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Grid-based simulation of river flows in Northern Ireland: Model performance and future flow changes

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ABSTRACT

Study region: Northern Ireland (NI), and sub-catchments in the Republic of Ireland that drain to NI rivers,
Study focus: Information on the potential future impacts of climate change on river flows is necessary for adaptation planning. There have been many such studies for Great Britain, but fewer for NI. Here, a grid-based hydrological model is configured for NI, and used to investigate changes in seasonal mean, extreme high and extreme low flows.
New Hydrological Insights: When driven by observed climate data, the model shows good performance for a wide range of catchments, particularly where artificial influences are limited. When driven by ensemble data from the UKCP18 Regional (12 km) projections, model performance for the baseline period (1981–2010) is similar to that using observed data, especially when using a simple precipitation bias-correction. Model projections for a future time-slice (2051–2080) generally suggest decreases in spring–autumn mean flows, especially in summer (median −44%), but possible increases in winter mean flows (median 9%), with some variation between ensemble members, particularly in winter when some show large increases to the west. Consistent with this are large projected reductions in 10-year return period low flows everywhere (median −45%), and large increases in 10-year return period high flows for some locations and ensemble members (median 16%). Future applications could include expanding the range of climate data applied.

1. Introduction

Information on the potential future impacts of climate change on river flows is necessary to enable appropriate planning and adaptation (Huntjens et al., 2012). There is already evidence of increases in floods in north-west Europe and the UK (Blöschl et al., 2019), but changes in hydrological droughts are less clear (Hanel et al. 2018, Rudd et al. 2017). Broad-scale modelling studies suggest that parts of north-west Europe will continue to see increases in floods, with possible decreases in low flows and increases in drought duration in western/southern regions (Marx et al., 2018, Thober et al., 2018, Roudier et al. 2016).

A large number of studies have looked at the potential impacts of climate change on river flows in Great Britain (GB) using the UK Climate Projections 2009 (UKCP09; Murphy et al., 2009), which provided a number of products giving information on potential future changes in a range of climatic variables up to 2100. Examples include investigating changes in; seasonal mean flows (Prudhomme et al., 2012); average, low and high flows (Cloke et al., 2010, Charlton and Arnell, 2014); floods (Kay and Jones, 2012, Cloke et al. 2013, Smith et al. 2014, Kay et al., 2014, Bell et al., 2016); water resources (Christierson et al., 2012, Harris et al., 2013); both floods

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and droughts (Collet et al., 2018). Some studies concentrate on a single catchment or small number of catchments (e.g. Cloke et al., 2010, Smith et al. 2014, Harris et al. 2013) while others cover a large number of catchments or use distributed modelling (e.g. Prudhomme et al., 2012, Collet et al., 2018, Bell et al., 2016). Studies used a range of different UKCP09 products, including probabilistic projections, a perturbed parameter ensemble (PPE) of a Regional Climate Model (RCM), and a weather generator.

Studies including the potential impacts of climate change on river flows in Northern Ireland (NI) using UKCP09 are more limited. For example, a water resources assessment including five catchments in NI alongside 65 in GB (Christierson et al., 2012), and a study of seasonal runoff covering the whole of the UK (Sanderson et al., 2012). Studies using other climate projection data for Northern Ireland include an investigation of compound hydro-hazards for 239 catchments across the UK (~10 in NI; Visser-Quinn et al., 2019), and an assessment of changes in annual and seasonal runoff across the whole of Ireland (Charlton et al., 2006). Further studies cover only catchments in the Republic of Ireland (RoI) (e.g. Bastola et al., 2011b, Steele-Dunne et al., 2008). Studies typically suggest future increases in winter flows and flood magnitude but decreases in summer flows in NI; similar to GB. However, a study of historical flow observations for a set of near-natural catchments spread across the whole of Ireland shows trends that are not entirely consistent with the changes expected under climate change (Murphy et al., 2013).

The UK Climate Projections 2018 (UKCP18; Lowe et al., 2018) provide an update to UKCP09, again giving information on potential future changes in a range of climatic variables via a number of products. A small number of studies have so far been published looking at the potential impacts on flows in GB using these updated projections, focussing on changes in average, low and high flows for 10 catchments (Kay et al., 2020), seasonal mean flows across GB (Kay, 2021), floods and low flows across GB (Arnell et al., 2021; Kay et al., 2021a; Lane and Kay, 2021), and the feasibility of inter-basin water transfers to support water supplies in SE England (Khadem et al., 2021).

Here, a fully distributed grid-based hydrological model, previously applied across GB, is configured for NI. Model performance is assessed against available gauged river flows. Time-series data from the UKCP18 12 km RCM 12-member PPE are then used to drive the model, to look at potential future changes in seasonal mean flows as well as extreme high and low flow flows, thus extending the GB results of Kay (2021) and Lane and Kay (2021) to cover NI. The methods are described in Section 2, with results presented in Section 3, a discussion in Section 4 and conclusions in Section 5.

2. Methods

2.1. Hydrological model setup

The Grid-to-Grid (G2G) is a national-scale hydrological model that typically runs on a 1 km x 1 km grid, at a 15-minute time-step, and is parameterised using digital datasets (e.g. soil types, land-cover, flow directions) (Bell et al., 2009). It was originally configured for application across GB, on a spatial domain aligned with the GB national grid. A version has now been configured to cover Northern Ireland and sub-catchments in the RoI that drain to NI rivers, also on a spatial domain aligned with the GB national grid.

G2G has been shown to perform well for a wide range of catchments across GB (Bell et al., 2009, 2016; Formetta et al., 2018) particularly those with more natural flow regimes as it does not routinely take account of the effect of artificial influences such as abstractions and discharges on river flows. It has also been shown to perform well for low flows and for drought identification (Rudd et al., 2017). The G2G generally uses spatial datasets for model configuration in preference to parameter identification via calibration, and where model parameters are required (such as the kinematic wave speeds used in lateral routing) nationally-applicable values are used.

Spatial data, such as flow-directions, land-cover and soils, used to configure G2G are as in Bell et al., (2009). The effect of urban and suburban land-cover on runoff and downstream flows is accounted for in the model. But the impact of water bodies such as lakes and reservoirs on downstream river flows is generally neglected at the national scale; lake storage and regulation is not accounted for, and lake grid-cells are treated as though they were rivers. For NI, the hydrological landscape is dominated by Lough Neagh, a large freshwater lake with an area of approximately 390 km^2, as well as Lough Erne, which consists of two connected lakes (Upper and Lower) with a combined area of approximately 144 km^2 located to the south-west of NI. Thus the exclusion of lake storage and regulation is most likely to impact on model performance for river locations downstream of Lough Neagh (the Lower Bann river).

G2G requires input time-series of precipitation and potential evaporation (PE), as well as temperature data for the optional snow module (Bell et al., 2016) which is applied here. Model outputs include gridded time-series of monthly mean flows, annual maxima of daily mean flows, and 7-day minima of daily mean flows. In addition, time-series of daily mean river flows can be output for 1 km grid boxes corresponding to specific catchments for which gauged flow data are available from the National River Flow Archive (NRFA; www.ceh.ac.uk/data/nrfa/). Although 'river flows' are produced for every 1 km grid box, only data from non-tidal grid boxes with a catchment area of at least 50 km^2 are analysed here. Pixels within Lough Neagh and Lough Erne are also excluded (if they are at least 70% water according to 25 m data from Land Cover Map 2015; Rowland et al., 2017). The remaining 1468 pixels are hereafter termed '1 km river pixels', of which 1106 are within NI.

2.2. Observation-based simulation

An observation-based simulation is performed for Dec 1980–Nov 2011 (hereafter termed SIMOBS) using the following gridded datasets:

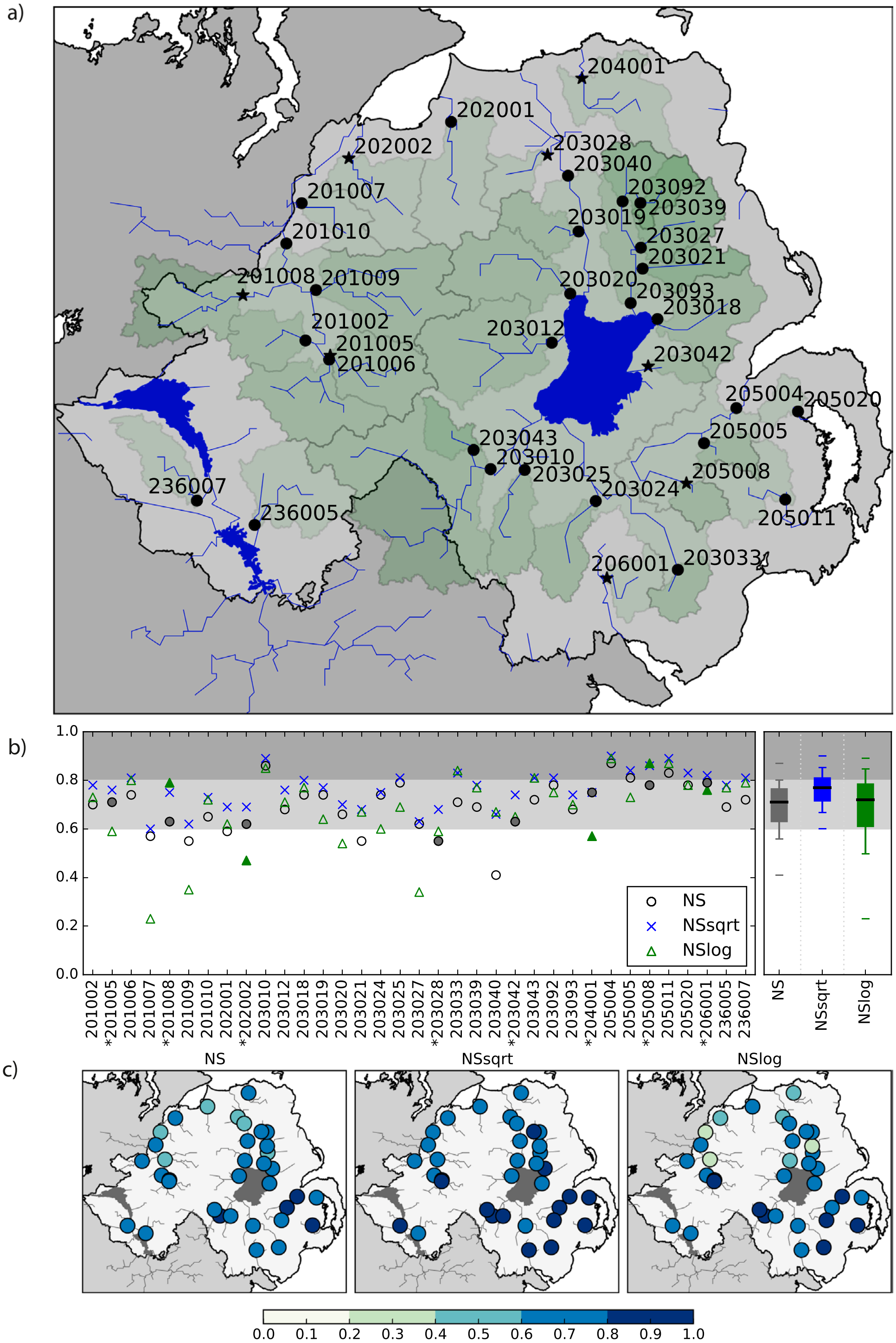

Fig. 1. a) The 35 catchments used for the SIMOBS performance assessment (green shading, with nested catchments darker), along with main rivers (blue lines) and Lough Neagh and Lough Erne (blue shading). Benchmark catchments are shown with an asterisk (*). b) NS, NSsqrt and NSlog values for each catchment (left; filled circles/triangles indicate benchmark catchments suitable for high/low flows) and boxplots showing the performance range across the set of catchments (right). Boxes show the 25th-75th percentile range, with the median marked by the line, whiskers show the 10th-90th percentile range, and further markers show the overall min and max. c) Maps showing the spatial variation in each performance measure.

- Daily 1 km grids of precipitation (CEH-GEAR; Tanguy et al., 2016). These data are on the Irish national grid (and cover the required parts of the RoI), so have been re-projected to the GB national grid as a 50 m grid and the mean in each 1 km cell estimated. They are then divided equally over each model time-step within a day.
- Monthly 40 km grids of PE for short grass (MORECS; Hough and Jones, 1997). These data are on the Irish national grid, so have been re-projected to the 1 km GB national grid using the majority MORECS square in each 1 km cell. The data do not cover all the required parts of the RoI, or indeed all of NI, so have been extended where necessary by copying from the nearest 1 km grid cell with data. They are then divided equally over each model time-step within a month.
- Daily 1 km grids of min and max temperature (Met Office et al., 2019). These data are on the GB national grid but do not cover the required parts of the RoI, so have been infilled from the nearest 1 km grid cell with data, using altitude information and a lapse rate. They are then interpolated through the day using a sine curve.

The simulation is initialised using a states file saved at the end of a prior observation-based run (Jan 1970–Nov 1980) using the same driving datasets as above.

2.3. Climate change simulations

The climate change simulations use daily precipitation, daily min and max temperature data and daily PE derived from the UKCP18 Regional (12 km) projections (Met Office Hadley Centre, 2018). These comprise a 12-member RCM PPE (nested in an equivalent GCM PPE) covering Dec 1980–Nov 2080 under RCP8.5 emissions (Riahi et al., 2011). Ensemble member 01 uses the standard parameterisation. The data are available re-projected onto a 12 km grid aligned with the GB national grid.

Biases in the 12 km RCM precipitation (Murphy et al., 2018, Fig. 4.4) are adjusted using monthly correction factor grids, derived by comparing baseline mean monthly precipitation totals (from each PPE member separately) against those from CEH-GEAR averaged up to the RCM grid, with smoothing based on weighting in a 3 × 3 neighbourhood (Supp. Fig. 1; Guillod et al., 2018). The precipitation data are then spatially downscaled using patterns derived from 1 km Standard Average Annual Rainfall data (1961–1990; Bell et al., 2007), and temporally downscaled in the same way as for observed rainfall data (Section 2.2). The 12 km RCM temperature data are downscaled to 1 km using a lapse rate with elevation data (Morris and Flavin, 1990), and temporally downscaled in the same way as for observed temperature data (Section 2.2). The 12 km RCM PE is estimated from (re-projected) daily climate variables using a formulation replicating that of MORECS as closely as possible, including an interception correction. Potential future increases in stomatal resistance under higher atmospheric CO_2 concentrations are also included (Rudd and Kay, 2016, Guillod et al., 2018). PE is only estimated for RCM boxes classed as 'land', with any other required 12 km boxes infilled by copying from the nearest 12 km box with data. The 12 km RCM PE data are spatially and temporally downscaled in the same way as for observed data (Section 2.2).

The same state initialisation file is used for each RCM-based simulation (hereafter termed SIMRCM) as for SIMOBS (Section 2.2).

The central projection from the RCM PPE suggests typical decreases in summer precipitation of around −25% and increases in winter precipitation of around 15% over NI by 2061–2080 (Murphy et al., 2018, Fig. 4.8 c,d). However, summer decreases can be as much as −50% and winter increases as high as 30% for some NI locations in some ensemble members, and winter decreases of −10% or more are possible in NI for some ensemble members. Temperature increases by ~2–5 °C in summer and ~1–4 °C in winter over NI by 2061–2080, depending on location and ensemble member (Murphy et al., 2018, Fig. 4.8 a,b). PE between spring and autumn typically increases by ~7–15%, with increases of 20% or more in some locations for some ensemble members. Winter PE also generally increases, by ~2% on average and up to ~19% in some locations for some ensemble members, but there are decreases of as much as ~−10% in places, although these are not likely to be important as winter PE is fairly low.

2.4. Analysis of simulated flows

A 30-year time-slice is used to assess performance of the G2G river flow simulations, comparing the SIMOBS run against gauged flows (Section 2.4.1) and comparing the SIMRCM runs against the SIMOBS run (Section 2.4.2). These performance assessments use the time-slice 1981–2010.

A 30-year future time-slice is compared against a 30-year baseline time-slice for the SIMRCM runs, to assess potential future changes in flows (Section 2.4.3). The precise time-slices differ slightly depending on the flows under consideration; the periods Dec 1980–Nov 2010 and Dec 2050–Nov 2080 are used for seasonal mean flows and low flows (to fit most closely with the available RCM data; Section 2.3), but the periods Oct 1981–Sep 2011 and Oct 2050–Sep 2080 (i.e. 30 water years) are used for high flows (Section 2.4.3).

2.4.1. Performance using observed data

Three time-series performance measures are used to quantify different aspects of the agreement between simulated and observed flows, for 35 catchments (those NRFA catchments with an area of at least 50 km^2 and no more than 20% missing flow data in the baseline period; Fig. 1a). Eight of these are designated as benchmark catchments (UKBN2; Harrigan et al., 2018); a set of catchments across the UK where human disturbance to flows is considered minimal and flow gauging is generally considered reliable (although there are additional flags highlighting gauging issues for high/low flows). Information on the 35 catchments is provided in Supp. Table 1.

The three performance measures are based on the model efficiency criterion of Nash and Sutcliffe (1970), including versions adapted to focus on average flows (using the square root) and low flows (using logarithms). Specifically, the measures are defined as

$$NS = 1 - \frac{\sum (Q_t - M_t)^2}{\sum \left(Q_t - \overline{Q_t}\right)^2},$$

$$NSsqrt = 1 - \frac{\sum \left(\sqrt{Q_t} - \sqrt{M_t}\right)^2}{\sum \left(\sqrt{Q_t} - \overline{\sqrt{Q_t}}\right)^2},$$

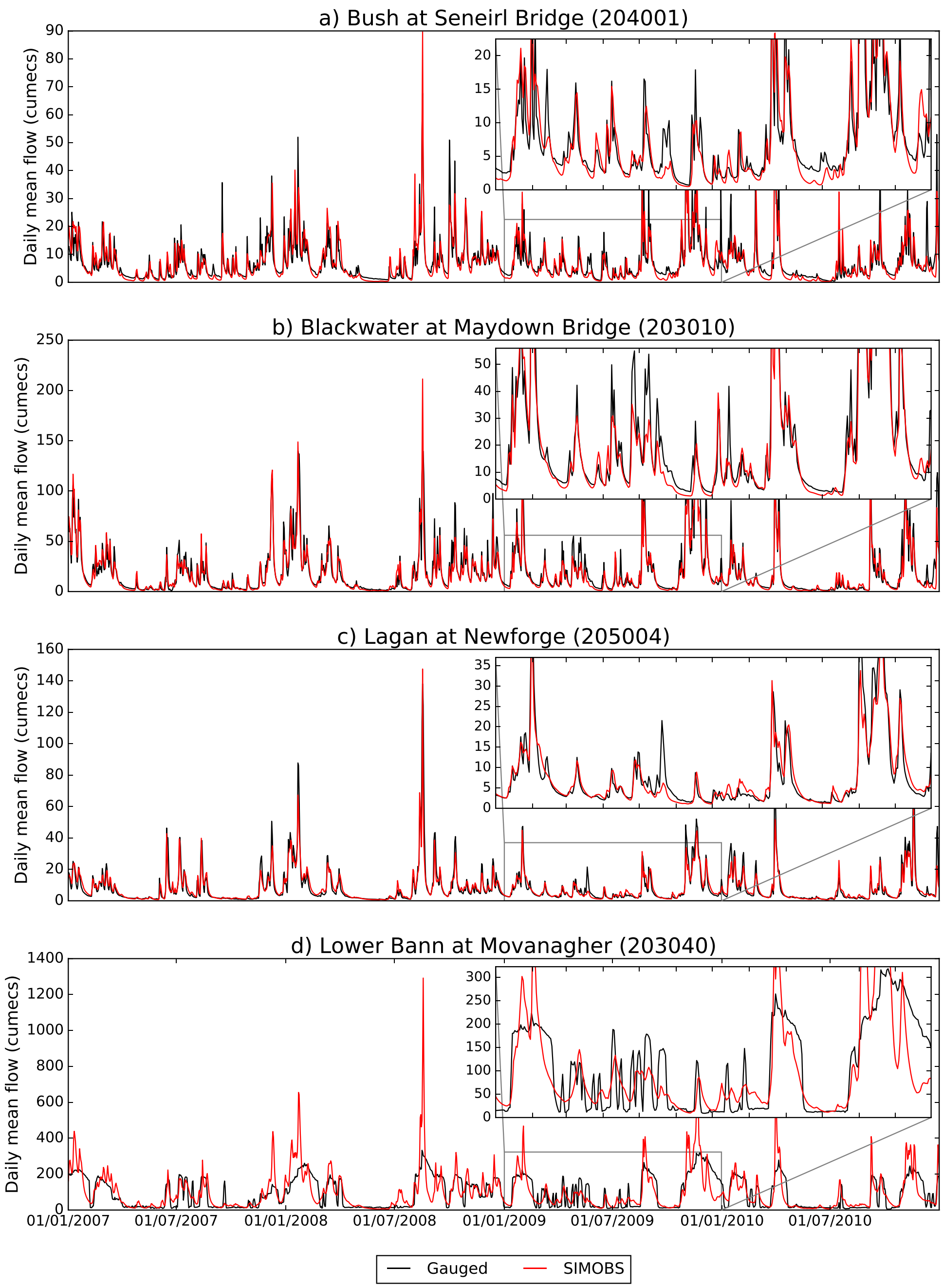

Fig. 2. Hydrographs for a) Bush at Seneirl Bridge (204001), b) Blackwater at Maydown Bridge (203010), c) Lagan at Newforge (205004) and d) Lower Bann at Movanagher (203040), downstream of Lough Neagh.

$$NSlog = 1 - \frac{\sum (ln(Q_t + \epsilon) - ln(M_t + \epsilon))^2}{\sum \left(ln(Q_t + \epsilon) - \overline{ln(Q_t + \epsilon)} \right)^2} \qquad with \ \epsilon = \frac{\overline{Q_t}}{100},$$

where Q_t are the observed flows, M_t are the modelled flows, ε is a small value (usually taken to be the observed mean flow divided by 100) and t is time. An NS, NSsqrt or NSlog value of 1 indicates a perfect fit, whilst a negative value indicates that the fit is worse than the mean flow. The results are presented in Section 3.1.

2.4.2. Performance using baseline climate model data

Assessment of the performance using baseline climate model data uses measures derived from flow duration curves, thus comparing statistical characteristics of flows rather than day-to-day equivalence (because weather events in the RCM PPE will not follow the observed weather over the baseline period; Kay, 2021).

The analysis uses gauged flows for 35 catchments (Section 2.4.1) and compares these with simulated daily mean flows for corresponding locations from the SIMOBS run, from each SIMRCM run individually, and from pooling the 12 SIMRCM runs together (both with and without bias correction). The analysis involves three measures, quantifying the percentage bias for different parts of the flow duration curve; low flow volume (lfv_70–95; bias in the 70th-95th quantiles), median flow (mdf; bias in the 50th quantile), and high flow volume (hfv_5–30; bias in the 5th-30th quantiles). The results are presented in Section 3.2.

2.4.3. Future changes in flows using climate model data

To assess potential future changes in flows, for each SIMRCM run the following analyses are performed:

- Gridded time-series of monthly mean flows are used to derive seasonal mean flows for each time-slice, using the standard seasons (winter: December–February, spring: March–May, summer: June–August, autumn: September–November) (as for GB; Kay, 2021).
- Gridded time-series of the annual maxima of daily mean flows are used to derive flood frequency curves for each time-slice. The generalised logistic distribution is fitted to the 30 annual maxima for each time-slice using the method of L-moments (Hosking, 1996; Robson & Reed, 1999), to produce flood frequency curves covering 1- to 25-year return period events (as for GB; Lane and Kay, 2021).
- Gridded time-series of the annual minima of 7-day mean flows are used to derive low flow frequency curves for each time-slice. A generalised extreme value distribution is applied to the 7-day annual minimum flows using the method of L-moments (Hosking, 1996; Zaidman et al., 2002), to produce low flow frequency curves (as for GB; Lane and Kay, 2021).

Percentages changes from the baseline time-slice to the future time-slice are calculated for each SIMRCM run separately (Section 3.3). For flood/low flow frequency, the analysis focuses on 10-year return period events. Flow changes are mapped, but also summarised for the three river-basin regions covering Northern Ireland; NW Ireland, Neagh Bann and NE Ireland (Supp. Fig. 2).

3. Results

3.1. Performance using observed data

The G2G shows good overall performance for the SIMOBS run (Fig. 1b-c). The model performs well across the flow range, with the median performance across the set of catchments for the three performance measures (Section 2.4.1) being 0.71 for NS (high flows), 0.77 for NSsqrt (average flows) and 0.72 for NSlog (low flows) Fig. 1b). Some example hydrographs are shown in Fig. 2.

In Fig. 1b, the eight benchmark catchments are marked with an asterisk, with those specifically suitable for either high or low flows having filled markers. The benchmark catchments show good model performance for all three scores, except for catchment 202002 (Faughan at Drumahoe) and 204001 (Bush at Seneirl Bridge; Fig. 2a), which have slightly poorer performance for low flows, and catchment 203028 (Agivey at Whitehill), which has slightly poorer performance for high flows. Despite being benchmark catchments, both 202002 and 204001 do have some abstractions and discharges, and 204001 has an upstream reservoir (NRFA, 2021); although the effect of these on gauged flows is considered small, they could still affect model performance particularly for low flows.

Catchments not in the benchmark network show more scatter in the performance scores. The best performing non-benchmark catchments are 203010 (Blackwater at Maydown Bridge; Fig. 2b), 205004 (Lagan at Newforge; Fig. 2c) and 205011 (Annacloy at Kilmore Bridge), which have values greater than 0.8 for all three performance measures. The NSsqrt values are at least 0.6 for all catchments, but there are some catchments with NS and NSlog values less than 0.6, with the NSlog (low flow) values tending to be worse. The simulated low flows for 201007 (Burn Dennet at Burndennet) tend to be too low (simulated Q70 about 57% of observed; not shown), which could be due to difficulties in measuring low flow in the wide and shallow channel at this station (NRFA, 2021). Catchment 203027 (Braid at Ballee) also has simulated low flows that are lower than the observed flows, which could be due to effluent returns affecting the flow at this station, and the gauged low flows are affected by weed growth (NRFA, 2021). There are no obvious reasons for the poorer simulation of low flows for catchment 201009 (Owenkillow at Crosh). Maps of the performance scores (Fig. 1c) show that the lowest performing catchments are generally located to the north-west, with the highest performing catchments often located to the south-east.

Catchment 203040 (Lower Bann at Movanagher) is the only gauged catchment located downstream of Lough Neagh, on the Lower Bann River, and its poorer model performance for high flows is due to the regulation of Lough Neagh. The Department for

Infrastructure (DfI) Rivers are required to regulate water levels in Lough Neagh within a specific range, to reduce the flood risk (DfI, 2021). This is achieved using flood gates at the head of the Lower Bann River, where it exits from Lough Neagh, with two additional flood gates down the Lower Bann River which further control levels. The regulation heavily influences the observed flows by capping high flows (Fig. 2d). Currently the G2G does not account for such flow regulation.

3.2. Performance using baseline climate model data

Boxplots summarising the three measures of fit of the flow duration curves (for low, median and high flows; Section 2.4.2) across the set of 35 gauged catchments show that the bias correction makes the performance of the pooled SIMRCM ensemble more similar to the performance of the SIMOBS run (Fig. 3). Maps of the measures (Supp. Fig. 3) indicate that a tendency for over-estimation of median

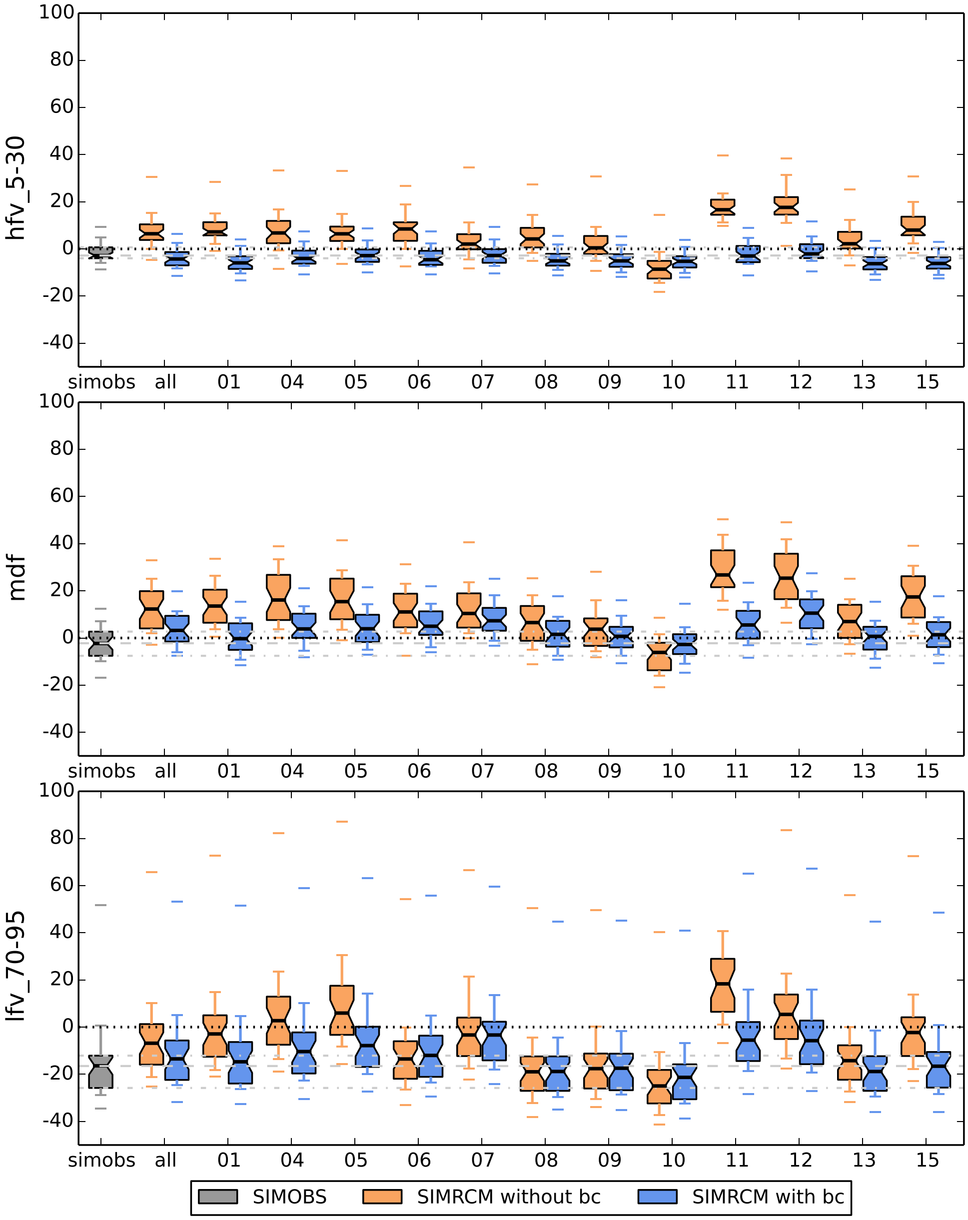

Fig. 3. Boxplots summarising the three measures of fit of the flow duration curve — high flow volume (hfv_5–30), median flow (mdf), low flow volume (lfv_70–95) — across the set of 35 gauged catchments, for the SIMOBS run (left), the pooled SIMRCM ensemble (‘all’), and each SIMRCM run separately. Each box shows the 25th-75th percentile range, with the line indicating the 50th percentile and the whiskers the 10th-90th percentiles. Lines outside the box show the overall min and max (if within the plotted range). The SIMRCM results are shown both with and without bias correction (bc).

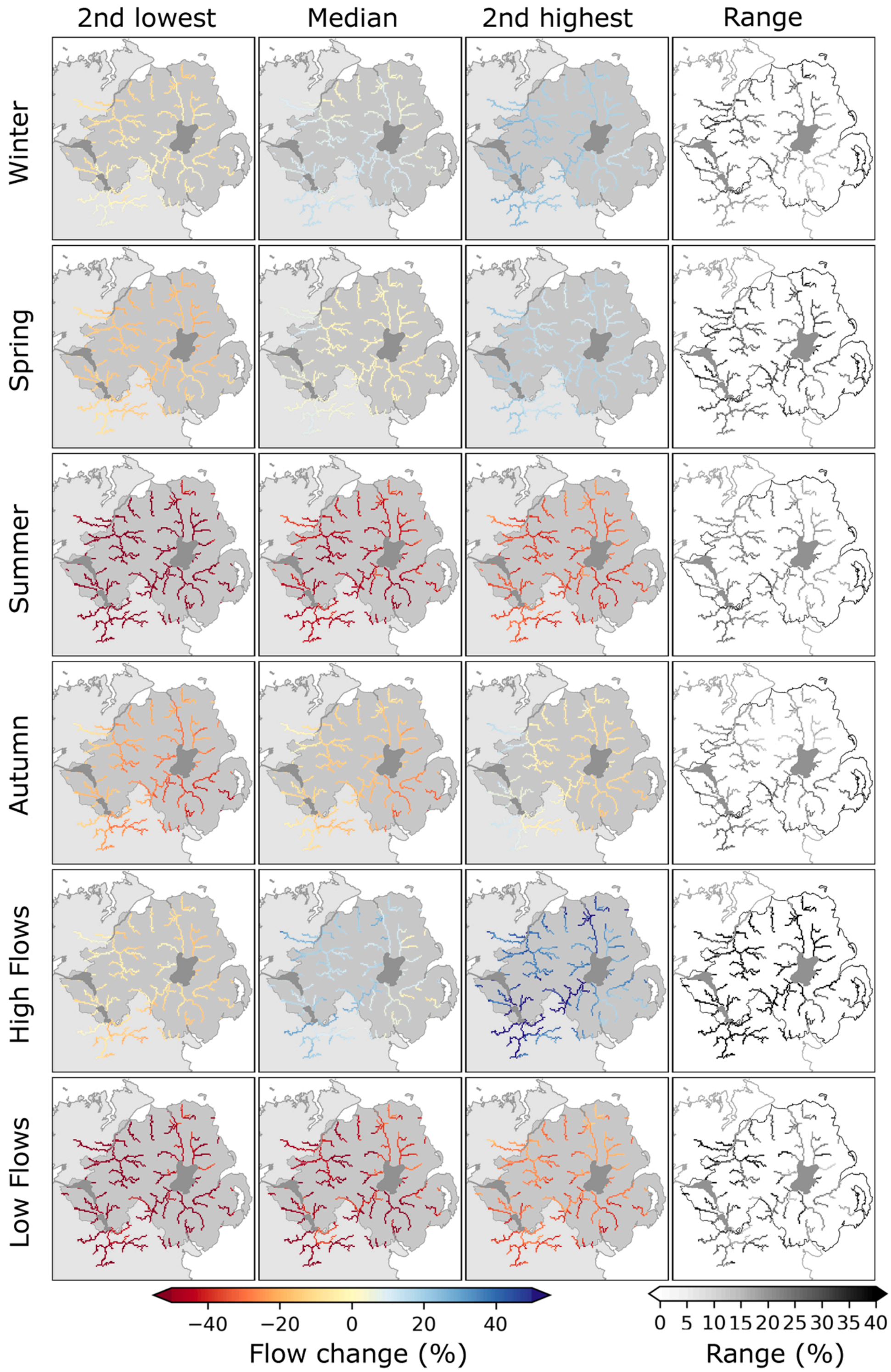

Fig. 4. Maps summarising change in river flows from the 12 SIMRCM ensemble members, showing the 2nd lowest (left), median (left-middle), 2nd highest (right-middle) ensemble members for each river pixel, and the range between the 2nd lowest and 2nd highest (right). From top to bottom, these show changes in winter flows (Dec–Feb), spring flows (Mar–May), summer flows (Jun–Aug), autumn flows (Sep–Nov), 10-year return period high flows, and 10-year return period low flows.

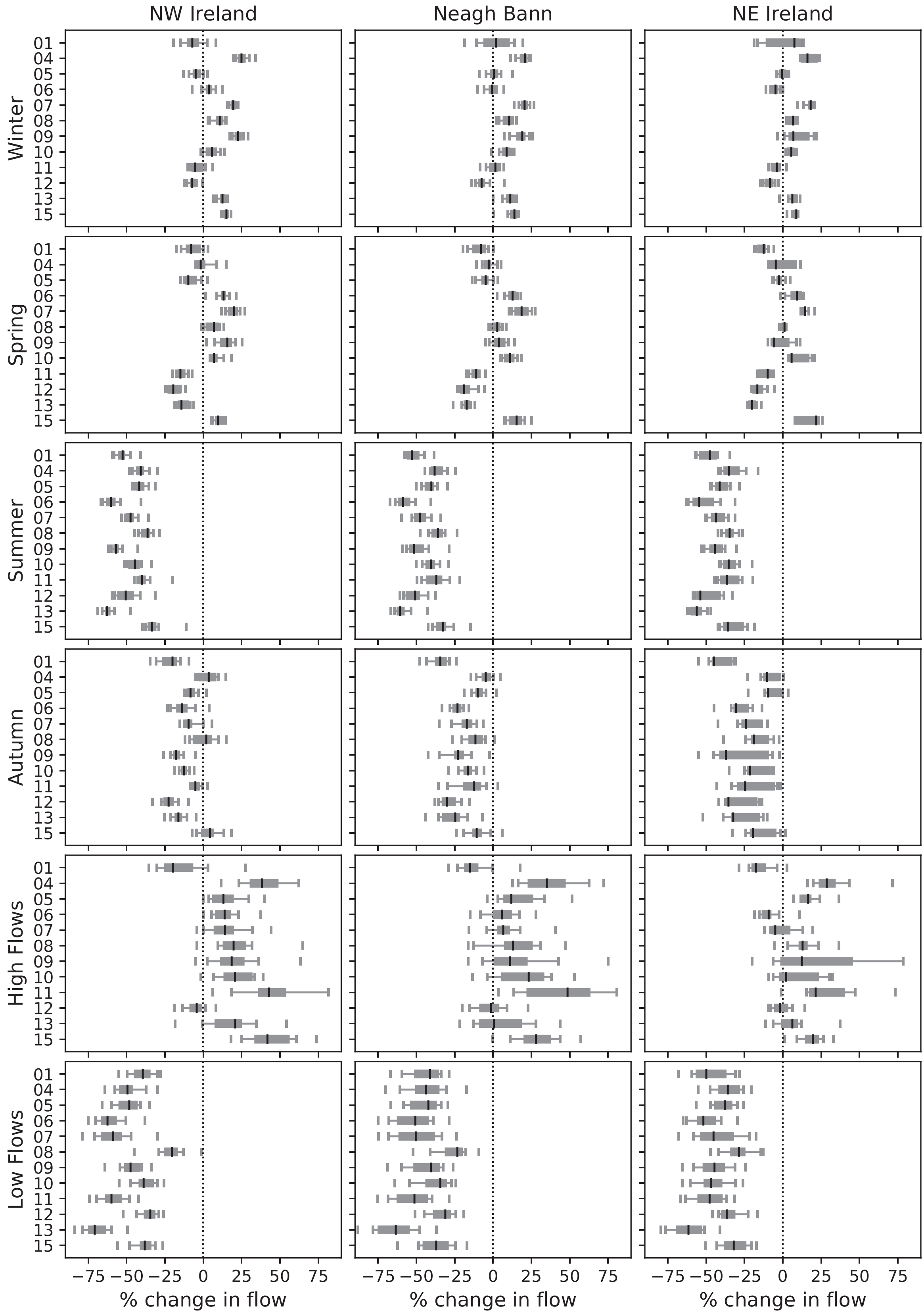

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Fig. 5. Boxplots showing the change in seasonal mean flows, 10-year return period high flows, and 10-year return period low flows summarised over three regions of NI (Supp. Fig. 2). Each box indicates the 25th–75th percentile range, with the whiskers showing the 10th–90th percentile range, and bars outside the whiskers showing the overall min and max.

and high flows has been reduced by the bias correction. There is a tendency towards under-estimation of low flows in most catchments though, for the SIMOBS run as well as the SIMRCM runs.

An additional assessment of the baseline monthly mean flows, flood frequency curves and low-flow frequency curves for the eight benchmark catchments shows good agreement between the RCM and observation-based runs, with the SIMRCM ensemble generally bounding the SIMOBS data (Supp. Fig. 4). There is a large spread in the SIMRCM ensemble for higher return period (>~15 years) flood flows, which is unsurprising when estimating these rarer events from a relatively short 30-year flow time series. For low flows, there is a tendency for the SIMRCM ensemble to over-estimate flows at low return periods (1–3 years), compared to the SIMOBS run.

3.3. Future changes in flows using climate model data

Maps of the seasonal mean flow changes from the SIMRCM ensemble, presented as the median and the 2nd lowest and 2nd highest projection for each river pixel, almost exclusively show decreases in each season, especially for the ensemble median change (Fig. 4). The exception is small increases in the ensemble median winter flows (median 9%), mainly to the south and west, and increases in the 2nd highest in winter and spring. In contrast, large reductions in summer flows are predicted by all ensemble members (median −44%), and autumn decreases can also be large (median −13%), particularly to the south and east. Results for individual SIMRCM ensemble members further show the variation between members (Supp. Fig. 5).

Maps of the 10-year low flow changes from the SIMRCM ensemble, again presented as the median and the 2nd lowest and 2nd highest projection for each river pixel, show large reductions, with the ensemble median showing reductions of −25 to −64% across NI (Fig. 4; overall median −45%). These widespread decreases in low flows are seen across all the SIMRCM ensemble members (Supp. Fig. 6b). Alongside decreasing low flows there is also a trend towards annual minimum events occurring later in the year by up to around 30 days, although these are only significant in a few of the ensemble members (Supp. Fig. 7b).

The sign of change for 10-year high flows is less clear. Maps summarising results from the SIMRCM ensemble show average changes ranging from −7.5% to + 40% between the 2nd lowest and 2nd highest ensemble members (Fig. 4; overall median 16%). There is much variation between the SIMRCM ensemble members, with some predicting large increases in high flows (e.g. 04, 11, 15), some predicting overall decreases in high flows (e.g. 01, 12), and others showing a more mixed picture (Supp. Fig. 6a). This results in the particularly large ensemble range for changes to high flows, when compared to the low flow or seasonal changes (Fig. 4). Analysis of the dates of occurrence of AMAX showed few significant changes in timing (Supp. Fig. 7a).

Summary distributions of seasonal mean flow, high flow, and low flow changes for three regions clearly show the differences in response for different ensemble members, seasons, and regions (Fig. 5). There are clear differences between ensemble members in all regions and seasons (with it being possible to select pairs of ensemble members with no or very little overlap in response in all cases), although for NE Ireland in autumn there are broader ranges of change for most ensemble members, and thus often more overlap between them. The difference between ensemble members is most stark for the high flow changes, where there are large differences between ensemble members for both the flow change values and ranges.

4. Discussion

The application of a national-scale grid-based hydrological model for Northern Ireland with observed driving data has shown generally good performance for catchments across the country and across the flow range. The exception is flows downstream of Lough Neagh, where flood regulation essentially caps the observed river flows. Since the hydrological model currently does not include any artificial influences on flows, so essentially simulates natural flows, the pattern of observed flows downstream of Lough Neagh cannot be replicated in the simulations. However, it may be possible to enhance the model to include such regulation. It would also be possible, provided appropriate datasets were available, to incorporate abstraction and discharges into the model, and to use estimates of open-water PE for the lake pixels.

The use of the G2G model with driving data from the UKCP18 Regional projection ensemble shows that performance for a baseline period is similar to that of observed driving data, especially after application of a simple bias correction to climate model precipitation. Comparison of ensemble modelling results for a future time-slice, compared to the baseline time-slice, generally suggests future decreases in seasonal mean flows, especially in summer and autumn. There is some variation between ensemble members, particularly in winter when some show large increases in flows to the west. Consistent with this, the analysis of 10-year return period low flows shows large reductions across the country, and the analysis of 10-year return period high flows shows large increases for some locations and ensemble members. These flow changes are consistent with the typical decreases in summer precipitation, increases in winter precipitation, and increases in PE (Section 2.3), and similar to the flow changes simulated for north-west England (Kay, 2021; Lane & Kay, 2021).

Decreasing summer and autumn flows, with possible small increases to winter flows, are broadly consistent with previous climate impact studies to have included NI catchments (Christierson et al., 2012, Sanderson et al., 2012, Arnell et al., 2021). Christierson et al. (2012) also indicated reductions in summer flows for five catchments in NI. However, by using the UKCP09 probabilistic projections they were better able to sample modelling uncertainties, finding that increases in summer flows were also within the ensemble spread of their projections. Sanderson et al. (2012) also found that whilst the ensemble mean change in runoff showed summer reductions, a reduction in summer flows was not unanimously predicted by all models by the 2050s. Whilst few studies have focused on changes to extreme flows for Northern Ireland, the increases in flood flows found here are consistent with projections of increasing 5–100 year return period flows for Irish catchments (Bastola et al., 2011b), and results for Ireland within a European analysis of changing high and flood flows (Thober et al., 2018). Declining summer flows, which may also indicate a reduction in discharge associated with low flow extremes, are consistent with studies of Irish catchments (Bastola et al., 2011a, Steele-Dunne et al., 2008).

Since the model essentially simulates natural river flows, the climate change impact modelling does not account for potential future changes in artificial influences such as abstractions or discharges. Neither does it allow for potential future changes in land-use or land-cover. Also, only one global/regional climate model is applied (albeit as a perturbed parameter ensemble), under only one emissions scenario (RCP8.5). The climate model is typically considered the largest source of uncertainty in hydrological impact modelling (Vetter et al., 2017, Roudier et al., 2016), although the hydrological model can be particularly important for low flows (Giuntoli et al., 2015). The RCP8.5 emissions scenario is considered a high scenario, and lower pathways should give lesser impacts (e.g. Kay et al., 2020). Further sources of uncertainty include the estimation of future PE (Kay and Davies, 2008, Dallaire et al., 2021) and the choice of bias correction approach (e.g. Lafon et al., 2013).

5. Conclusions

Developing a national-scale grid-based hydrological model for NI, and the parts of the Republic of Ireland that drain into NI, has enabled the simulation of river flows across the country (at gauged and ungauged locations). The model builds on one used extensively for modelling river flows across Great Britain, and takes advantage of digital datasets to enable the simulation of varying hydrological responses due to spatial differences in landscape characteristics. The model performance is good for a wide range of catchments, provided flows are not heavily affected by artificial influences (e.g. river regulation, abstractions or discharges). Although such models may not perform as well as calibrated catchment models at specific locations, they have the advantage of simulating flows across a wide area in a consistent way.

Analysis of the potential impacts of climate change on river flows across NI, using the UKCP18 Regional projections, suggests significant impacts on seasonal mean flows and extreme flows. Such information is vital to enable the development of appropriate adaptation strategies, particularly for flood risk management and drought and water resource management.

Potential future uses of the model could include the application of a sensitivity-based approach to estimating the impacts of climatic change on flood peaks, which can be combined with the UKCP18 Probabilistic projections to provide information for a broader range of climate model and emissions uncertainty than covered here (Kay et al., 2021b). Such an approach would enable NI to move away from the current blanket + 20% allowance for climate change impacts on peak river flows (Wasko et al. 2021), by developing regional or location-specific values as for England, Wales and Scotland (Reynard et al., 2017). Other applications could include river flood forecasting and warning (Cranston et al., 2012, Price et al., 2012), surface water flood and impact forecasting (Cole et al., 2016, Aldridge et al., 2020) and investigating the potential impacts of climate change on surface water flood hazard and risk (Rudd et al., 2020).

CRediT authorship contribution statement

A.L. Kay: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **H.N. Davies:** Methodology, Data curation, Writing – original draft. **R.A. Lane:** Formal analysis, Visualization, Writing – original draft. **A.C. Rudd:** Formal analysis, Visualization, Writing – original draft. **V.A. Bell:** Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2021.100967.

References

Aldridge, T., Gunawan, O., Moore, R.J., et al., 2020. Developing an impact library for forecasting surface water flood risk. J. Flood Risk Manag. 13 (3), e12641.

Arnell, N.W., Kay, A.L., Freeman, A., Rudd, A.C., Lowe, J.A., 2021. Changing climate risk in the UK: a multi-sectoral analysis using policy relevant indicators. Clim. Risk Manag. 31, 100265.

Bastola, S., Murphy, C., Sweeney, J., 2011a. The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. Adv. Water Resour. 34 (5), 562–576.

Bastola, S., Murphy, C., Sweeney, J., 2011b. The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios. Sci. Total Environ. 409, 5403–5415.

Bell, V.A., Kay, A.L., Davies, H.N., Jones, R.G., 2016. An assessment of the possible impacts of climate change on snow and peak river flows across Britain. Clim. Change 136 (3), 539–553.

Bell, V.A., Kay, A.L., Jones, R.G., Moore, R.J., 2007. Development of a high resolution grid-based river flow model for use with regional climate model output. Hydrol. Earth Syst. Sci. 11, 532–549.

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

Blöschl, G., Hall, J., Viglione, A., Perdigão, R., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G.T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., Živković, N., 2019. Changing climate both increases and decreases European river floods. Nature 573, 108–111.

Charlton, M.B., Arnell, N.W., 2014. Assessing the impacts of climate change on river flows in England using the UKCP09 climate change projections. J. Hydrol. 519, 1723–1738.

Charlton, R., Fealy, R., Moore, S., Sweeney, J., Murphy, C., 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, 475–491.

Christierson, Bv, Vidal, J.-P., Wade, S.D., 2012. Using UKCP09 probabilistic climate information for UK water resource planning. J. Hydrol. 424–425, 48–67.

Cloke, H.L., Jeffers, C., Wetterhall, F., Byrne, T., Lowe, J., Pappenberger, F., 2010. Climate impacts on river flows: projections for the Medway catchment, UK, with UKCP09 and CATCHMOD. Hydrol. Process 24, 3476–3489.

Cloke, H.L., Wetterhall, F., He, Y., Freer, J.E., Pappenberger, F., 2013. Modelling climate change impact on floods with ensemble climate projections. QJR Meteorol. Soc. 139, 282–297.

Cole S.J., Moore R.J., Wells S.C., Mattingley P.S., 2016. Real-time forecasts of flood hazard and impact: some UK experiences. FLOODrisk 2016, 3rd European Conference on Flood Risk Management, E3S Web of Conferences, 7, 18015, 11pp. doi:10.1051/e3sconf/20160718015.

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

Cranston M., Maxey R., Tavendale A. et al., 2012. Countrywide flood forecasting in Scotland: challenges for hydrometeorological model uncertainty and prediction. In: Weather Radar and Hydrology (ed. by RJ Moore, SJ Cole & AJ Illingworth) (Proc. Exeter Symp., April 2011), IAHS Publ. no. 351, 538–543.

Dallaire, G., Poulin, A., Arsenault, R., Brissette, F., 2021. Uncertainty of potential evapotranspiration modelling in climate change impact studies on low flows in North America. Hydrol, Sci, J, 66 (4), 689–702.

DfI, 2021. https://www.infrastructure-ni.gov.uk/articles/lough-neagh-levels (Accessed on 4 January 2021).

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

Giuntoli, I., Vidal, J.-P., Prudhomme, C., Hannah, D.M., 2015. Future hydrological extremes: the uncertainty from multiple global climate and global hydrological models. Earth Syst. Dyn. 6 (1), 267–285.

Guillod, B.P., Jones, R.G., Dadson, S.J., Coxon, G., Bussi, G., Freer, J., Kay, A.L., Massey, N.R., Sparrow, S.N., Wallom, D.C.H., Allen, M.R., Hall, J.W., 2018. A large set of potential past, present and future hydro-meteorological time series for the UK. Hydrol. Earth Syst. Sci. 22 (1), 611–634.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J., Kumar, R., 2018. Revisiting the recent European droughts from a long-term perspective. Sci. Rep. 8, 9499.

Harris, C.N.P., Quinn, A.D., Bridgeman, J., 2013. Quantification of uncertainty sources in a probabilistic climate change assessment of future water shortages. Clim. Change 121, 317–329.

Harrigan, S., Hannaford, J., Muchan, K., Marsh, T.J., 2018. Designation and trend analysis of the updated UK Benchmark Network of river flow stations: the UKBN2 dataset. Hydrol. Res. 49 (2), 552–567.

Hosking J.R.M., 1996. Fortran Routines for Use with the Method of L-Moments. New York.

Hough, M., Jones, R.J.A., 1997. The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0– an overview. Hydrol. Earth Syst. Sci. 1 (2), 227–239.

Huntjens, P., Lebel, L., Pahl-Wostl, C., Camkin, J., Schulze, R., Kranz, N., 2012. Institutional design propositions for the governance of adaptation to climate change in the water sector. Glob. Environ. Change 22, 67–81.

Kay, A.L., 2021. Simulation of river flow in Britain under climate change: baseline performance and future seasonal changes. Hydrol Process 121, 800. https://doi.org/10.1002/hyp.14137.

Kay, A.L., Crooks, S.M., Davies, H.N., Reynard, N.S., 2014. Probabilistic impacts of climate change on flood frequency using response surfaces. I: England and Wales. Reg. Environ. Change 14 (3), 1215–1227.

Kay, A.L., Davies, H.N., 2008. Calculating potential evaporation from climate model data: a source of uncertainty for hydrological climate change impacts. J. Hydrol. 358, 221–239.

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

Kay, A.L., Jones, R.G., 2012. Comparison of the use of alternative UKCP09 products for modelling the impacts of climate change on flood frequency. Clim. Change 114 (2), 211–230.

Kay, A.L., Rudd, A.C., Fry, M., Nash, G., Allen, S., 2021b. Climate change impacts on peak river flows: combining national-scale hydrological modelling and probabilistic projections. Clim. Risk Manag. 31, 100263.

Kay, A.L., Watts, G., Wells, S.C., Allen, S., 2020. The impact of climate change on UK river flows: a preliminary comparison of two generations of probabilistic climate projections. Hydrol. Process 34 (4), 1081–1088.

Khadem, M., Dawson, R.J., Walsh, C.L., 2021. The feasibility of inter-basin water transfers to manage climate risk in England. Clim. Risk Manag. 33, 100322.

Lafon, T., Dadson, S., Buys, G., Prudhomme, C., 2013. Bias correction of daily precipitation simulated by a regional climate model: a comparison of methods. Int. J. Climatol. 33 (6), 1367–1381.

Lane, R.A., Kay, A.L., 2021. Climate change impact on the magnitude and timing of hydrological extremes across Great Britain. Front. Water 3, 684982. https://doi.org/10.3389/frwa.2021.684982.

Lowe, J.A., Bernie, D., Bett, P., et al., 2018. UKCP18 Science Overview Report. Met Office Hadley Centre, Exeter, UK.

Marx, A., Kumar, R., Thober, S., Rakovec, O., Wanders, N., Zink, M., Wood, E.F., Pan, M., Sheffield, J., Samaniego, L., 2018. Climate change alters low flows in Europe under global warming of 1.5, 2, and 3°C. Hydrol. Earth Syst. Sci. 22, 1017–1032.

Met Office Hadley Centre, 2018. UKCP18 Regional Projections on a 12km grid over the UK for 1980–2080. CEDA, September 2019. catalogue.ceda.ac.uk/uuid/589211abeb844070a95d061c8cc7f604.

Met Office, Hollis D., McCarthy M. et al., 2019. HadUK-Grid Gridded Climate Observations on a 1km grid over the UK, v1.0.0.0 (1862–2017). Centre for Environmental Data Analysis, 14 November 2019. doi:10.5285/2a62652a4fe6412693123dd6328f6dc8.

Morris D.G., Flavin R.W., 1990. A digital terrain model for hydrology. In: Proceedings of the 4th International Symposium on Spatial Data Handling, Zurich, Switzerland, 23–27 July 1990, 250–262.

Murphy, C., Harrigan, S., Hall, J., Wilby, R.L., 2013. Climate-driven trends in mean and high flows from a network of reference stations in Ireland. Hydrol. Sci. J. 58 (4), 755–772.

Murphy, J.M., Harris, G.R., Sexton, D.M.H., et al., 2018. UKCP18 Land Projections: Science Report. Met Office Hadley Centre, Exeter, UK.

Murphy J.M., Sexton D.M.H., Jenkins G.J. et al. (2009). UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter, UK.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I – a discussion of principles. J. Hydrol. 10, 282–290.

NRFA, 2021. https://nrfa.ceh.ac.uk/data/search. (Accessed Januray 2021).

Price D., Hudson K., Boyce G. et al. (2012). Operational use of a grid-based model for flood forecasting. Proceedings of the Institution of Civil Engineers: Water Management, 165, 65–77.

Prudhomme, C., Young, A., Watts, G., Haxton, T., Crooks, S., Williamson, J., Davies, H., Dadson, S., Allen, S., 2012. The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. Hydrol. Process. 26 (7), 1115–1118.

Reynard, N.S., Kay, A.L., Anderson, M., Donovan, B., Duckworth, C., 2017. The evolution of climate change guidance for flood risk management. Prog. Phys. Geog. 41 (2), 222–237.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP-8.5: exploring the consequence of high emission trajectories. Clim. Change 109, 33–57.

Robson, A.J., Reed, D.W., 1999. Statistical procedures for flood frequency estimation. Flood Estimation Handbook. Institute of Hydrology, Wallingford, UK.

Roudier, P., Andersson, J.C.M., Donnelly, C., Feyen, L., Greuell, W., Ludwig, F., 2016. Projections of future floods and hydrological droughts in Europe under a +2C global warming. Clim. Change 135, 341–355.

Rowland, C.S., Morton, R.D., Carrasco, L. et al., 2017. Land Cover Map 2015 (25m raster, N. Ireland). NERC EIDC, doi:10.5285/47f053a0-e34f-4534-a843–76f0a0998a2f.

Rudd, A.C., Bell, V.A., Kay, A.L., 2017. National-scale analysis of simulated hydrological droughts (1891-2015). J. Hydrol. 550, 368–385.

Rudd, A.C., Kay, A.L., 2016. Use of very high resolution climate model data for hydrological modelling: estimation of potential evaporation. Hydrol. Res. 47, 660–670.

Rudd, A.C., Kay, A.L., Wells, S.C., Aldridge, T., Cole, S.J., Kendon, E.J., Stewart, E.J., 2020. Investigating potential future changes in surface water flooding hazard and impact. Hydrol. Process 34, 139–149.

Sanderson, M.G., Wiltshire, A.J., Betts, R.A., 2012. Projected changes in water availability in the United Kingdom. Water Resour. Res. 48, W08512.

Smith, A., Freer, J., Bates, P., Sampson, C., 2014. Comparing ensemble projections of flooding against flood estimation by continuous simulation. J. Hydrol. 511, 205–219.

Steele-Dunne, S., Lynch, P., McGrath, R., Semmler, T., Wang, S., Hanafin, J., Nolan, P., 2008. The impacts of climate change on hydrology in Ireland. J. Hydrol. 356, 28–45.

Tanguy M., Dixon H. et al. (2016). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890–2015) [CEH-GEAR]. NERC EIDC. https://doi.org/10.5285/33604ea0-c238-4488-813d-0ad9ab7c51ca.

Thober, S., Kumar, R., Wanders, N., Marx, A., Pan, M., Rakovec, O., Samaniego, L., Sheffield, J., Wood, E.F., Zink, M., 2018. Multi-model ensemble projections of European river floods and high flows at 1.5, 2, and 3 degrees global warming. Environ. Res. Lett. 13, 014003.

Vetter, T., Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F., Huang, S., Koch, H., Pechlivanidis, I.G., Plötner, S., Seidou, O., Su, B., Vervoort, R.W., Krysanova, V., 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. Clim. Change 141, 419–433.

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

Wasko, C., Westra, S., Nathan, R., Orr, H.G., Villarini, G., Villalobos Herrera, R., Fowler, H.J., 2021. Incorporating climate change in flood estimation guidance. Phil. Trans. R. Soc. A 379, 20190548.

Zaidman, M.D., Keller, V., Young, A.R., 2002. Low flow frequency analysis: guidelines for best practice. R&D Technical Report W6–064/TR1. Bristol, Environment Agency.