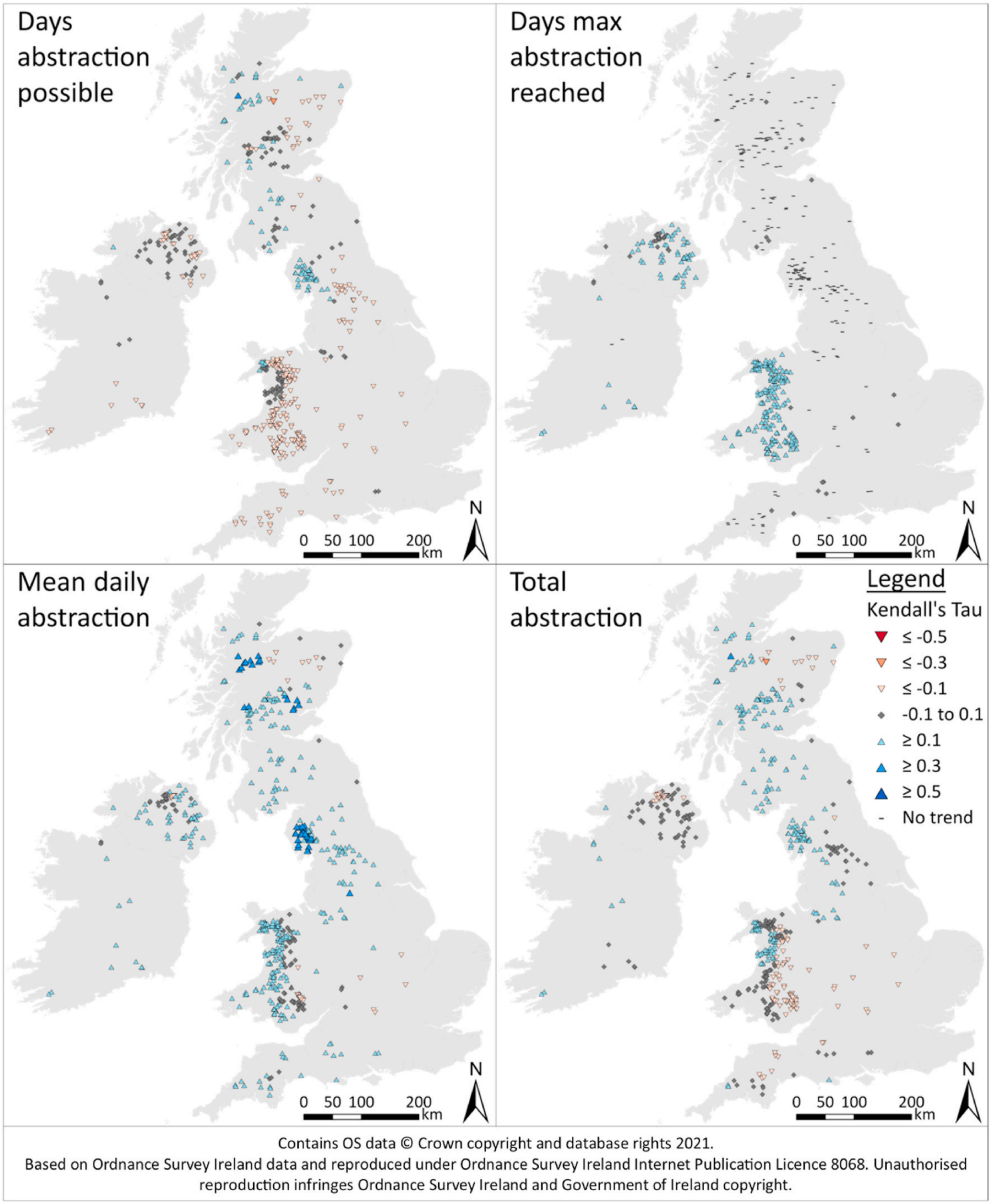

Fig. A3. Spring (March–May) Mann-Kendall trend analysis results for change in water abstraction characteristics (2021–2080).

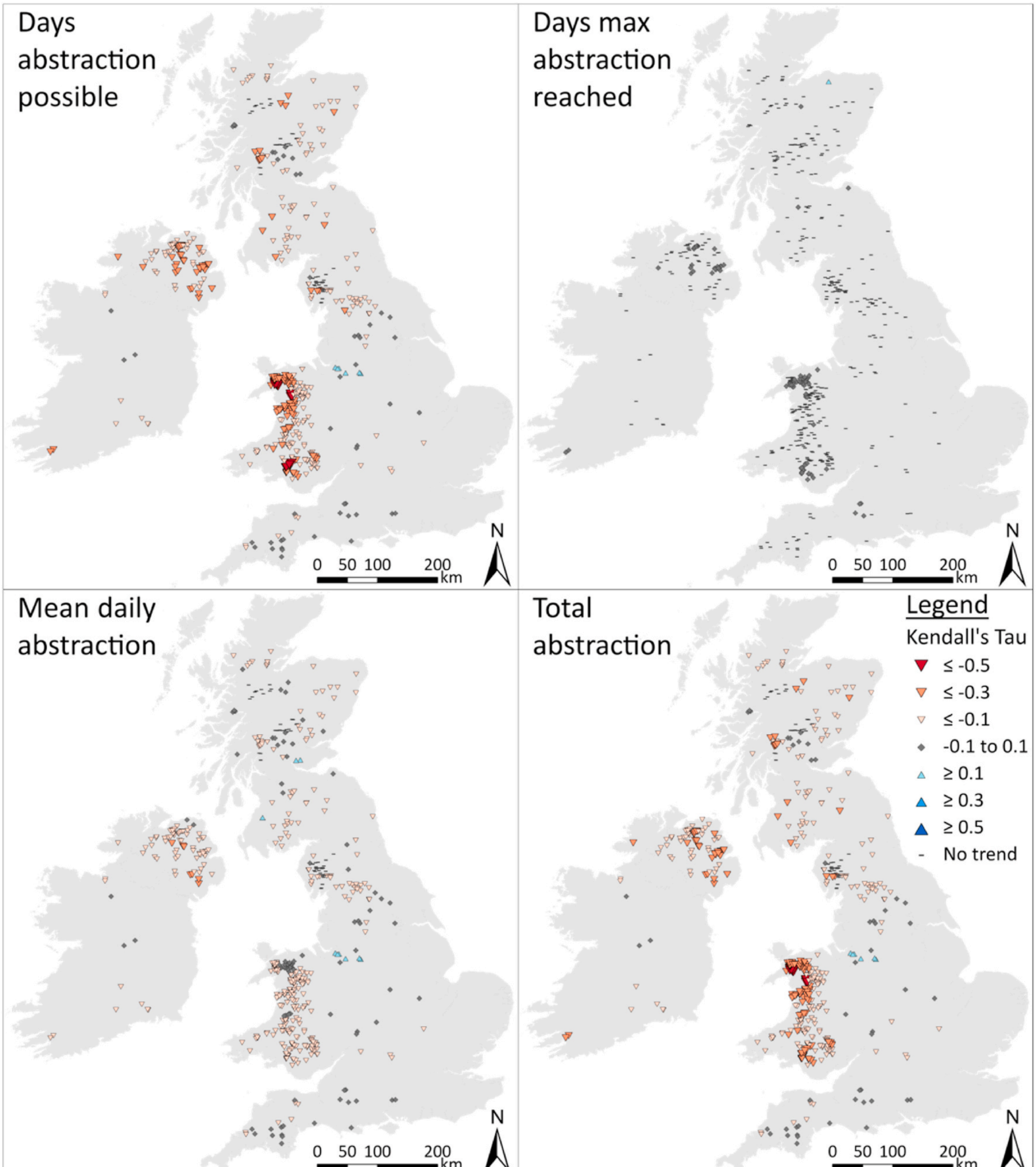

Fig. A4. Summer (June–August) Mann-Kendall trend analysis results for change in water abstraction characteristics (2021–2080).

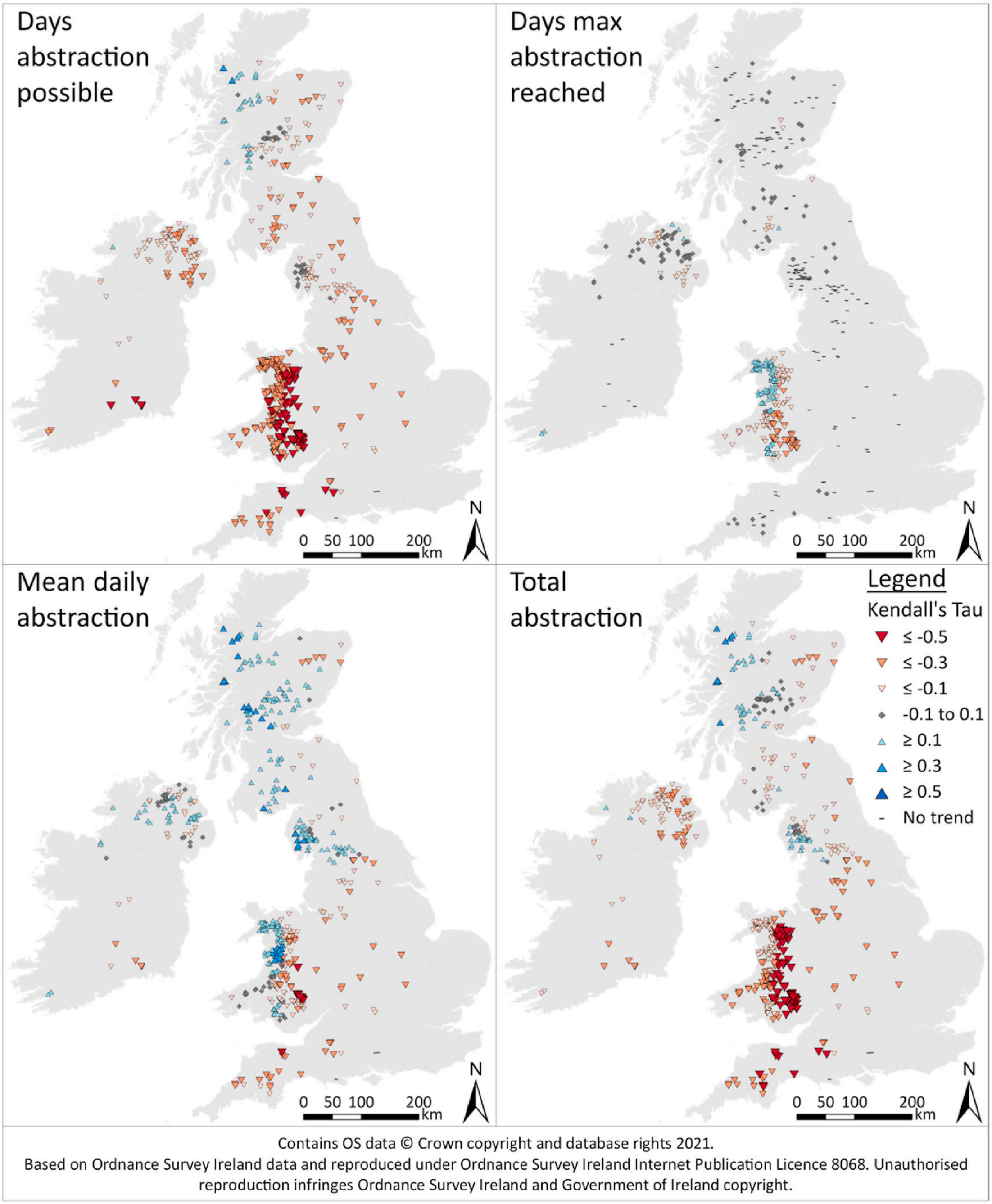

Fig. A5. Autumn (September–November) Mann-Kendall trend analysis results for change in water abstraction characteristics (2021–2080).

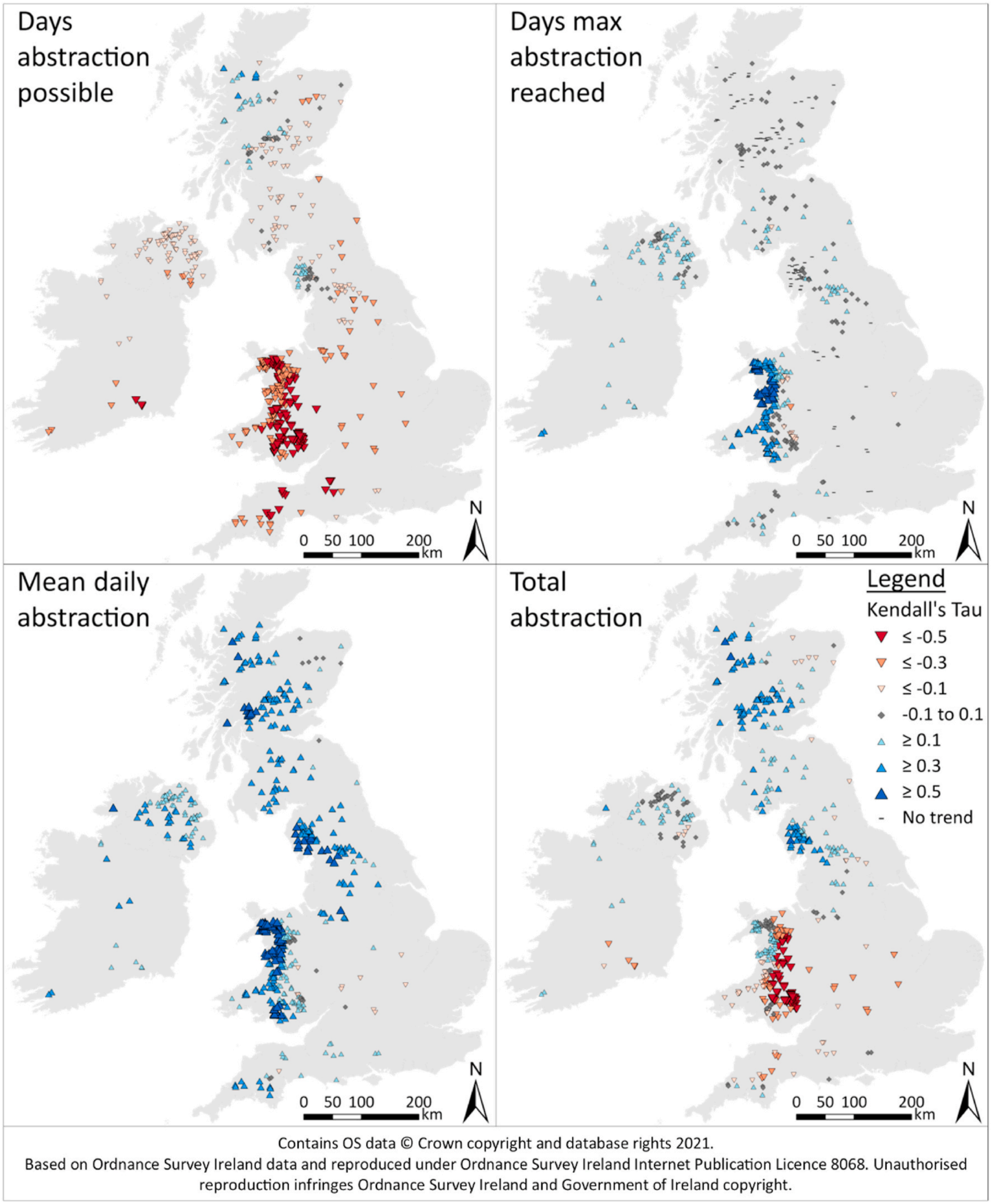

Fig. A6. Annual (hydrological year) Mann-Kendall trend analysis results for change in water abstraction characteristics (2021–2080).

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