



# Climate Change Impacts on Irish River Flows: High Resolution Scenarios and Comparison with CORDEX and CMIP6 Ensembles

Conor Murphy<sup>1</sup> · Anthony Kettle<sup>1</sup> · Hadush Meresa<sup>1</sup> · Saeed Golian<sup>1</sup> · Michael Bruen<sup>2</sup> · Fiachra O'Loughlin<sup>2</sup> · Per-Erik Mellander<sup>3,4</sup>

Received: 2 December 2022 / Accepted: 1 February 2023 / Published online: 16 February 2023  
© The Author(s) 2023

## Abstract

Climate change is likely to impact water quality, resource availability and riverine ecosystems. While large ensembles are available to assess future impacts (e.g., the Coupled Model Intercomparison Projects (CMIP) and/or CORDEX) many countries have developed their own high-resolution ensembles. This poses a selection problem with robust adaptation dependent on plausible ranges of change being adequately quantified. Therefore, it is important to compare projected changes from available ensembles. Here we assess future climate change impacts for 26 Irish catchments. Using a high-resolution national ensemble of climate models projected impacts in mean, low and high flows are assessed and uncertainties in future projections related to catchment size. We then compare future impacts from CORDEX and CMIP6 ensembles for a subset of catchments. Results suggest increases in winter flows (-3.29 to 59.63%), with wide ranges of change simulated for summer (-59.18 to 31.23%), low (-49.30 to 22.37%) and flood (-19.31 to 116.34%) flows across catchments under RCP8.5 by the 2080s. These changes would challenge water management without adaptation. Smaller catchments tend to show the most extreme impacts and widest ranges of change in summer, low and flood flow changes. Both the ensemble mean and range of changes from the national ensemble were more modest and narrower than the CMIP6 and CORDEX ensembles, especially for summer mean and low flows, highlighting the importance of evaluating impacts across ensembles to ensure adaptation decisions are informed by plausible ranges of change.

**Keywords** Climate change · River flows · Hydrological model · Ensemble selection · Ireland

# 1 Introduction

Understanding climate change impacts on catchment hydrology is critical for adaptation. However, which ensemble to use is a key scientific and policy conundrum. Robust assessment of hydrological impacts requires understanding the spread among available projections (Cunha 2023), with research moving away from the use of small single simulation or small ensembles towards larger ensembles to better quantify the full range of plausible changes (Chegwidden et al. 2019; Tegegne and Melesse 2020).

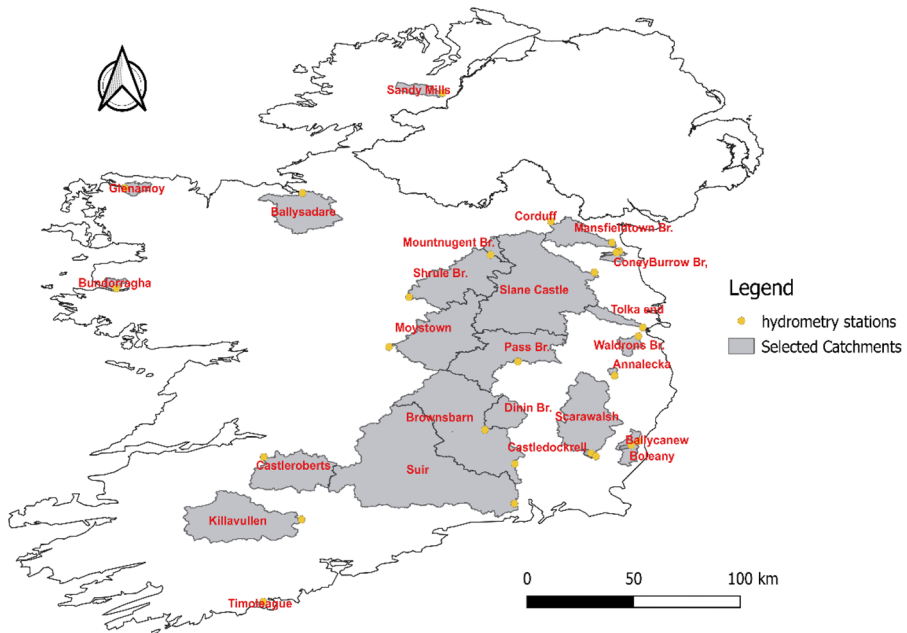
Use of large ensembles is not always feasible for integrated assessments where multiple drivers of change are assessed simultaneously, complex modelling chains increase the computation burden, or where high-resolution gridded datasets are necessary for impacts models (Smith et al. 2018). Despite availability of large ensembles such as the Coupled Model Intercomparison Projects (CMIPs) and/or regionally downscaled ensembles such as CORDEX, many countries advocate use of national ensembles. The latter often have increased salience and credibility among users (Vaughan and Dessai 2014). It is therefore important to evaluate differences in impacts and ranges of change projected across available ensembles to ensure robust adaptation decision-making.

Previous research investigating climate change impacts for Irish catchments has ranged from use of a small ensemble (x3) of statistically downscaled climate models (Charlton et al. 2006) to a single, regionally downscaled model (Steele-Dunne et al. 2008), to assessments using larger ensembles (x12) from the CMIP6 archive to evaluate future impacts (Meresa et al. 2022). Recent research has established an ensemble of high resolution, regionally downscaled scenarios for Ireland (Nolan and Flanagan 2020) which has informed Ireland's first sectoral adaptation plans. However, this ensemble has yet to be deployed to assess future impacts on catchment hydrology. Here we use the high-resolution ensemble produced by the Irish Centre for High End Computing (ICHEC) (Nolan and Flanagan 2020; henceforth the ICHEC ensemble) to evaluate climate change impacts for 26 catchments across the Republic of Ireland. For a subset of catchments for which projections from CORDEX and CMIP6 ensembles are available, we compare simulated changes from across all three ensembles to examine how the ICHEC ensemble represents the range of change across the flow regime. In addition to exploring projected changes across multiple ensembles, a key novelty of the work is linking projected ranges of change with catchment area.

## 2 Data and Methods

### 2.1 Catchments and Data

Climate change impacts are evaluated for 26 catchments (Fig. 1), selected to be of interest from a range of management perspectives, including water quality, ecology and water resource management. Selected catchments are representative of different hydrological characteristics, with a range of sizes (3.3 to 2460 km<sup>2</sup>) and good quality, long-term flow records. For each catchment daily gridded (1 km × 1 km) temperature and precipitation data (Walsh 2012) (catchment averaged for the reference period 1976–2005) were used as inputs to a hydrological model and as a reference series for bias correcting climate model output. Daily Potential Evapotranspiration (PET) was calculated from temperature using



**Fig. 1** Location of the 26 catchments

the method of Oudin et al. (2005). Daily discharge data was obtained from the Office of Public Works (<https://waterlevel.ie/hydro-data/>), the Environmental Protection Agency (<https://epawebapp.epa.ie/hydronet/#Water%20>) and the Teagasc Agricultural Catchments Programme (<https://www.teagasc.ie/environment/water-quality/agricultural-catchments/>).

## 2.2 Climate Model Ensembles

Three climate model ensembles are employed and detailed below. A full list of models comprising each is provided in Supplementary Information (SI). The ICHEC ensemble is used to examine future changes across all catchments. To evaluate differences in projected changes across each ensemble we focus on a subset of six catchments.

### 2.2.1 ICHEC Ensemble

Nolan and Flanagan (2020) developed high resolution climate scenarios for Ireland using the regional climate model COSMO-CLIM Version 5 to downscale five CMIP5 models (see Table S1) (HadGEM2, EC-Earth, CNRM-CM5, MIROC5, MPI-ESM-LR). Downscaled GCM simulations were treated as independent and given equal weight. Regionalisation was undertaken for two emissions pathways – RCP4.5, an intermediate pathway, whereby global emissions peak around 2040, then decline and RCP8.5, a fossil fuel intensive future. COSMO-CLIM was driven by GCM boundary conditions with a one-way nesting strategy to obtain a horizontal resolution of 4 km, with projections derived for historical (1975–

2005) and future (2006–2100) time periods. Nolan et al. (2017) and Nolan and Flanagan (2020) evaluated the ability of COSMO-CLIM to simulate Irish climate variables, finding that the model does well at simulating the magnitude and spatial variability of precipitation and temperature. Nolan and Flanagan (2020) used the Penman–Monteith FAO-56 method to compute daily potential evapotranspiration (PET in mm) for historical and future simulations (see Werner et al. (2019) for full methods and evaluation). Gridded simulations of daily precipitation, temperature and PET were extracted and averaged for each catchment. Following Morrissey et al. (2021) we do not further bias correct the ICEHC ensemble before application.

### 2.2.2 CORDEX Ensemble

Euro-CORDEX provides a high resolution (12.5 km) dynamically downscaled regional climate change ensemble for Europe forced with RCP4.5 and RCP8.5 (Jacob et al. 2014). Eleven CORDEX members (6 GCMs downscaled by different RCMs) were extracted and bias corrected at a national scale before corrected precipitation was extracted for each catchment. National scale daily temperature and precipitation data for the period 1976–2005 (Walsh 2012) were re-gridded to match the CORDEX resolution. For precipitation, bias correction was undertaken using Double Gamma Quantile Mapping (DGQM) following Meresa et al. (2021). For every N year, we excluded zero precipitation days before fitting a gamma distribution to the lower/upper 75% of daily precipitation as follows;

$$P_{\text{corr}} = F_{\text{dg}}^{-1}(F_{\text{dg}}(P_{\text{raw}}(t), \bullet_{\text{raw}}, \bullet_{\text{raw}}), \bullet_{\text{Obs}}, \bullet_{\text{Obs}}) \quad (1)$$

where  $P_{\text{corr}}$  represents the bias-corrected daily precipitation,  $P_{\text{raw}}$  is the raw climate model precipitation.  $F_{\text{dg}}$  is the inverse cdf of raw climate model precipitation. dg subscripts represent the Gamma distributions and the shape ( $\alpha$ ) and scale ( $\beta$ ) parameters.

To bias correct daily temperature, we employ empirical quantile matching using pairwise comparison between the empirical cdf (*ecdf*) of raw climate model and observed temperature for the period (1976–2005). Future temperature projections are then corrected using the inverse *ecdf* ( $ecdf^{-1}$ ) and fitted *ecdf* as follows;

$$T_{\text{hst}}^{\text{cor}} = (ecdf_{\text{obs}}^{-1}(ecdf_{\text{hst}}, (T_{\text{hst}}))) \quad (2)$$

Where  $T_{\text{hst}}^{\text{cor}}$  is corrected temperature, *hst* is the raw climate model and *obs* is the observed temperature for the period 1976–2005. PET is estimated using the Oudin et al. (2005) method applied to bias corrected temperature. Bias correction results were evaluated using Percent Bias (PBIAS) for precipitation and absolute differences for temperature.

### 2.2.3 CMIP6 Ensemble

Phase 6 of the Coupled Model Intercomparison Project (CMIP6) forms the future climate evidence base of the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (O'Neill et al., 2016). Meresa et al. (2022) evaluated the impacts of climate change on Irish catchments using an ensemble of 12 CMIP6 models. We use the CMIP6 ensemble from Meresa et al. (2022) for six catchments overlapping with our sample (Brownsbarn,

Castleroberts, Glenamoy, Killavullen, Shrulc Bridge, and Scarawalsh). Daily precipitation and air temperature data for the period 1976–2100 were extracted from 12 CMIP6 ensemble members (see Table S1) forced by the Shared Socioeconomic Pathway SSP585 (a fossil-fuel-dependent future analogous to RCP8.5). For each catchment, data were extracted from the closest land-based GCM grid. Bias-correction was undertaken using DGQM (precipitation) and EQM (temperature), as for the CORDEX ensemble, but applied to catchment average series. The Oudin et al. (2005) method was used to calculate PET.

### 2.3 Hydrological Model

Climate change projections were used to force the SMART hydrological model (see Mockler et al. 2016; Hallouin et al. 2020 for full model description) to evaluate climate change impacts for each catchment. SMART is a lumped hydrological model and has been used for the assessment of climate change impacts on water quality (O’Driscoll et al. 2018) and changes in the flow regime (Meresa et al. 2022). The model, coded in Python, is freely available at <https://github.com/ThibHlln/smarty>. Table S2 lists the model parameters and plausible ranges. To calibrate the model we employed memetic algorithms with local search chains (MA-LS-Chains) (Bergmeir et al. 2016). Given the objective of evaluating changes across the flow regime, SMART was calibrated independently using the Nash-Sutcliffe (NSE) and the logNSE objective functions, both widely used in the hydrologic literature (e.g., Tian et al. 2019). Using available observations, 70% of data were used for calibration and 30% for verification.

### 2.4 Hydrological Indices

The following indices were extracted for each catchment for the simulated reference period (1976–2005) and time-slices representing the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099) for both RCP4.5 and RCP8.5;

- Seasonal mean flows (winter [DJF], spring [MAM], summer [JJA] and autumn [SON]).
- Annual mean flow.
- Q95: flow exceeded 95% of the time.
- Q20 year: flow associated with a flood with a 20-year return period/5% annual exceedance probability, estimated using a GEV distribution fitted to annual maxima series for historical and future periods using Maximum Likelihood Estimation (MLE).

Changes in Q20 year and winter, spring and annual flows were assessed using simulations calibrated using NSE, while changes in Q95 and summer and autumn flows were assessed using simulations calibrated using logNSE.

### 2.5 Relating Future Changes to Catchment area

We investigate relationships between catchment area ( $\text{km}^2$ ) and simulated changes across the catchment sample. Area was log-transformed and regressed onto the mean, upper/lower bound and the range of change simulated for each catchment in the 2080s under RCP8.5, assuming that the signal of change is greatest for this RCP and period. Given the relatively

**Table 1** Calibration (Cal) and verification (Ver) results. \* indicates catchments where poor results were obtained during calibration and/or verification

Catchment	Area (Km <sup>2</sup> )	NSE Cal	NSE Ver	LogNSE Cal	LogNSE Ver
Slane Castle	2460.3	0.92	0.94	0.89	0.91
Suir	2143.7	0.90	0.93	0.91	0.93
Brownsbarn	2119.7	0.89	0.90	0.86	0.86
Killavullen	1253.6	0.90	0.89	0.85	0.83
Moystown	1188.4	0.94	0.91	0.86	0.84
Pass Bridge	1111.7	0.85	0.90	0.81	0.83
Scarawalsh	1035.4	0.76	0.83	0.74	0.78
Shrulle Bridge	985.8	0.92	0.96	0.91	0.95
Castleroberts	801.9	0.89	0.87	0.85	0.83
Ballysadare	638.3	0.93	0.93	0.93	0.93
Mansfieldtown Bridge	327.4	0.89	0.85	0.87	0.87
Dinin Bridge	300.3	0.82	0.82	0.75	0.72
Boleany	154.8	0.76	0.80	0.70	0.83
Tolka	135.6	0.82	0.80	0.71	0.73
Sandy Mills	113.0	0.79	0.82	0.71	0.74
Waldrons Bridge	95.1	0.75	0.67	0.71	0.60
Mountnugent Bridge	84.5	0.80	0.80	0.79	0.82
Glenamoy	75.6	0.76	0.81	0.74	0.79
ConeyBurrow Bridge	56.9	0.76	0.69	0.68	0.56
Bundorragha	48.8	0.85	0.82	0.80	0.77
Annalecka*	14.9	0.57	0.50	0.41	0.38
Ballycanew*	11.9	0.79	0.72	0.58	0.49
Castledockrell	11.2	0.87	0.83	0.81	0.82
Dunleer*	9.4	0.71	0.82	0.53	0.75
Timoleague*	7.5	0.72	0.68	0.62	0.57
Corduff*	3.3	0.48	0.62	-0.12	0.20

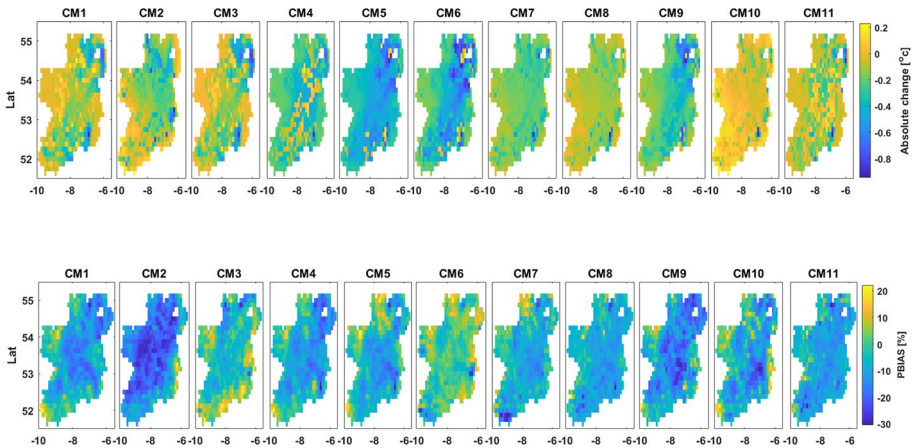
small number of catchments we do not evaluate p-values, but highlight cases where area explains more than 10% of the variance in the predictand.

### 3 Results

#### 3.1 Hydrological Model Calibration and bias Correction

Calibration and verification results for SMART are shown in Table 1 with scatter plots of observed and simulated flows for selected catchments shown in Fig. S1. Results indicate the ability of SMART to capture the flow regime of each catchment. Across catchments the median calibration scores are 0.84 and 0.80 for NSE and LogNSE, respectively. For verification, median scores are 0.83 (NSE) and 0.82 (LogNSE). Some smaller catchments return among the lowest scores, especially for LogNSE, (e.g., Ballycanew and Timoleague).

Results from bias correction of the CORDEX ensemble are shown in Fig. 2 with no consistent pattern of bias across models for either variable. CM5 and CM6 underestimate temperature in the midlands and east, while CM1 and CM10 overestimate temperature in the west. For precipitation, CM6 underestimates precipitation by approximately 5% in uplands of the southwest, west, and east, but performs well elsewhere. CM2 returns the highest



**Fig. 2** Bias correction results for 11 CORDEX members for the period 1976–2005 for annual mean temperature (top) and precipitation (bottom)

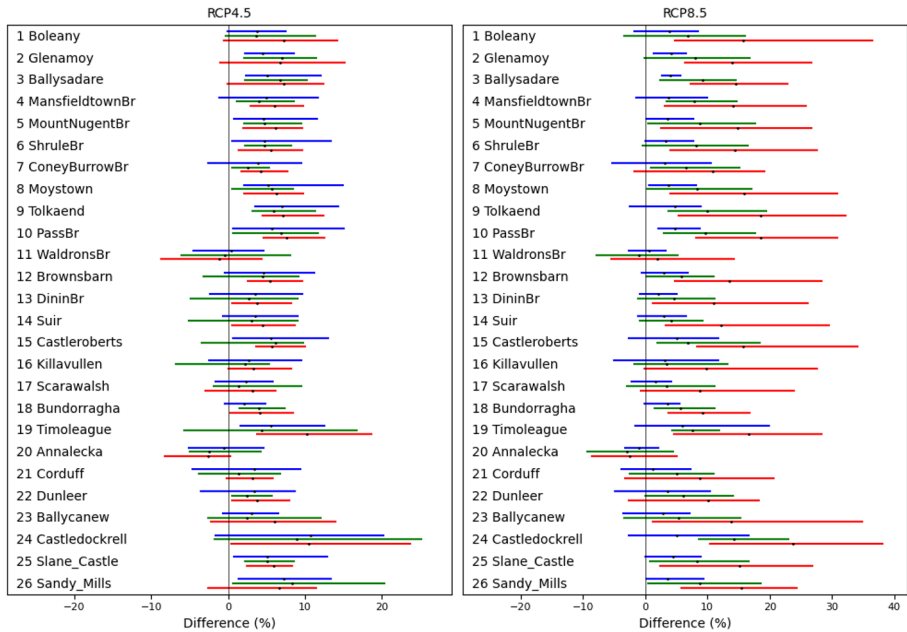
PBIAS for precipitation, even after correction, with large underestimates across the island (~10–20%). For the CMIP6 ensemble, bias correction results can be found in Meresa et al. (2022). In summary, raw climate model outputs underestimated precipitation in most catchments. Bias correction improved the agreement between observed and simulated data in each catchment.

### 3.2 Simulated Changes from the ICHEC Ensemble

#### 3.2.1 Annual Mean Flows

Annual mean flows are projected to increase across most catchments under RCP8.5 (Fig. 3) with a substantial range of change. Across catchments the average of the ensemble mean shows increases of 3.43% for the 2020s, 6.68% for the 2050s and 13.09% for the 2080s. However, some catchments show modest decreases in the ensemble mean, including Waldron’s Bridge and Annalecka. By the 2080s largest increases in the ensemble mean are for Castledockrell (23.76%). The simulated range of change across catchments spans  $-5.27$  to 19.86% in the 2020s,  $-9.25$  to 23.04% in the 2050s, and  $-8.48$  to 38.07% by the 2080s under RCP8.5.

For RCP4.5 simulations show increased annual mean flows, but less marked. Waldron’s Bridge and Annalecka show decreases in the ensemble mean. Averaged across catchments the ensemble mean increases are 4.34% for the 2020s, 4.20% for the 2050s and 5.37% for the 2080s. The ranges of change simulated are narrower than RCP8.5, ranging from  $-5.09$  to 20.18% for the 2020s,  $-6.80$  to 25.09% for the 2050s and  $-8.74$  to 23.74 for the 2080s.



**Fig. 3** Changes (percent) in annual mean flow from the ICEHC ensemble for each catchment for the 2020s (blue), 2050s (green) and 2080s (red) under RCP4.5 and RCP8.5. Dots represent the ensemble mean for each catchment/period

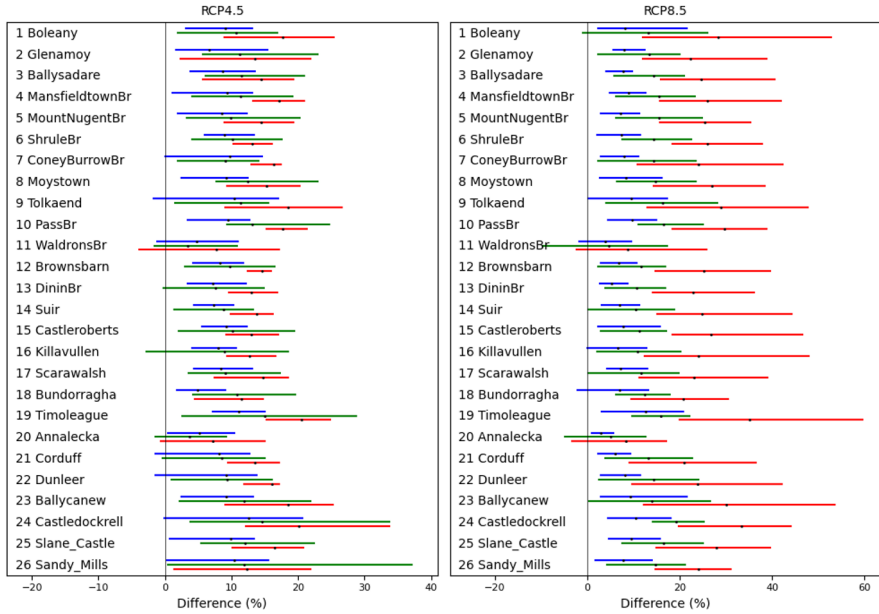
### 3.2.2 Seasonal mean Flows

Projected changes in winter [DJF] mean flows for RCP8.5 show increases for most catchments (Fig. 4a), although for Waldron's Bridge and Annalecka projected changes span a sign change, especially for the 2050s. Averaged across catchments the ensemble mean returns increases of 7.88% in the 2020s, 13.56% by the 2050s and 25.13% by the 2080s. Ranges of change are large, though for most catchments are positive in all future periods. Projected changes span  $-2.04$  to  $21.65\%$  in the 2020s,  $-9.67$  to  $31.76\%$  in the 2050s and  $-3.29$  to  $59.63\%$  by the 2080s. By the end of the century under RCP8.5 most catchments show ensemble mean increases in winter mean flow  $>20\%$ , with some (Timoleague, Ballycanew and Castledockrell) showing increases  $>30\%$ . The latter are amongst the smallest catchments.

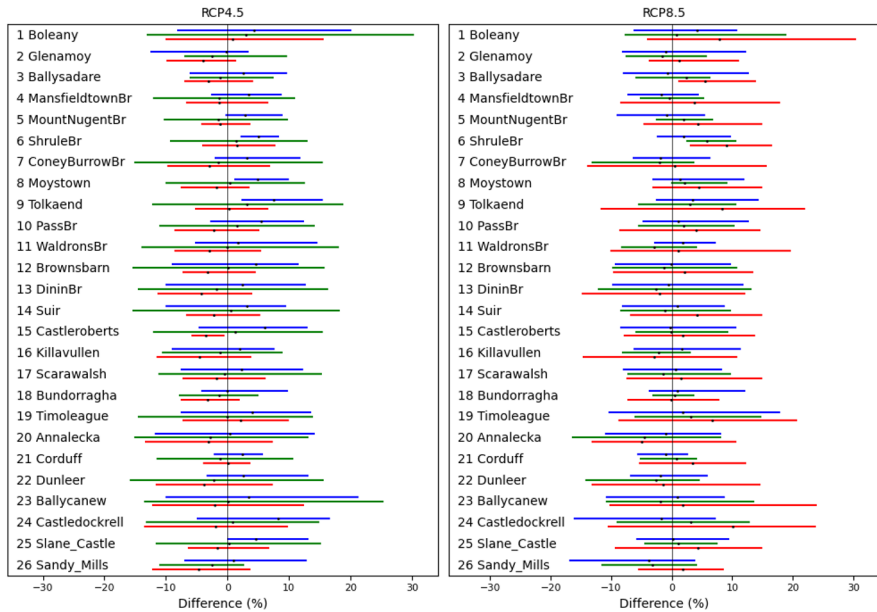
For RCP4.5 winter simulations also tend towards increases but are less pronounced than RCP8.5. Averaged across catchments, ensemble mean changes of 8.64% for the 2020s, 10.43% for the 2050s and 14.92% for the 2080s are projected. The ranges of change simulated are also narrower with changes across catchments spanning  $-1.7$  to  $20.69\%$  in the 2020s,  $-2.84$  to  $37.03\%$  in the 2050s and  $-3.79$  to  $33.73\%$  by the 2080s.



a)



b)



**Fig. 4** Changes (percent) in a) winter and b) spring mean flows from the ICEHC ensemble for each catchment for the 2020s (blue), 2050s (green) and 2080s (red) under RCP4.5 and RCP8.5. Dots represent the ensemble mean for each catchment/period

For spring [MAM] mean flows the direction of change is uncertain for both RCPs and each future time period (Fig. 4b). Ensemble mean changes across catchments are modest; 0.39, 0.29 and 3.37% for the 2020s, 2050 and 2080 s, respectively for RCP8.5. Ranges of change are wide for both RCPs. For the 2080s simulated changes across catchments span  $-14.69$  to  $30.29\%$ .

Summer [JJA] mean flows show a wide range of change (Fig. 5a). Ensemble mean changes range from  $4.34\%$  in the 2020s to  $-6.81\%$  in the 2050s and  $-6.48\%$  by the 2080s. The full ensemble spans a sign change across most catchments and time periods. Ranges simulated under RCP8.5 span  $-44.02$  to  $76.31\%$  in the 2020s,  $-38.86$  to  $43.40$  in the 2050s and  $-59.18$  to  $31.23\%$  in the 2080s. Largest reductions, whereby the lower range of change exceeds  $-40\%$  relative to the reference period are returned for Annalecka, Corduff, Dunleer and Ballycanew (all small catchments) 2020s,  $-32.99$  to  $32.89\%$  for the 2050s and  $-49.48$  to  $21.94\%$  by the 2080s. The same catchments show the most extreme changes as for RCP8.5.

For RCP4.5 summer ensemble mean changes across catchments range from  $-1.24\%$  in the 2020s,  $0.30\%$  in the 2050s and  $-6.33\%$  by the 2080s. Ranges of change span increases and decreases for all catchments except Annalecka which shows decreases in each future period. Simulated changes across catchments range from  $-44.16$  to  $52.59\%$  in the.

Autumn [SON] mean flows show a tendency for increases under RCP8.5, but no clear signal of change for RCP4.5 (Fig. 5b). For RCP8.5, ensemble mean changes across catchments are  $0.66\%$  for the 2020s,  $9.47\%$  for the 2050s and  $14.85\%$  for the 2080s. Largest increases are simulated for the 2080s with the upper bound ranging from  $8.96\%$  (Annalecka) to  $114\%$  (Castledockrell). For the same period, the lower bound ranges from  $-15.24\%$  (Annalecka) to  $11.03\%$  (Ballysadare).

### 3.2.3 Low Flows

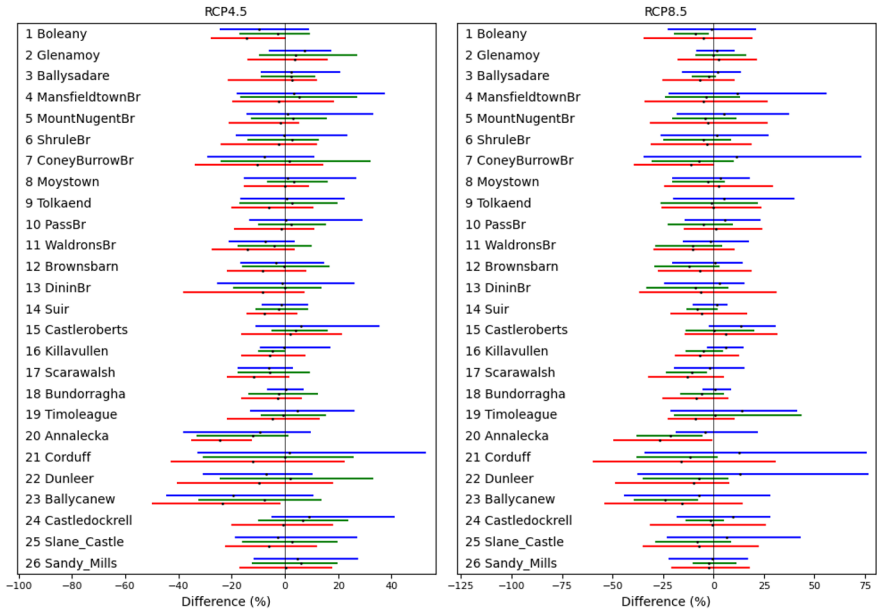
For low flows a tendency for decreases in Q95 for both RCPs is evident (Fig. 6). For RCP8.5 ensemble mean changes across catchment are  $-4.44$  for the 2020s,  $-11.59$  for the 2050s and  $-15.94$  for the 2080s. Ranges of change are also wide, spanning  $-23.55$  to  $36.38$  in the 2020s,  $-32.28$  to  $9.10\%$  in the 2050s and  $-49.30$  to  $22.37\%$  in the 2080s.

Reductions in the ensemble mean and range across catchments are less extreme under RCP4.5. Ensemble mean changes across catchments range from  $-2.62\%$  in the 2020s,  $-3.55\%$  in the 2050s and  $-10.80\%$  in the 2080s. By the 2080s most catchments show clear reductions in Q95. Ranges of change across catchments span  $-26.48$  to  $30.09\%$  in the 2020s,  $-30.04$  to  $18.45$  in the 2050s and  $-37.46$  to  $8.51\%$  in the 2080s. Largest reductions are simulated for Timoleague, Slane Castle and Dunleer. Apart from Slane Castle, these are amongst the smallest catchments.

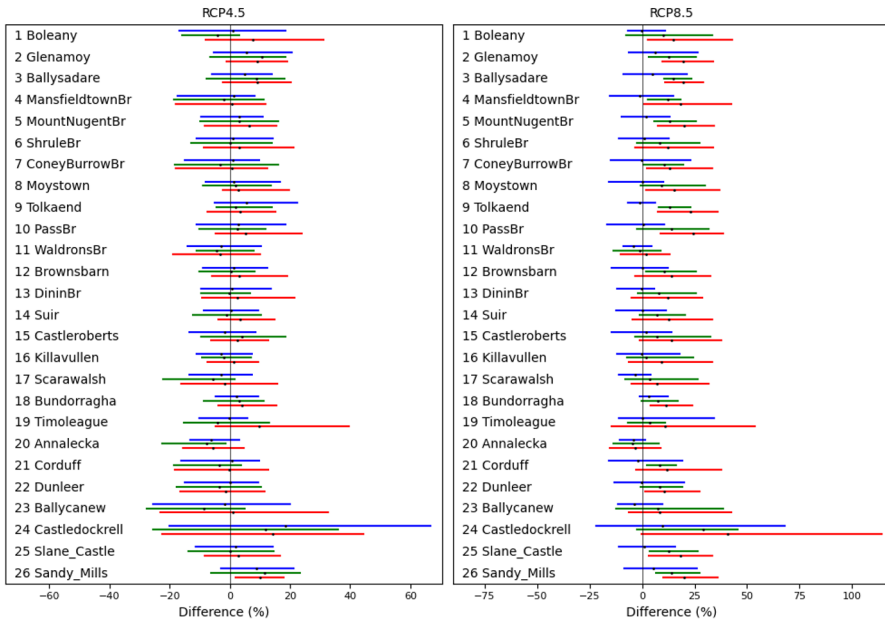
### 3.2.4 Floods

For RCP8.5 increases in Q20 year are simulated for the 2050 and 2080 s across most catchments (Fig. 6). Ensemble mean changes across catchments are  $8.47\%$  for the 2020s,  $18.14\%$  for the 2050s and  $27.01\%$  for the 2080s. Largest ensemble mean changes ( $>40\%$  increase) are simulated for Glenamoy, Bundorragha, Castledockrell and Sandy Mills. For RCP8.5 ranges of change span  $-30.53$  to  $55.55\%$  in the 2020s,  $-19.08$  to  $73.57$  for the 2050s and  $-19.31$  to  $116.34$  for the 2080s.

a)

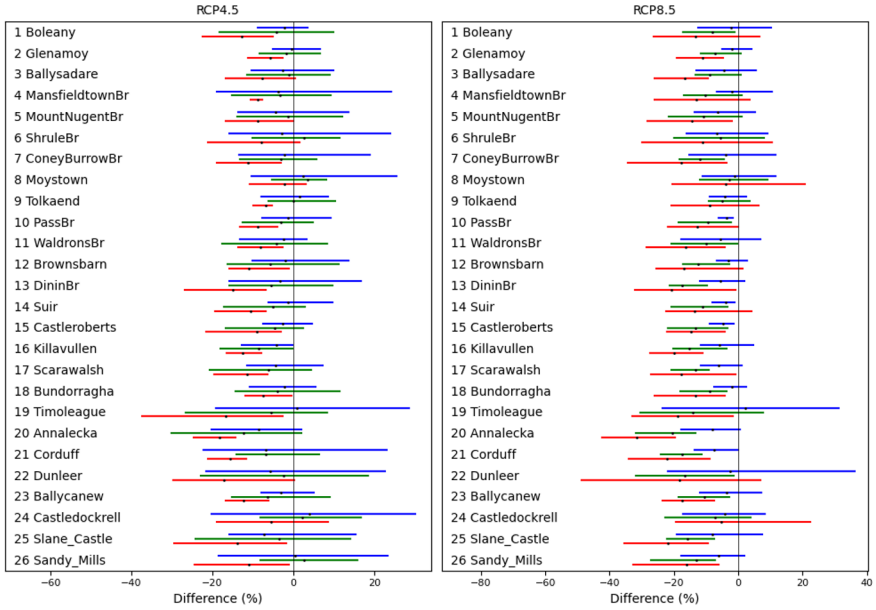


b)

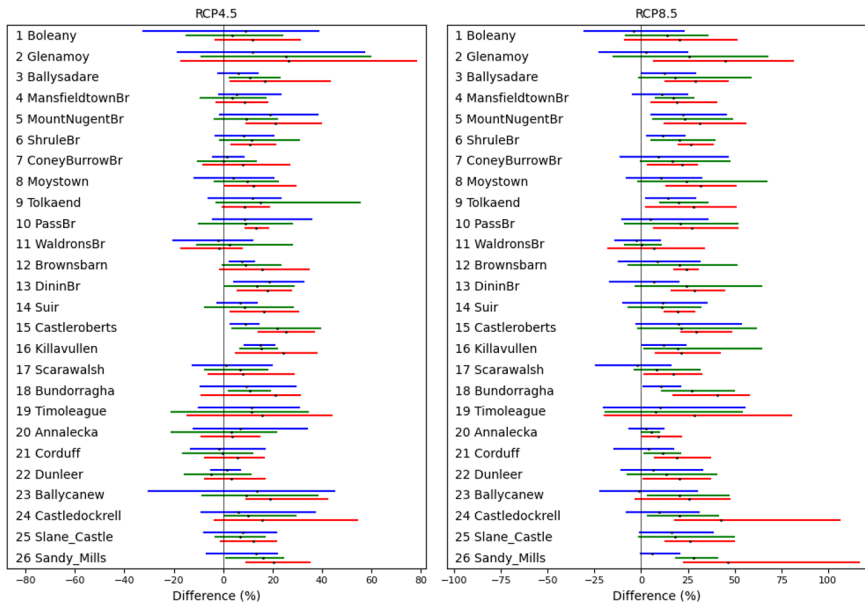


**Fig. 5** Changes (percent) in a) summer and b) autumn mean flows from the ICEHC ensemble for each catchment for the 2020s (blue), 2050s (green) and 2080s (red) under RCP4.5 and RCP8.5. Dots represent the ensemble mean for each catchment/period

a)



b)



**Fig. 6** Changes (percent) in (a) Q95 and (b) Q20 year flows from the ICEHC ensemble for each catchment for the 2020s (blue), 2050s (green) and 2080s (red) under RCP4.5 and RCP8.5. Dots represent the ensemble mean for each catchment/period.

### 3.2.5 Relationship of Simulated Changes with Area

The role of catchment area in explaining variations in simulated changes was examined for the 2080s under RCP8.5. For Q95 the lower bound of changes is more extreme for smaller catchments ( $R^2$  0.16). For floods, catchment area explains 20% of the variance in the range simulated for Q20 year, with smaller catchments tending to show a wider range of change. The lower bound of changes in Q20 year tends to be higher and positive for larger catchments ( $R^2$  0.10). For summer mean flows, area explains 20% of the variance in ensemble mean changes, with smaller catchments tending to show more extreme reductions. The range of change for summer mean flows also tends to be greater for smaller catchments ( $R^2$  0.11), with the lower bound being more extreme ( $R^2$  0.12). For autumn flows area explains 12% of the variance in the range of change, with larger catchments showing a narrower range.

### 3.3 Comparison of ICHEC with CORDEX and CMIP6 Ensembles

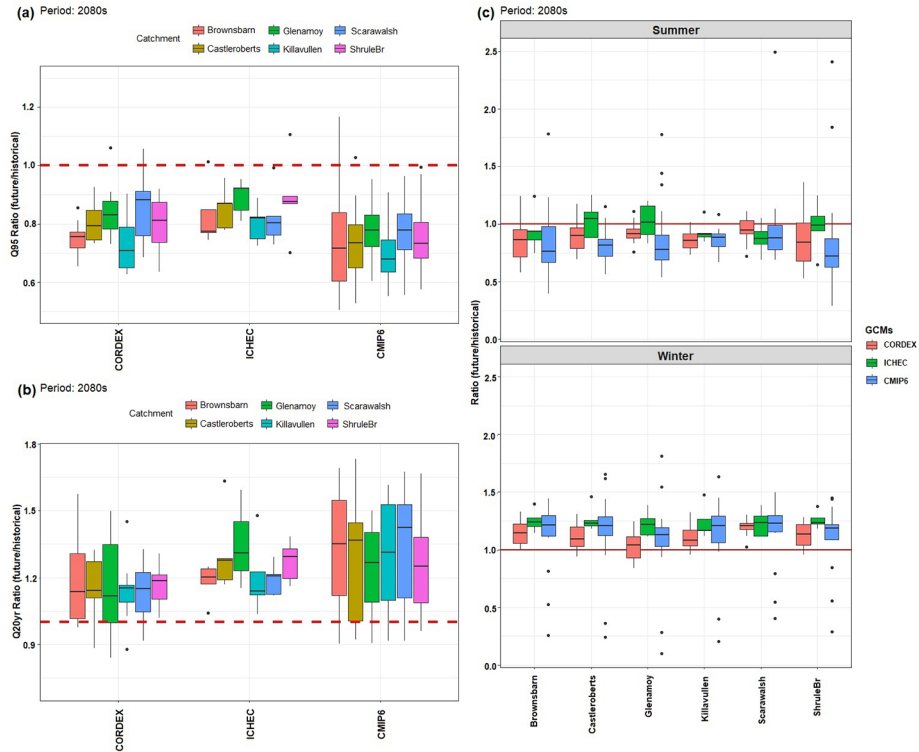
Projected changes in hydrological indices for six sample catchments from CMIP6, CORDEX and ICHEC were compared using RCP8.5 and SSP585 for the 2080s. For winter and summer means the range of change is widest for CMIP6 and narrowest for ICHEC, reflecting sample size of the respective ensembles (Fig. 7). For summer flows projected changes from each ensemble show uncertainty in the direction of change. The ensemble mean tends towards decreases, with greatest reductions for CMIP6 and CORDEX and more modest changes for ICHEC. For the 2080s ICHEC shows increases in summer flow for Castleroberts and Glenamoy, and little change for Shrulce Bridge, while both CMIP6 and CORDEX show decreases for these catchments. There are, therefore, considerable differences in projected changes in summer mean flows depending on ensemble selection.

Q95 changes (Fig. 7) from CMIP6 show the largest spread across catchments, followed by CORDEX, with the narrowest range simulated by ICHEC. For RCP8.5 the signal of change across each ensemble is towards reductions in Q95, becoming more notable as the century progresses. The ICHEC ensemble returns the most modest reductions in Q95 and CMIP6 the largest.

Changes in Q20 year flows for each ensemble shows increases in flood magnitude (Fig. 7). CMIP6 shows the widest range of change. Typically, but not always, ICHEC shows the narrowest range. Ensemble mean changes in Q20 year tend to be greatest for CMIP6, followed by ICHEC, with most modest changes simulated by CORDEX. However, there is variability on a catchment-by-catchment basis. Of note is the relatively narrow range in Q20 year projected by ICHEC for the 2080s relative to other ensembles.

## 4 Discussion

This study evaluated the impact of climate change for 26 Irish catchments using a high resolution regionally downscaled ensemble produced by Nolan and Flanagan (2021) (ICHEC ensemble). This ensemble is widely used for adaptation planning in Ireland. Changes in hydrological indices representing low, mean and flood flows were assessed for RCP4.5 and RCP8.5. Results emphasise the wide range of changes expected for catchment hydrology.



**Fig. 7** Projected changes in a) Q95, b) Q20yr and c) summer and winter mean flows for the 2080s simulated by the CMIP6, CORDEX and ICHEC ensembles under a high emissions scenario (RCP8.5 and SSP585). Red horizontal line indicates a ratio of 1 or zero change

Increases in annual/winter mean and flood (Q20 year) flows become more pronounced as the century progresses. Decreases in low flows (Q95) predominate with most catchments showing greatest decreases by the 2080s. For summer mean flows, changes span increases and decreases for most catchments and periods, however changes show a tendency towards reductions as the century progresses. For spring and autumn, the direction of future change is uncertain. For most indices both the magnitude (as inferred from the ensemble mean) and range of changes by the 2080s are less for RCP4.5 than for RCP8.5, indicating the importance of mitigation in avoiding the worst impacts of climate change.

For summer mean flows ensemble mean reductions tend to be greater for smaller catchments, and the range of change wider due to a more extreme lower bound. For low flows (Q95) the lower bound of changes tends to be more extreme for smaller catchments. Small catchments are likely to be located at higher elevations, with lower groundwater storage and higher runoff coefficients, therefore, their greater sensitivity to changing precipitation inputs and evaporative losses makes sense. Catchment size was also found to explain up to 20% of the variance in the range of Q20 year changes, with wider ranges likely for smaller catchments. Future work could expand the catchment sample to more fully evaluate relationships between simulated changes and catchment characteristics. Such insight could

facilitate more nuanced ensemble selection, process understanding (Lane et al. 2022) and regionalisation to ungauged catchments (Capell et al. 2013).

Results from the ICHEC ensemble are broadly consistent with previous research, indicating higher winter flows and more severe low flows and floods (e.g., Charlton et al. 2006; Steele Dunne et al. 2008; Meresa et al. 2022). Such changes in extremes would result in increased flashiness, with implications for sediment and phosphorus delivery in catchments (Mellander and Jordan 2021). Future work should examine the impacts of climate change on nutrient dynamics in catchments. For a subset of six catchments, we compared changes from ICHEC with the larger CORDEX and CMIP6 ensembles. Results indicate the importance of ensemble choice to both the magnitude and range of change. The ICHEC ensemble was found to underestimate the range of change from both CORDEX and CMIP6 for winter and summer mean flows and for changes in low flows (Q95). Moreover, the magnitude of change in the ensemble mean was more moderate for ICHEC. For some catchments/indices even the direction of change indicated by the ensemble mean was different for ICHEC relative to the others. For floods, while the range of change using the ICHEC ensemble is less than for CMIP6, the ICHEC ensemble mean changes tend to be higher than CORDEX, despite its smaller sample size, and more representative of CMIP6. These results highlight the importance of ensemble selection and design for hydrological impacts and adaptation planning (Clarke et al. 2016; Chegwidan et al. 2019; Golian and Murphy 2021) and the inability to a priori generalise the influence of ensemble choice across hydrological indices.

Projected changes are likely to pose challenges for water management. For effective adaptation it is critical that the range of changes are assessed (Kundzewicz et al. 2018). Use of only the ensemble mean in adaptation planning is likely to result in underestimation of plausible future changes and maladaptation (Woodruff 2016). Underestimation of the range of change in summer mean and low flows by the ICHEC ensemble should be noted in future adaptation actions. All indices evaluated show large ranges of change, planning should leverage these ranges to stress test vulnerability and failure points in existing systems and to evaluate the robustness of adaptation options (e.g., Wilby 2022).

Projected changes are likely to underestimate plausible ranges of change as we do not include uncertainty in hydrological models (e.g., Wagener et al. 2022). Meresa et al. (2021) show how uncertainties in projected changes are sensitive not just to the choice of climate models, but hydrological model structure/parameters, bias correction technique and extreme value distribution used. Moreover, we do not assess the transferability of the SMART hydrological model to conditions outside those used for calibration and validation dataset (Broderick et al. 2016). Our aim was to evaluate to evaluate impacts from the ICHEC ensemble and compare those against available CORDEX and CMIP6 ensembles. Despite the existence of biases in the ICHEC ensemble for the historical period (Nolan and Flanagan 2020), we follow Morrissey et al. (2021) and refrain from bias correction. Finally, we note that some catchments are very small and challenge the application of climate change projections, even at high resolution.

## 5 Conclusion

This study assessed climate change impacts for 26 Irish catchments using a high-resolution national ensemble and evaluated if uncertainties in future projections are related to catchment size. Results suggest large changes in winter and summer mean flows, low flows and flood magnitude, which would pose significant challenges for water management. Uncertainty ranges are large for all indices, especially summer mean flows. Catchment area is associated with both the ensemble mean and range of summer simulations with small catchments tending to show the most extreme impacts and widest range of change. Similarly, smaller catchments were also found to show the widest range of change in flood magnitude. Despite being widely used for adaptation planning in Ireland, comparison of results from the national ensemble with CORDEX and CMIP6 show that the magnitude and range of changes are more modest and narrower, respectively, especially for summer and low flows. This has implications for adaptation where decisions should be informed by the plausible range of future changes.

**Acknowledgements** We thank Met Éireann, the Office of Public Works, Environmental Protection Agency and Teagasc for observed data and Paul Nolan for the ICHEC ensemble. This work was supported by the Irish Environmental Protection Agency through the WaterFutureS project (2020-W-CD-3) and HydroPredict (2018-CCRP-MS.51).

**Author Contributions** C.M., A.K., H.M., S.G., M.B., F.O., P.E.M. contributed to study conception, material preparation and data collection. Analysis was performed by C.M., A.K., S.G. and H.M. The first draft was written by C.M., all authors edited subsequent versions. All authors read and approved the final manuscript.

**Funding** This work was supported by the Irish Environmental Protection Agency through the WaterFutureS project (2020-W-CD-3) and HydroPredict (2018-CCRP-MS.51). Open Access funding provided by the IReL Consortium

**Data Availability** Available from the corresponding author upon request.

## Statements and Declarations

**Competing Interests** The authors have no relevant financial or non-financial interests to disclose.

**Ethical Approval** The authors confirm that the submission is original work and not published elsewhere.

**Consent to Participate** All authors consented to participate in this study.

**Consent to Publish** All authors consented to publish this study.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.



## References

- Bergmeir C, Molina D, Benítez JM (2016) Memetic algorithms with local search chains in R: the Rmals-chains package. *J Stat Softw* 75:1–33. <https://doi.org/10.18637/jss.v075.i04>
- Broderick C, Matthews T, Wilby RL et al (2016) Transferability of hydrological models and ensemble averaging methods between contrasting climatic periods. *Water Resour Res* 52(10):8343–8373. <https://doi.org/10.1002/2016WR018850>
- Capell R, Tetzlaff D, Soulsby C (2013) Will catchment characteristics moderate the projected effects of climate change on flow regimes in the scottish highlands? *Hydrol Process* 27(5):687–699. <https://doi.org/10.1002/hyp.9626>
- Charlton R, Fealy R, Moore S et al (2006) Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques. *Clim Change* 74(4):475–491. <https://doi.org/10.1007/s10584-006-0472-x>
- Chegwidden OS, Nijssen B, Rupp DE et al (2019) How do modeling decisions affect the spread among hydrologic climate change projections? Exploring a large ensemble of simulations across a diversity of hydroclimates. *Earths Future* 7(6):623–637. <https://doi.org/10.1029/2018EF001047>
- Clark MP, Wilby RL, Gutmann ED et al (2016) Characterizing uncertainty of the hydrologic impacts of climate change. *Curr Clim Change Rep* 2(2):55–64. <https://doi.org/10.1007/s40641-016-0034-x>
- Cunha M (2023) Water and Environmental Systems Management under uncertainty: from scenario construction to Robust Solutions and Adaptation. *Water Resour Manage*. <https://doi.org/10.1007/s11269-023-03429-9>. Published Online
- Golian S, Murphy C (2021) Evaluation of Sub-Selection methods for assessing Climate Change Impacts on Low-Flow and Hydrological Drought Conditions. *Water Resour Manag* 35(1):113–133. <https://doi.org/10.1007/s11269-020-02714-1>
- Jacob D, Petersen J, Eggert B et al (2014) EURO-CORDEX: new high-resolution climate change projections for european impact research. *Reg Environ Change* 14(2):563–578. <https://doi.org/10.1007/s10113-013-0499-2>
- Kundzewicz ZW, Krysanova V, Benestad RE et al (2018) Uncertainty in climate change impacts on water resources. *Environ Sci Policy* 79:1–8. <https://doi.org/10.1016/j.envsci.2017.10.008>
- Lane RA, Coxon G, Freer J et al (2022) A large-sample investigation into uncertain climate change impacts on high flows across Great Britain. *Hydrol Earth Syst Sci* 26:5535–5554. <https://doi.org/10.5194/hess-26-5535-2022>
- Mellander PE, Jordan P (2021) Charting a perfect storm of water quality pressures. *Sci Total Environ* 787:147576. <https://doi.org/10.1016/j.scitotenv.2021.147576>
- Meresa H, Murphy C, Fealy R et al (2021) Uncertainties and their interaction in flood hazard assessment with climate change. *Hydrol Earth Syst Sci* 25(9):5237–5257. <https://doi.org/10.5194/hess-25-5237-2021>
- Meresa H, Donegan S, Golian S et al (2022) Simulated changes in Seasonal and Low flows with Climate Change for Irish catchments. *Water* 14(10):1556. <https://doi.org/10.3390/w14101556>
- Mockler EM, O’Loughlin FE, Bruen M (2016) Understanding hydrological flow paths in conceptual catchment models using uncertainty and sensitivity analysis. *Comput Geosci* 90:66–77. <https://doi.org/10.1016/j.cageo.2015.08.015>
- Hallouin T, Bruen M, O’Loughlin FE (2020) Calibration of hydrological models for ecologically relevant streamflow predictions: a trade-off between fitting well to data and estimating consistent parameter sets? *Hydrol Earth Syst Sci* 24:1031–1054. <https://doi.org/10.5194/hess-24-1031-2020>
- Morrissey P, Nolan P, McCormack T et al (2021) Impacts of climate change on groundwater flooding and ecohydrology in lowland karst. *Hydrol Earth Syst Sci* 25(4):1923–1941. <https://doi.org/10.5194/hess-25-1923-2021>
- Nolan P, Flanagan J (2020) High-resolution climate projections for Ireland—A multi-model ensemble approach. EPA Research Report 329. [https://www.epa.ie/publications/research/climate-change/Research\\_Report\\_339\\_Part1.pdf](https://www.epa.ie/publications/research/climate-change/Research_Report_339_Part1.pdf). Accessed 27 November 2022
- Nolan P, O’Sullivan J, McGrath R (2017) Impacts of Climate Change on Mid-Twenty-First-Century Rainfall in Ireland: A High-Resolution Regional Climate Model Ensemble Approach: impacts of Climate Change on Mid-21st-Century rainfall in Ireland. *Int J Climatol* 37:4347–4363. <https://doi.org/10.1002/joc.5091>
- O’Driscoll C, Ledesma JL, Coll J et al (2018) Minimal climate change impacts on natural organic matter forecasted for a potable water supply in Ireland. *Sci Total Environ* 630:869–877. <https://doi.org/10.1016/j.scitotenv.2018.02.248>
- O’Neill BC, Tebaldi C, Van Vuuren DP et al (2016) The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geosci Model Dev* 9(9):3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>

- Oudin L, Hervieu F, Michel C et al (2005) Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *J Hydrol* 303:290–306. <https://doi.org/10.1016/j.jhydrol.2004.08.026>
- Smith KA, Wilby RL, Broderick C et al (2018) Navigating cascades of uncertainty—as easy as ABC? Not quite... *J Extreme Events* 5(01):1850007. <https://doi.org/10.1142/S2345737618500070>
- Steele-Dunne S, Lynch P, McGrath R et al (2008) The impacts of climate change on hydrology in Ireland. *J Hydrol* 356(1–2):28–45. <https://doi.org/10.1016/j.jhydrol.2008.03.025>
- Tegegne G, Melesse AM (2020) Multimodel Ensemble Projection of Hydro-climatic extremes for Climate Change Impact Assessment on Water Resources. *Water Resour Manage* 34:3019–3035. <https://doi.org/10.1007/s11269-020-02601-9>
- Tian F, Hu H, Sun Y et al (2019) Searching for an optimized single-objective function matching multiple objectives with automatic calibration of hydrological models. *Chin Geogr Sci* 29(6):934–948. <https://doi.org/10.1007/s11769-019-1068-5>
- Vaughan C, Dessai S (2014) Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdiscip Rev Clim* 5(5):587–603. <https://doi.org/10.1002/wcc.290>
- Wagner T, Reinecke R, Pianosi F (2022) On the evaluation of climate change impact models. *Wiley Interdiscip Rev Clim*, 13(3): p.e772. <https://doi.org/10.1002/wcc.772>
- Walsh S (2012) A Summary of Climate Averages for Ireland 1981–2010. Climatological Note 14, Met Éireann. <https://www.met.ie/climate-ireland/SummaryClimAvgs.pdf>. Accessed 27 November 2022
- Werner C, Nolan P, Naughton O (2019) High-resolution Gridded Datasets of Hydro-climate Indices for Ireland, EPA Research Report 267. <https://www.epa.ie/publications/research/water/research-267-high-resolution-gridded-datasets-of-hydro-climate-indices-for-ireland.php>. Accessed 27 November 2022
- Wilby RL (2022) Stress-testing adaptation options. *Climate Adaptation Modelling*. Springer Climate. Springer, Cham. [https://doi.org/10.1007/978-3-030-86211-4\\_6](https://doi.org/10.1007/978-3-030-86211-4_6)
- Woodruff SC (2016) Planning for an unknowable future: uncertainty in climate change adaptation planning. *Clim Change* 139(3):445–459. <https://doi.org/10.1007/s10584-016-1822-y>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

## Authors and Affiliations

Conor Murphy<sup>1</sup> · Anthony Kettle<sup>1</sup> · Hadush Meresa<sup>1</sup> · Saeed Golian<sup>1</sup> · Michael Bruen<sup>2</sup> · Fiachra O'Loughlin<sup>2</sup> · Per-Erik Mellander<sup>3,4</sup>

✉ Conor Murphy  
conor.murphy@mu.ie

<sup>1</sup> Irish Climate Analysis and Research Units, Department of Geography, Maynooth University, Co. Kildare, North Kildare, Ireland

<sup>2</sup> Dooge Centre for Water Resources Research, School of Civil Engineering, University College Dublin, Dublin 4, Belfield, Ireland

<sup>3</sup> Agricultural Catchments Programme, Teagasc Environment Research Centre, Johnstown Castle, Wexford, Ireland

<sup>4</sup> Teagasc Environment Research Centre, Crops, Environment and Land Use Programme, Johnstown Castle, Wexford, Ireland