The UKSCAPE-G2G river flow and soil moisture datasets: Grid-to-Grid model estimates for the UK for historical and potential future climates

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Abstract

Appropriate adaptation planning is contingent upon information about the potential future impacts of climate change, and hydrological impact assessments are of particular importance. The UKSCAPE-G2G datasets were produced, as part of the NERC UK-SCAPE programme, to contribute to this information requirement. They use the Grid-to-Grid (G2G) national-scale hydrological model configured for both Great Britain and Northern Ireland (and the parts of the Republic of Ireland that drain to rivers in NI). Six separate datasets are provided, for two sets of driving data — one observation-based (1980–2011) and one climate projection-based (1980–2080) — for both river flows and soil moisture on 1 km x 1 km grids across GB and NI. The river flow datasets include grids of monthly mean flow, annual maxima of daily mean flow, and annual minima of 7-day mean flow (m^3s^{-1}). The soil moisture datasets are grids of monthly mean soil moisture content (m water / m soil), which should be interpreted as depth-integrated values for the whole soil column. The climate projection-based datasets are produced using data from the 12-member 12km regional climate model ensemble of the latest UK climate projections (UKCP18), which uses RCP8.5 emissions. The production of the datasets is described, along with details of the file format, and how the data should be used. Example maps are provided, as well as simple UK-wide analyses of the various outputs. These suggest potential future decreases in summer flows, annual minimum 7-day flows, and summer/autumn soil moisture, along with possible future increases in winter flows and annual maximum flows. References are given for published papers providing more detailed spatial analyses, and some further potential uses of the data are suggested.

Keywords

Climate change; hydrological impacts; rainfall-runoff; UK Climate Projections 2018; UKCP18

1 Introduction

Information on the potential future impacts of climate change is crucial to enable appropriate adaptation planning, and impacts on the hydrological cycle and river flows are one of the main ways by which climate change will affect both society and the natural environment. UK-SCAPE (UK Status, Change And Projections of the Environment; ukscape.ceh.ac.uk) is a five-year programme funded by the Natural Environment Research Council (NERC) as part of a National Capability Science Single Centre award, and the main aim of Work Package 2.2 of UK-SCAPE is to deliver data and analyses showing how future climate change could influence water quantity. The hydrological datasets presented here were produced as part of UK-SCAPE WP2.2.

The datasets consist of 1 km x 1 km gridded outputs from a national-scale hydrological model (Grid-to-Grid), and include both river flows and soil moisture, for Great Britain (GB) and Northern Ireland (NI). The model has been driven with observation-based data, and with an ensemble of Regional Climate Model (RCM) data from the latest climate projections for the UK (UKCP18; Lowe et al. 2018). A summary of the six available datasets, including references, is provided in Table 1. The datasets have been used within UK-SCAPE WP2.2 to support analyses of potential future changes in river flows and soil moisture (Kay 2021, Lane & Kay 2021, Kay et al. 2021a, Kay et al. 2022a), but could also be used to support other hydrological research and wider studies such as ecological and agricultural modelling.

Section 2 describes how the datasets were produced, including the hydrological model and the driving data applied. Section 3 presents some high-level analyses of the datasets, and describes the results of more detailed analyses presented in other published papers. Section 4 discusses potential uses and caveats, with conclusions in Section 5.

Table 1 Summary of the six UKSCAPE-G2G datasets.

Observation-driven	
River flow	GB: https://doi.org/10.5285/2f835517-253e-4697-b774-ab6ff2c0d3da (Kay et al. 2021c) NI: https://doi.org/10.5285/f5fc1041-e284-4763-b8b7-8643c319b2d0 (Kay et al. 2021d)
Soil moisture	GB and NI: https://doi.org/10.5285/c9a85f7c-45e2-4201-af82-4c833b3f2c5f (Kay et al. 2021e)
Climate projection-driven	
River flow	GB: https://doi.org/10.5285/18be3704-0a6d-4917-aa2e-bf38927321c5 (Kay et al. 2022b) NI: https://doi.org/10.5285/76057b0a-b18f-496f-891c-d5b22bd0b291 (Kay et al. 2022c)
Soil moisture	GB and NI: https://doi.org/10.5285/f7142ced-f6ff-486b-af33-44fb8f763cde (Kay et al. 2022d)

2 Data production methods

2.1 The hydrological model

The Grid-to-Grid (G2G) is a national-scale grid-based hydrological model which typically operates on a 1km x 1km grid at a 15-minute time-step (Bell et al. 2009), with an optional snow module (Bell et al. 2016). It was originally configured to cover Great Britain (GB), on a spatial domain aligned with the GB national grid, but more recently a version was configured to cover Northern Ireland (NI) and areas in the Republic of Ireland (RoI) that drain into NI, also on a domain aligned with the GB national grid (Kay et al. 2021a). The G2G is configured using spatial datasets (e.g. soil types, land-cover, flow directions), in preference to parameter identification via calibration; where model parameters are required (such as the wave speeds used in lateral routing) nationally-applicable values are applied (Bell et al. 2009).

G2G has been shown to perform well for a wide range of catchments across GB and NI, including for the modelling of high flows / floods and low flows / droughts (Bell et al. 2009, 2016; Rudd et al. 2017; Formetta et al. 2018; Kay et al. 2021a,b). This is particularly the case for catchments with more natural flow regimes, as the model does not routinely account for artificial influences like abstractions/discharges (Rameshwaran et al. 2022). While the effect of urban/suburban land-cover on runoff is accounted for, the effect of lake/reservoir storage and regulation is generally neglected at the national scale; lake grid-cells are treated as though they were rivers. This has a minimal effect across most of GB; the largest lake in Scotland, Loch Lomond, has an area of ~71km^2, and the largest lake in England, Windermere, has an area of ~15km^2. But in NI the dominant presence of Lough Neagh (~390km^2) limits model performance downstream (the Lower Bann river; Kay et al. 2021a), and Lough Erne in the south-west of NI is also relatively large (Upper and Lower Lough Erne have a combined area of ~144km^2).

2.2 Observation-based driving data

Gridded time-series of precipitation and potential evaporation (PE) are required to drive the G2G, plus temperature for the snow module. The observation-based driving data are applied as follows:

- Daily 1km grids of precipitation (CEH-GEAR; Tanguy et al. 2016) are divided equally over each model time-step within a day. For use in NI they are first re-projected from the Irish national grid to the GB national grid.
- Monthly 40km grids of PE for short grass (MORECS; Hough and Jones 1997) are copied down to the 1km grid, then divided equally over each model time-step within a month. For use in NI they are first re-projected from the Irish national grid to the GB national grid. The data do not cover all the required parts of the UK, so have been extended where necessary (i.e. some coastal areas and some parts of the RoI that drain into NI) by copying from the nearest cell with data.
- Daily 1km grids of min and max temperature (HadUK-Grid; Met Office 2019) are interpolated through the day using a sine curve (Kay and Crooks 2014). The data do not cover the required parts of the RoI, so have been infilled from the nearest cell with data, using a lapse rate with elevation data (Morris and Flavin 1990).

2.3 Climate projection-based driving data

The climate change simulations use data from the UKCP18 Regional projections (Met Office Hadley Centre 2018). These comprise a 12-member perturbed parameter ensemble (PPE) of the Hadley Centre ~12km Regional Climate Model (RCM) nested in an equivalent PPE of their ~60km Global Climate model (GCM) (Murphy et al. 2018). Ensemble member 01 represents the standard parameterisation, with members 02-15 representing a range of credible variations in parameters (note that there are no RCM equivalents for GCM PPE members 02, 03 and 14). The data cover Dec 1980–Nov 2080 under just one emissions scenario, RCP8.5 (Riahi et al. 2011), and have a 360-day year (twelve 30-day months). The data are available re-projected from the native climate model grid onto a 12km grid aligned with the GB national grid – the latter are used here.

The climate projection data are applied as follows:

- Daily 12km grids of precipitation are directly available from the UKCP18 Regional projections. These are first adjusted for bias using 12km grids of monthly correction factors derived by comparing baseline values against CEH-GEAR data averaged up to the 12km resolution (Kay 2021, Kay et al. 2021a). They are then spatially downscaled to 1km using patterns of average annual rainfall (1961–1990; Bell et al. 2007), and divided equally over each model time-step within a day (as for observed data).
- Daily 12km grids of PE are not directly available from the UKCP18 Regional projections. Instead, they are calculated from other meteorological variables in a way which closely replicates MORECS (as in Robinson et al. (2021, 2022), but using the bias-adjusted precipitation in the interception component). PE is only estimated for 12km 'land' RCM boxes; where PE is required for boxes classed as 'sea' in the RCM, it is copied from the nearest 12km 'land' box. The method also includes increased stomatal resistance under future higher atmospheric CO_2 concentrations (Rudd and Kay 2016, Guillod et al. 2018). The 12km PE are copied down to the 1km grid, then divided equally over each model time-step within a month (as for observed data).
- Daily 12km grids of min and max temperature are directly available from the UKCP18 Regional projections. These are downscaled to 1km using a lapse rate with elevation data, and interpolated through the day using a sine curve (as for observed data).

2.4 Hydrological model runs and outputs

The observation-based simulation (hereafter 'SIMOBS') is initialised using a states file saved at the end of a prior observation-based run (Jan 1970–Nov 1980). The same state initialisation file is used for each RCM-based simulation (hereafter 'SIMRCM').

Model outputs consist of 1km x 1km gridded time-series of

- monthly mean river flow (m^3s^{-1});
- annual maxima (AMAX) of daily mean river flow (m^3s^{-1}), for water years (October–September);
- annual minima (AMIN) of 7-day mean river flow (m^3s^{-1}), for years spanning December–November; and
- monthly mean soil moisture content (m water / m soil).

While it is possible to output 1km x 1km gridded daily time-series from G2G, these are not typically produced as they are very large files (especially if long time periods are covered, as is the case for the SIMRCM runs). Instead, the AMAX and AMIN flows are calculated and saved during the model run, to enable analyses of high and low flows without saving daily gridded flows. The AMAX of daily mean flows are extracted for water years (Oct–Sep), to try to avoid extraction of the same high flow event from consecutive years. AMIN extraction would usually use calendar years, but Dec-Nov is used here to match the climate model data running from December 1980 to November 2080, whilst still trying to avoid extraction of the same low flow event from consecutive years.

The flow variables are provided for all non-sea and non-tidal 1km cells with a catchment drainage area of at least $50km^2$, while the soil moisture is provided for all non-sea 1km cells. G2G soil moisture estimates are provided as monthly averages of daily mean soil moisture in the unsaturated zone, which can be interpreted as volumetric soil moisture content, θ, where $0 \leq \theta \leq 1$. In G2G soil depth can vary from a few centimetres to several metres, and soil moisture estimates should be interpreted as depth-integrated values for the whole soil column.

2.5 Format of the gridded datasets

The 1km x 1km gridded data are provided as a NetCDF4 file for each variable, following UKCEH gridded dataset conventions. The file naming convention is described in Table 2 for the observation-based datasets and Table 3 for the climate projection-based datasets.

Table 2 The file naming convention for the observation-based datasets.

Data	Names of NetCDF files	Years available
monthly mean river flow	G2G_GB_mmflow_obs_1980_2011.nc G2G_NI_mmflow_obs_1980_2011.nc	Dec 1980–Nov 2011
annual maxima of daily mean river flow	G2G_GB_amaxflow_obs_1980_2011.nc G2G_NI_amaxflow_obs_1980_2011.nc	Oct 1981–Sep 2011
annual minima of 7-day mean river flow	G2G_GB_aminflow_obs_1980_2011.nc G2G_NI_aminflow_obs_1980_2011.nc	Dec 1980–Nov 2011
monthly mean soil moisture content	G2G_GB_mmsoil_obs_1980_2011.nc G2G_NI_mmsoil_obs_1980_2011.nc	Dec 1980–Nov 2011

Table 3 The file naming convention for the climate projection-based datasets.

Data	Names of NetCDF files	Years available
monthly mean river flow	G2G_GB_mmflow_UKCP18RCM_ensnum_1980_2080.nc G2G_NI_mmflow_UKCP18RCM_ensnum_1980_2080.nc	Dec 1980–Nov 2080
annual maxima of daily mean river flow, and dates of occurrence	G2G_GB_amaxflow_UKCP18RCM_ensnum_1980_2080.nc G2G_NI_amaxflow_UKCP18RCM_ensnum_1980_2080.nc	Oct 1981–Sep 2080
annual minima of 7-day mean river flow, and dates of occurrence	G2G_GB_aminflow_UKCP18RCM_ensnum_1980_2080.nc G2G_NI_aminflow_UKCP18RCM_ensnum_1980_2080.nc	Dec 1980–Nov 2080
monthly mean soil moisture content	G2G_GB_mmsoil_UKCP18RCM_ensnum_1980_2080.nc G2G_NI_mmsoil_UKCP18RCM_ensnum_1980_2080.nc	Dec 1980–Nov 2080

ensnum is the number of the ensemble member (01, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 15)

For the observation-based datasets, the time stamp in the NetCDF files is “days since 1900-01-01”, and the monthly mean river flows and monthly mean soil moisture are nominally assigned to the first day of the month. The annual maximum/minimum flow values are nominally assigned to the start year of the 12-month period over which they are calculated, e.g. the annual maximum flow assigned to 1981 is for 1/10/1981–30/9/1982 (water years), while the annual minimum flow assigned to 1981 is for 1/12/1981–30/11/1982 (Dec–Nov years). The ‘time_bnds’ variable gives the start and end dates of the time period over which the annual maximum or minimum flow are extracted.

For the climate projection-based datasets, the data have 30-day months due to the “360_day” calendar of the Hadley Centre climate model. The files are otherwise as above, except that the dates of occurrence of the annual maximum and minimum flows are also provided, as additional variables in the ‘amaxflow’ and ‘aminflow’ NetCDF files respectively.

Table 4 summarises the spatial domains covered by the GB and NI datasets. River flows are only provided for non-sea and non-tidal river cells with a catchment area of at least 50km^2, and set to missing elsewhere. Soil moisture estimates are provided for all non-sea cells, and set to missing elsewhere.

Table 4 Summary of domain sizes and extents, including the OSGB co-ordinates for the lower left and upper right corners (m).

	GB	NI
Domain size	700 km × 1000 km	187 km × 170 km
Lower left corner	(0,0)	(-7000,440000)
Upper right corner	(700000,1000000)	(180000,610000)

To aid use of the datasets, further data files are provided for both GB and NI, including catchment area grids, grids identifying majority lake cells, and grids identifying the approximate locations of river flow gauging stations (Table 5). The catchment area grids are mapped in Figure 1, while the majority lake cells and gauging station locations are mapped in Figure 2 (note that although GB and NI are mapped together, the data for GB and NI are provided separately). At the gauging station locations the G2G flow estimates can be compared to observed river flows.

Table 5 The additional data files for GB and NI.

Data	File names	Description
Catchment area grid	UKSCAPE_G2G_GB_CatchmentAreaGrid.nc UKSCAPE_G2G_NI_CatchmentAreaGrid.nc	Digitally-derived catchment area (km^2) draining to every 1km x 1km grid box.
Majority lake cells grid	UKSCAPE_G2G_GB_SoilMoisture_LakeGrid.nc UKSCAPE_G2G_NI_SoilMoisture_LakeGrid.nc	Cells with greater than 85% of area covered by water (according to 25m data from Land Cover Map 2015, Rowland et al. 2017). These grids can be applied to exclude use of soil moisture data in majority lake cells. 1=land, 2=lake, and -9999=sea.
	UKSCAPE_G2G_NI_LakeGrid.nc	As above but cells with greater than 70% of area covered by water, plus some manual additions of cells for Lough Erne to avoid more than one change from river to lake to river for each flow pathway. This grid can be applied to exclude use of river flow data in lake cells in NI.
Gauging station location grid	UKSCAPE_G2G_GB_NRFAStationIDGrid.nc UKSCAPE_G2G_NI_NRFAStationIDGrid.nc	Best locations corresponding to 1038 gauging stations in GB and 43 gauging stations in NI, referenced by NRFA station number (nrfa.ceh.ac.uk). NRFA station number at gauging station locations, 0=land, and -9999=sea.
Gauging station info	UKSCAPE_GB_NRFAStationIDs.csv UKSCAPE_NI_NRFAStationIDs.csv	Information on stations included in location grids. Information for 18 additional stations is included in the GB file; these are each located in the same 1km cell as one of the stations in the grid (as detailed in the comments column of the csv file).

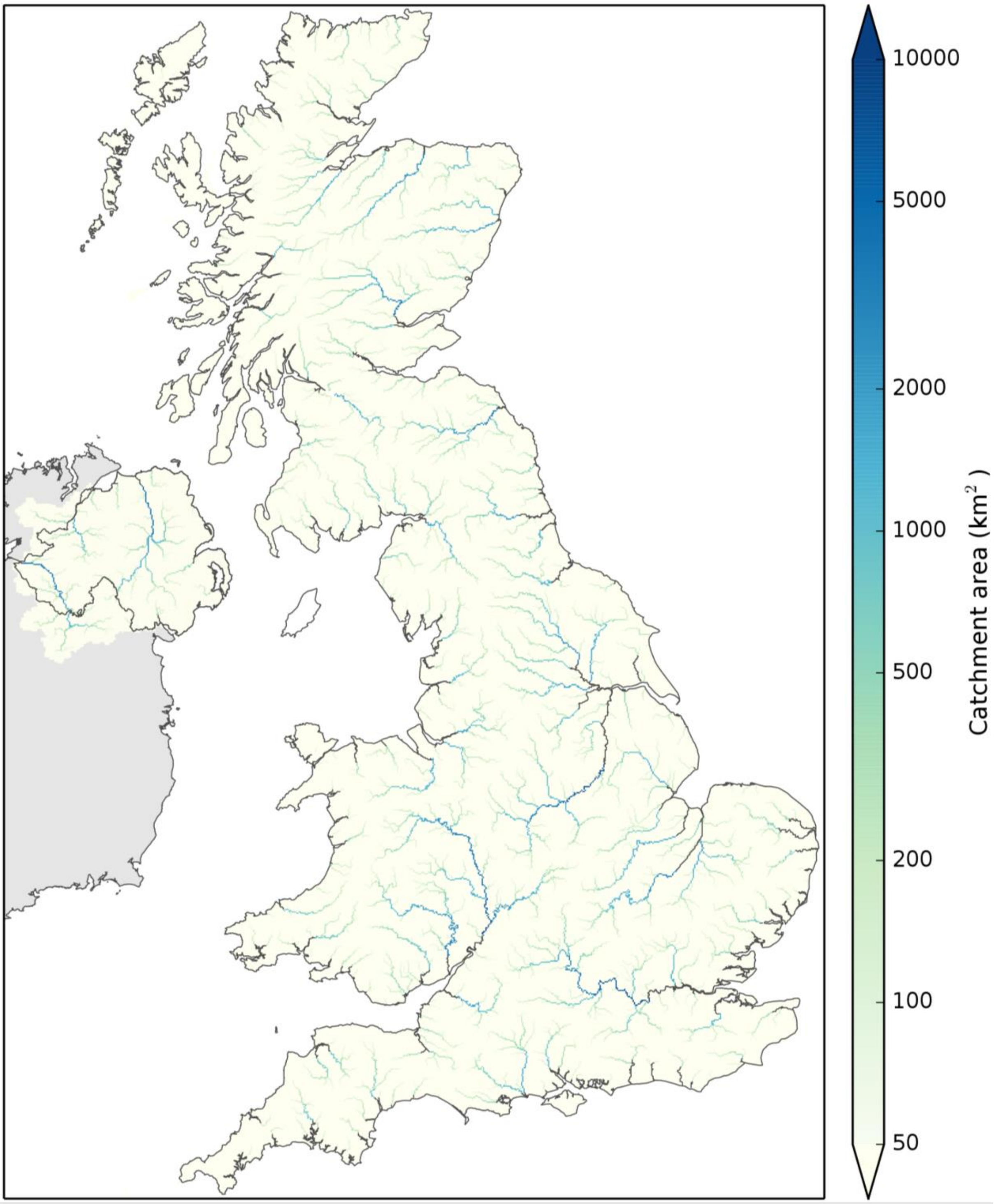

Figure 1 Map showing the catchment area grids for GB and NI (see Table 5).

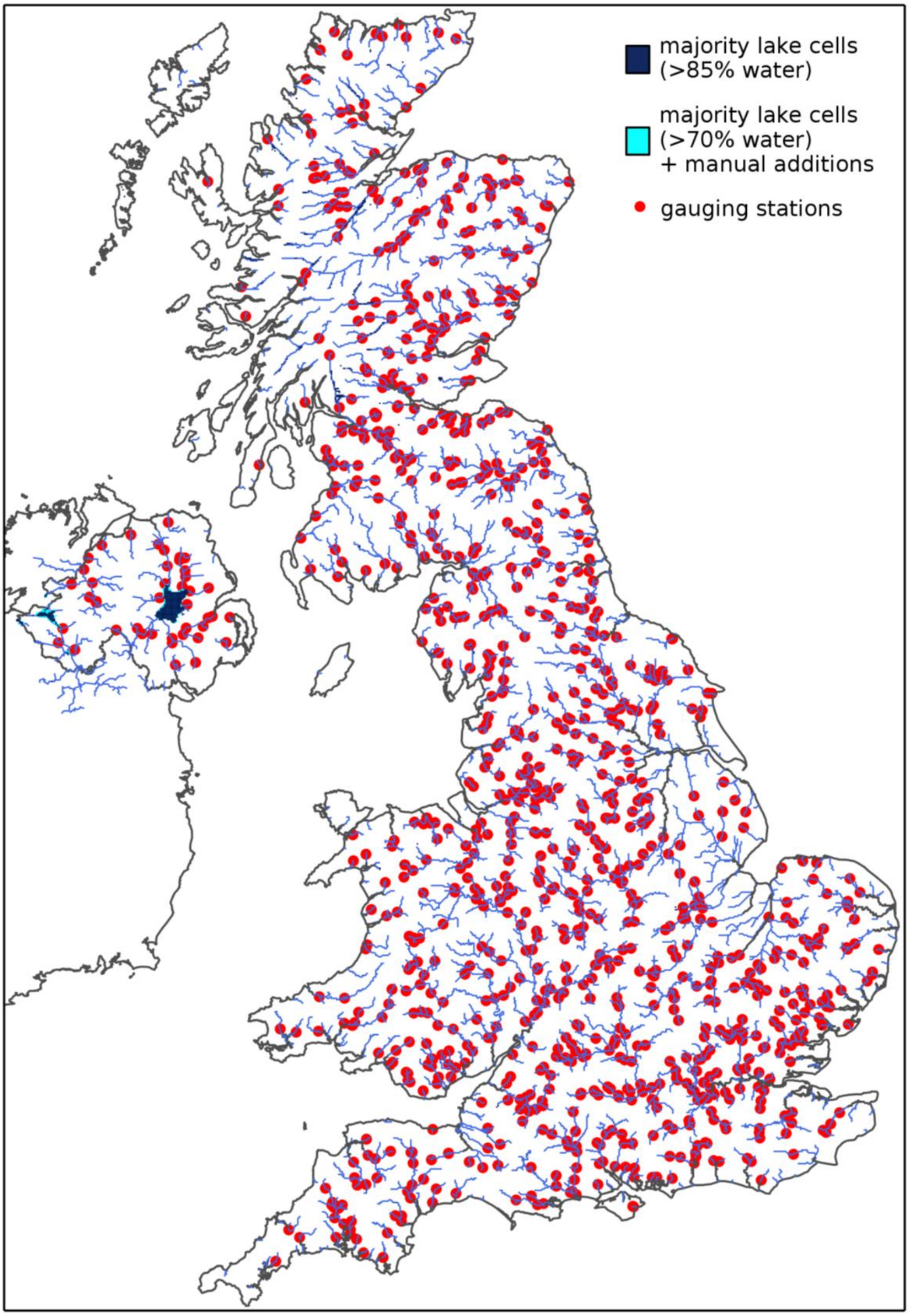

Figure 2 Map showing the majority lake cells and gauging station locations for GB and NI (see Table 5), along with the main rivers (catchment area ≥ 50km^2; blue lines). Note that the ‘majority lake cells (>70% water)’ cover small areas around Lough Neagh and Lough Erne in Northern Ireland only.

2.6 How to use the datasets

River flows from the observation-based simulation can be compared to observed (gauged) river flows (for example from the National River Flow Archive, NRFA; nrfa.ceh.ac.uk), and to facilitate such comparisons files identifying gauging station locations on the 1km G2G model grid for GB and NI are provided (see Table 5). However, it should be borne in mind that G2G provides natural flow estimates, so comparisons in catchments affected by artificial influences like abstractions and discharges may not be as good as those in catchments with relatively natural flow regimes (Rameshwaran et al. 2022). Also, although the gauging station locations have been identified as the G2G cell closest in terms of geographical location and catchment area, and checks have been undertaken to ensure that the G2G flows are for the correct river rather than a nearby river with a similar catchment area, in some cases the derived catchment area draining to the 1km x 1km cell will be different to the “observed” NRFA catchment area. This problem can particularly affect smaller catchments, for which discretisation to a 1km x 1km grid can lead to proportionally larger errors, although flow data provided here are in any case limited to catchments with drainage areas of at least $50km^2$. The catchment area grids (Table 5) can be used to check the drainage area of gauged catchments, and could also be used to identify the most appropriate 1km x 1km cell corresponding to any particular ungauged catchment of interest.

Users should be aware that the effect of water bodies such as lakes and reservoirs is not accounted for within the model; any impact of lake storage and regulation on downstream river flows has been neglected, and lake grid-cells are treated as though they were rivers. The data files thus include ‘river flows’ and ‘soil moisture’ for 1km cells located within lakes. Additional files identify majority lake cells in GB and NI, so that these can be excluded from analyses if desired (see Table 5).

The historical portion of the climate projection-based river flow and soil moisture datasets can be compared to the observation-based datasets, or to observed data. However, comparisons in either case should only be made statistically (over multi-decadal periods), not directly (time point by time point), as there will be no equivalence between observed weather features and those in the RCM PPE at the same date. An example of such a comparison is presented in Supp. Fig. 4 of Kay et al. 2021a, where mean monthly flows, flood frequency curves and low flow frequency curves are compared for the baseline SIMRCM ensemble and SIMOBS, for 8 catchments in NI. Comparison of climate projection-based simulations to the observation-based simulation will indicate how both natural variability and (remaining) biases in the climate projection data affect the hydrological model simulations for the baseline period, while comparison to observed data themselves will be additionally affected by the accuracy of the G2G model.

The climate projection-based datasets for baseline (historical) and future periods can be compared statistically, to investigate the potential future impacts of climate change on river flows (e.g. Kay 2021, Lane & Kay 2021, Kay et al.2021a) and soil moisture (e.g. Kay et al. 2022a). Analyses should use the full ensemble; each member should be considered as a different but plausible realisation. Comparison between periods should use the same ensemble member for each period, not a baseline from one member and a future from another member.

The observation-based datasets for GB can be considered updates to MaRIUS-G2G-MORECS-monthly flow and soil moisture data (Bell et al. 2018a). The main differences are the shorter simulation period here (Dec 1980–Nov 2011 vs 1960–2015 or 1891–2015), the inclusion here of the optional snow module, some changes to the land-sea mask, some changes related to infilling of missing soil type data, and minor changes to the discretised river flow network to improve the G2G model catchment areas (thus the additional spatial datasets provided here may differ in places to those provided with the MaRIUS dataset).

The climate projection-based datasets for GB are analogous to the MaRIUS-G2G-WAH2-monthly flow and soil moisture data (Bell et al. 2018b), which were driven by weather@home climate model data (Guillod et al. 2017). The main differences, as well as the factors listed above for the observation-based datasets, are the climate model version, the smaller ensemble size here (12 members vs 100 members), and the provision here of transient rather than time-slice data (Dec 1980–Nov 2080 vs 1900–2006, 2020–2049 and 2070–2099). Note that, as far as the authors are aware, there has been no comparison between the weather@home and UKCP18 RCM climate datasets.

3 Results

3.1 Monthly mean river flows

Maps of example monthly mean river flows across GB and NI from SIMOBS and two SIMRCM ensemble members (Figure 3) illustrate the accumulation of water as it flows downstream, with typically higher flows for downstream locations with larger catchment areas. The example maps also show the generally lower flows in summer (July) compared to winter (January). Note that, although GB and NI are mapped together, the data for GB and NI are provided separately.

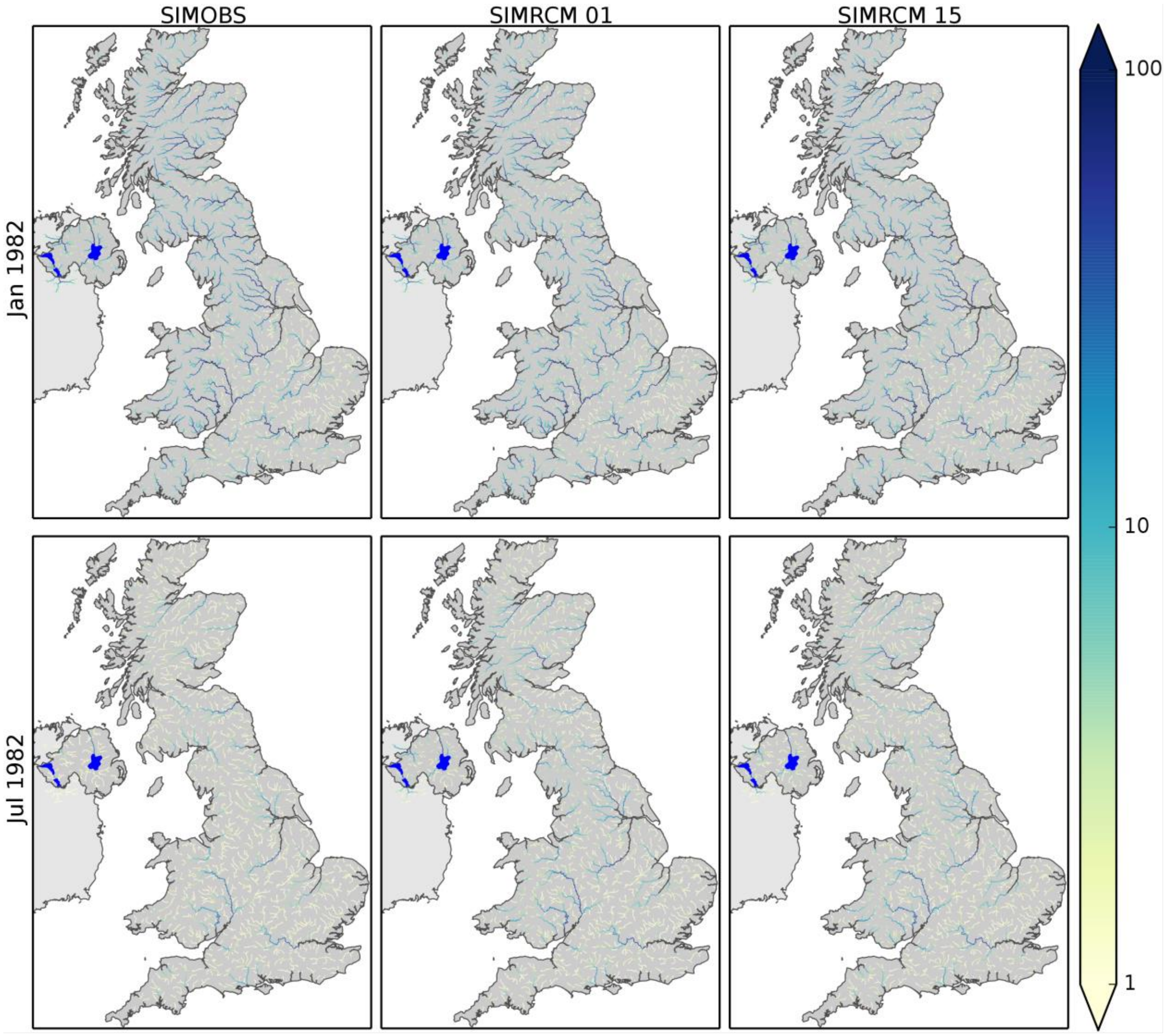

Figure 3 Maps of monthly mean river flows (m^3s^{-1}) for January and July 1982, from SIMOBS (left) and two SIMRCM ensemble members (01 – centre, and 15 – right). Also shown are Lough Neagh and Lough Erne in NI (bright blue shading).

Time-series plots of UK-mean annual mean river flows from SIMOBS and the SIMRCM ensemble show good correspondence (Figure 4). There is a relatively small but highly statistically significant decrease in the SIMRCM ensemble mean flow over Dec 1980–Nov 2080 (-0.695 m^3s^{-1} / 100 years) (Figure 4). Six of the 12 individual ensemble members show decreases significant at the 10% level, while four show non-significant decreases and two show non-significant increases. Plots of the monthly climatology of UK-mean river flows for the first and last 30 years (Dec 1980–Nov 2010 and Dec 2050–Nov 2080) show a clear reduction in flows during summer and early autumn, but a possible increase in winter (Figure 4).

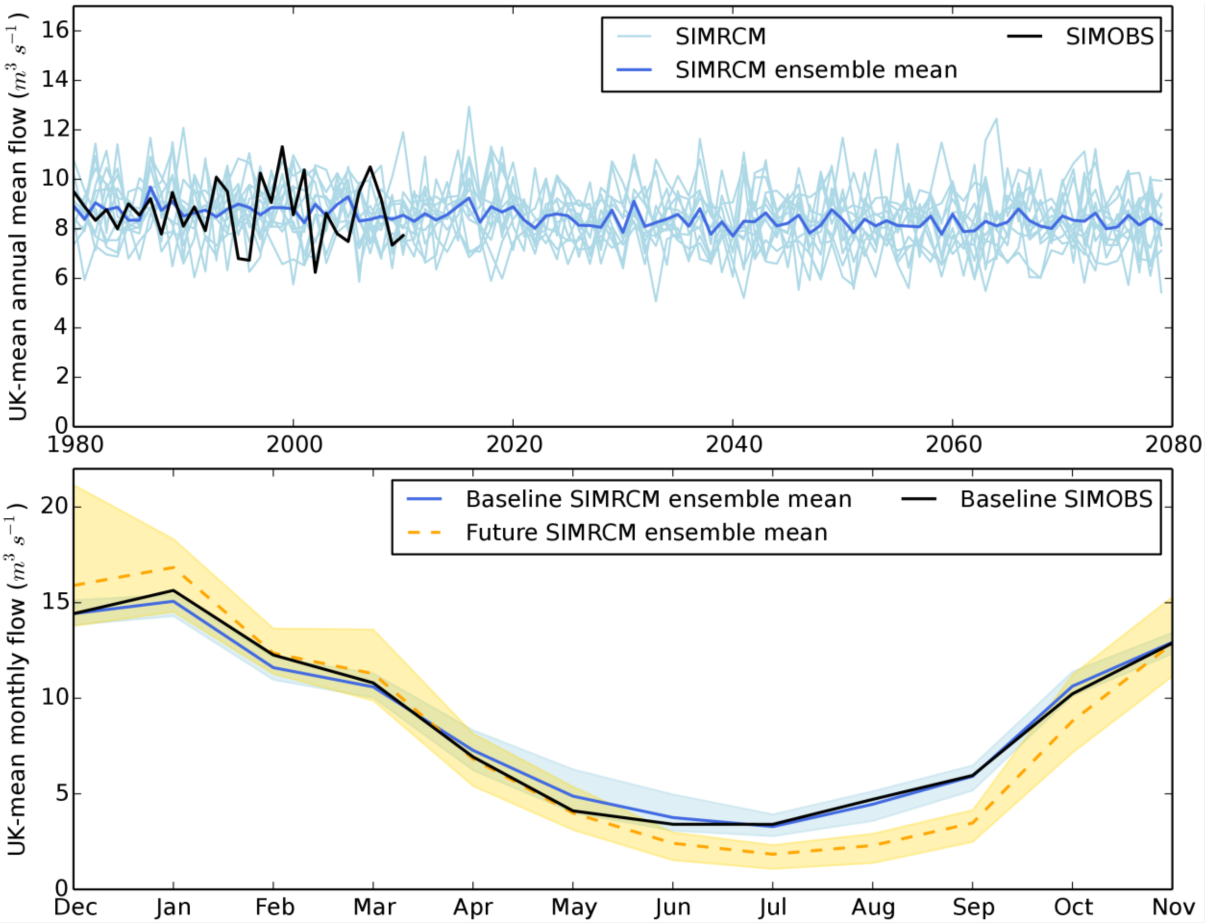

Figure 4 Time-series of UK-mean annual mean river flows (top), and the baseline (Dec 1980–Nov 2010) and future (Dec 2050–Nov 2080) monthly climatology of UK-mean river flows (bottom), for SIMOBS and the SIMRCM ensemble. The shading in the bottom plot shows the SIMRCM ensemble range for each period.

Kay (2021) used the GB SIMRCM monthly mean river flow data to investigate potential future changes in seasonal mean flows, for two future time-slices (2020–2050 and 2050–2080). This suggested large decreases in summer mean flows everywhere, but possible increases in winter mean flows, especially in the north and west. A similar analysis using the NI SIMRCM monthly mean river flow data (Kay et al. 2021a) suggested decreases in spring–autumn mean flows, especially in summer, but possible increases in winter mean flows.

3.2 Extreme river flows

Maps of example GB and NI AMAX of daily mean river flows and AMIN of 7-day mean river flows from SIMOBS and two SIMRCM ensemble members (Figure 5) show less spatial variation than those of monthly mean river flows (when plotted on the same scale). Note that, although GB and NI are mapped together, the data for GB and NI are provided separately.

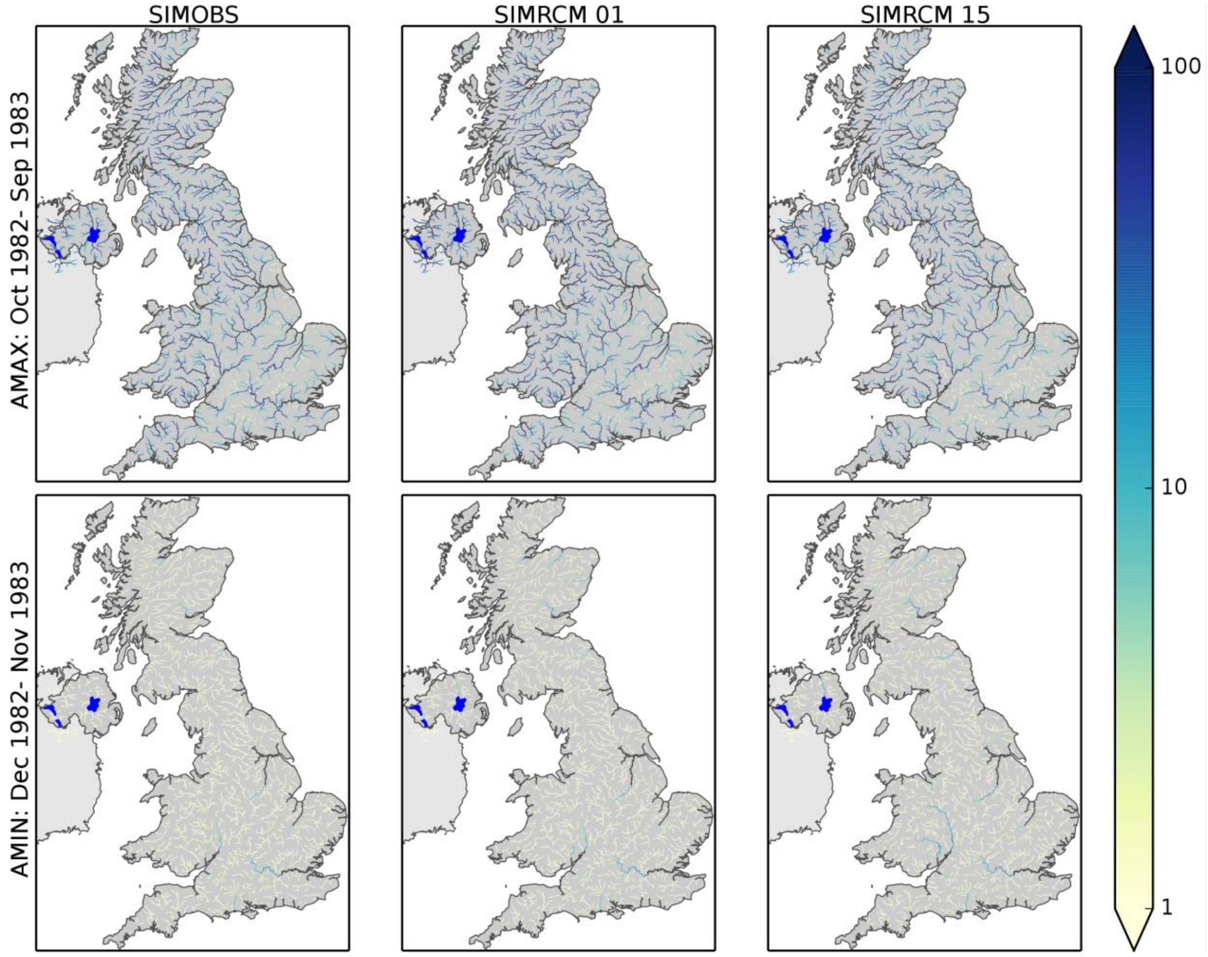

Figure 5 Maps of AMAX of daily mean river flows for Oct 1982–Sep 1983 (m^3s^{-1}; top) and AMIN of 7-day mean river flows for Dec 1982–Nov 1983 (m^3s^{-1}; bottom), from SIMOBS (left) and two SIMRCM ensemble members (01 – centre, and 15 – right). Also shown are Lough Neagh and Lough Erne in NI (bright blue shading).

Time-series plots of UK-mean AMAX and AMIN river flows from SIMOBS and the SIMRCM ensemble show good correspondence (Figure 6). The SIMRCM ensemble mean AMAX flows show a ~~highly~~ statistically significant increase over Oct 1981–Sep 2080 (8.51 m^3s^{-1} / 100 years) (Figure 6). Nine of the 12 individual ensemble members show increases in AMAX flows significant at the 10% level, while one shows non-significant increases and two show non-significant decreases. The SIMRCM ensemble mean AMIN flows show a highly statistically significant decrease over Dec 1980–Nov 2080 (-0.670 m^3s^{-1} / 100 years) (Figure 6), and all 12 individual ensemble members show decreases significant at the 10% level.

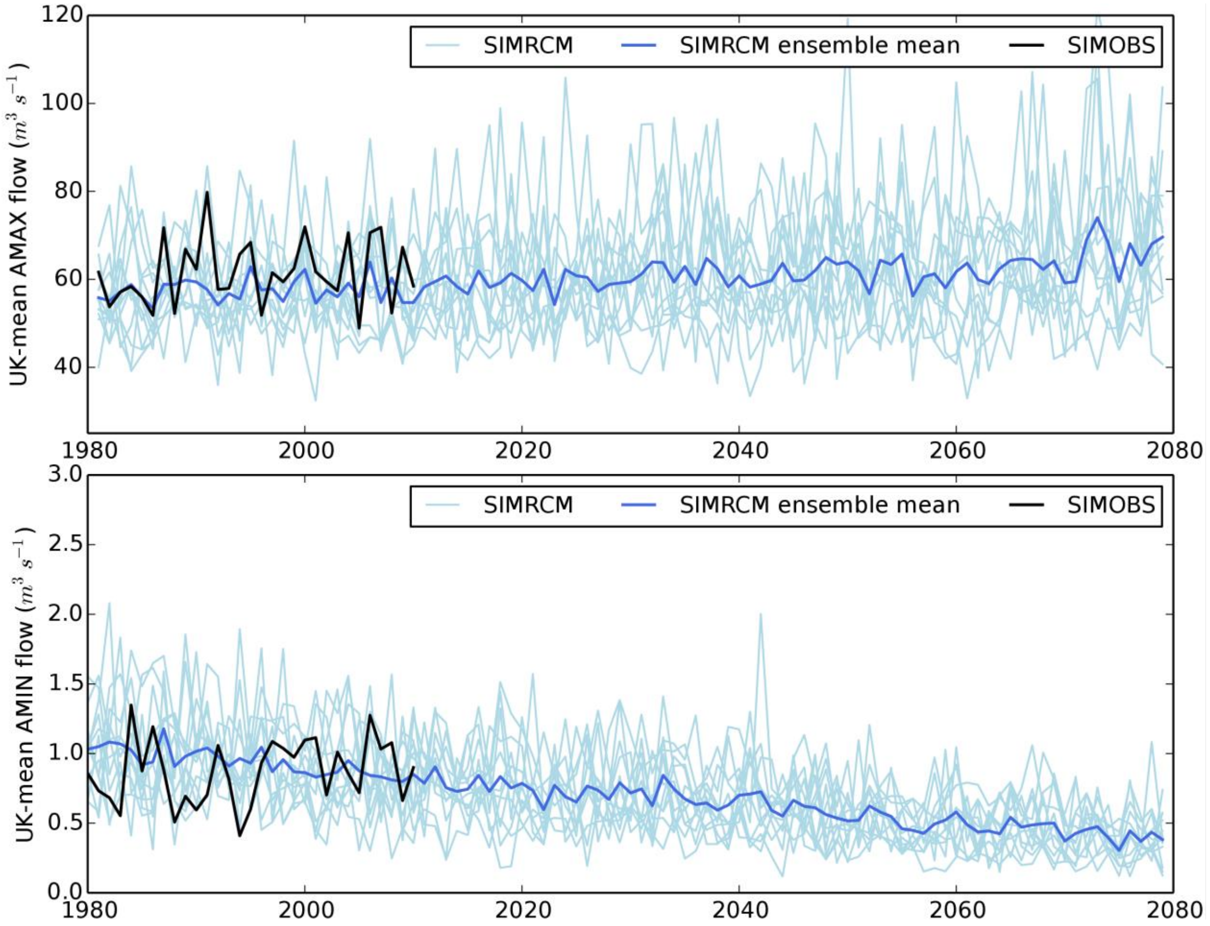

Figure 6 Time-series of UK-mean AMAX of daily mean river flows (top) and AMIN of 7-day mean river flows (bottom), for SIMOBS and the SIMRCM ensemble.

Lane & Kay (2021) used the GB SIMRCM AMAX and AMIN river flow data to investigate potential future changes in high/low flows by 2050–2080. All ensemble members showed large reductions in 10-year return period low flows. The direction of change for 10-year return period high flows was more uncertain, but increases of over 9% were possible in most areas. Simultaneous worsening of both high and low flow extremes was projected in the west. A similar analysis using the NI SIMRCM AMAX and AMIN flow data (Kay et al. 2021a) suggested large reductions in 10-year return period low flows everywhere, and large increases in 10-year return period high flows for some locations and ensemble members. Analyses of the GB and NI dates of occurrence of SIMRCM AMAX and AMIN showed few significant changes in timing (Lane & Kay 2021, Kay et al. 2021a).

3.3 Soil moisture

Maps of example GB and NI monthly mean soil moisture content from SIMOBS and two SIMRCM ensemble members (Figure 7) show the spatial variation, which is generally related to the variation in soil types. The example maps also show the generally drier soils in summer (July) compared to winter (January), and show differences between the two selected SIMRCM ensemble members. Note that, although GB and NI are mapped together, the data for GB and NI are provided separately.

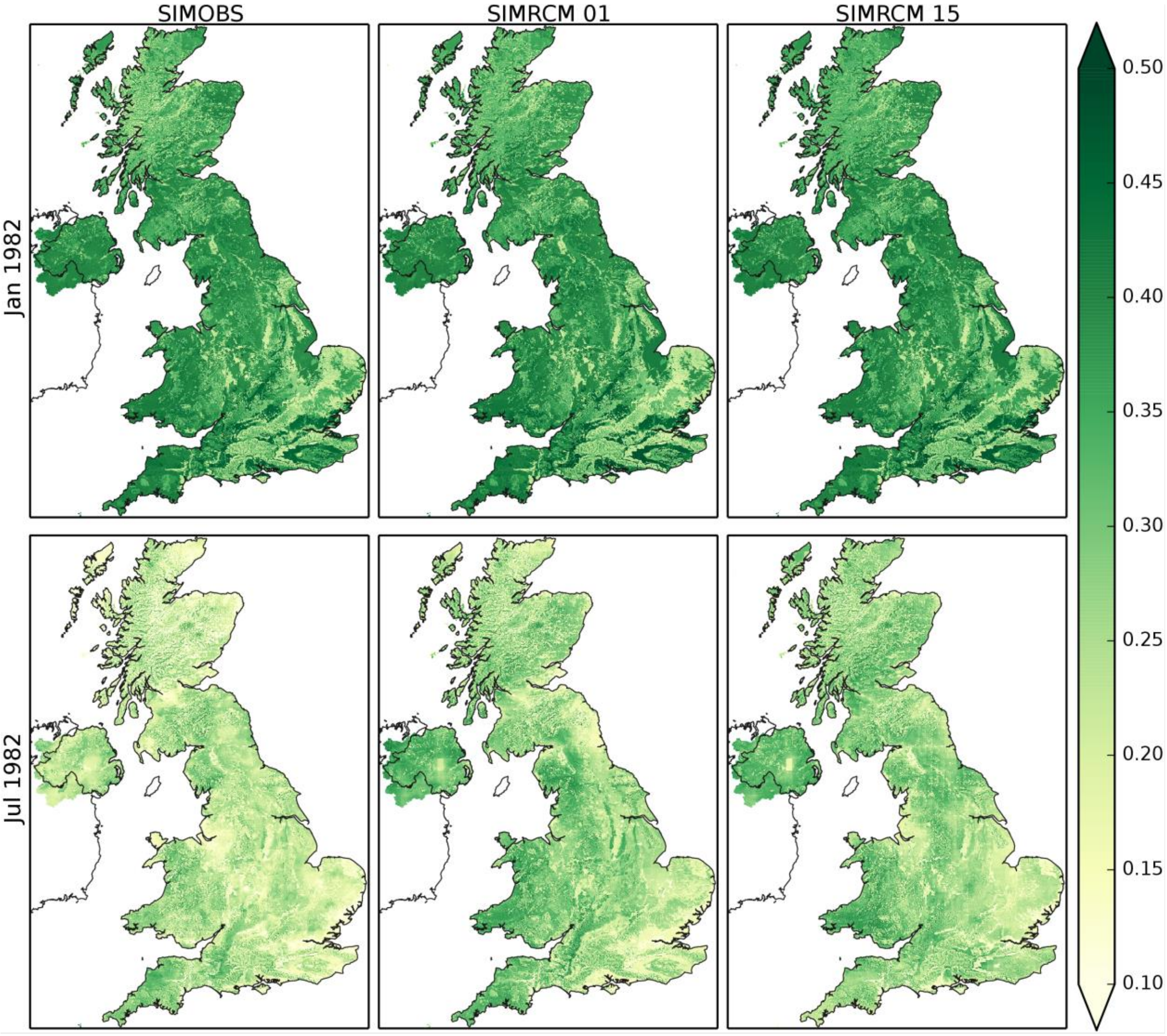

Figure 7 Maps of monthly mean soil moisture content (m water / m soil) for January and July 1982, from SIMOBS (left) and two SIMRCM ensemble members (01 – centre, and 15 – right).

Time-series plots of UK-mean annual mean soil moisture content from SIMOBS and the SIMRCM ensemble show good correspondence (Figure 8). The SIMRCM ensemble mean soil moisture content shows a highly statistically significant decrease over Dec 1980–Nov 2080 (-0.035 / 100 years) (Figure 8), and all 12 individual ensemble members show decreases significant at the 10% level. Plots of the monthly climatology of UK-mean soil moisture content for the first and last 30 years (Dec 1980–Nov 2010 and Dec 2050–Nov 2080) show a clear reduction in summer and autumn (Figure 8).

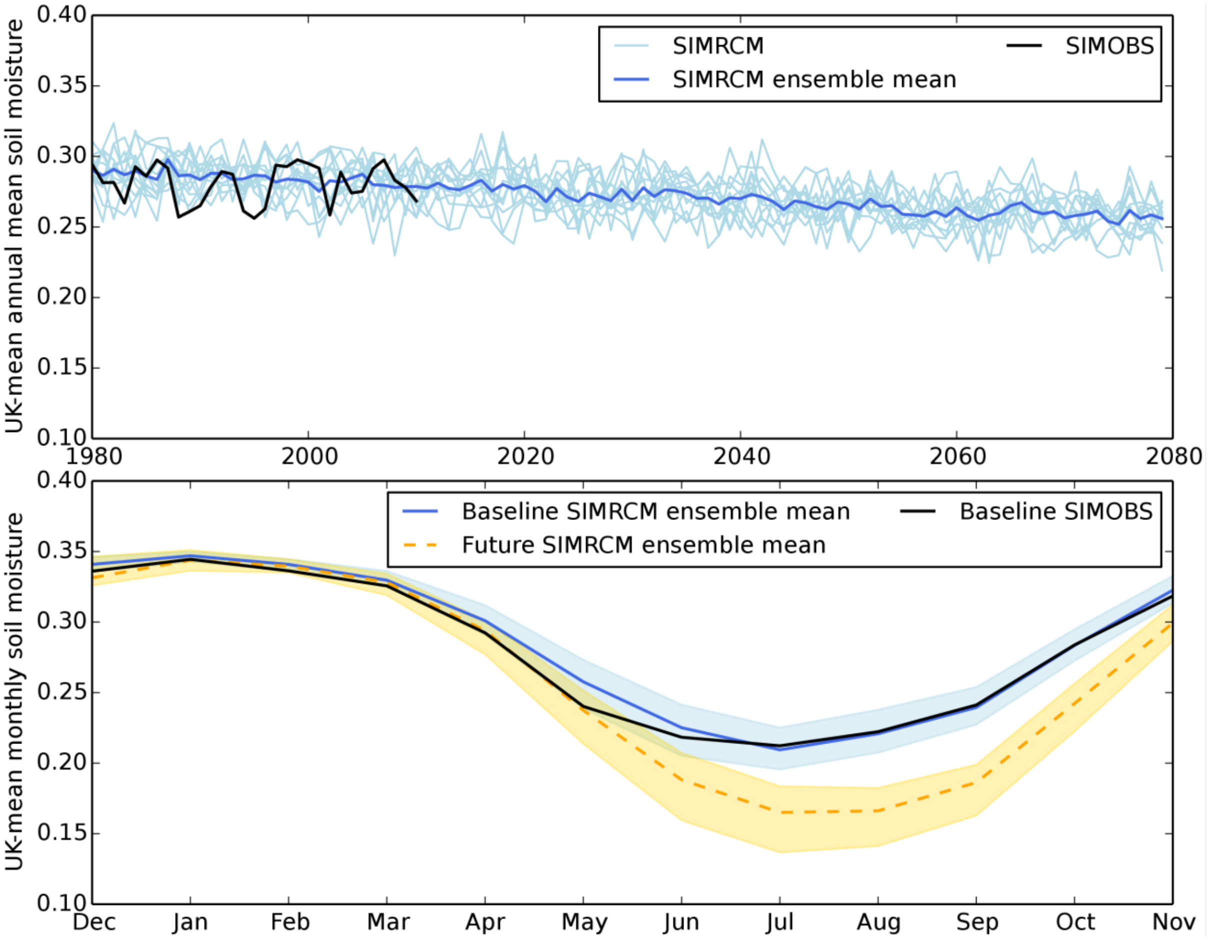

Figure 8 Time-series of UK-mean annual mean soil moisture content (m water / m soil; top), and the baseline (Dec 1980–Nov 2010) and future (Dec 2050–Nov 2080) monthly climatology of UK-mean soil moisture content (m water / m soil; bottom), for SIMOBS and the SIMRCM ensemble. The shading in the bottom plot shows the SIMRCM ensemble range for each period.

Kay et al. (2022a) used the GB and NI SIMRCM monthly mean soil moisture data to investigate potential future changes in occurrence of indicative soil moisture extremes and changes in typical wetting and drying dates of soils by 2050–2080 across the UK. This also suggested large increases in the spatial occurrence of low soil moisture levels, and later soil wetting dates. Changes to soil drying dates were less apparent.

4 Discussion

Ensemble data from the historical period of the climate projection-driven datasets show good correspondence with the observation-driven datasets, for both river flows (Figure 4 and Figure 6) and soil moisture (Figure 8). More detailed performance analyses are provided elsewhere (Kay 2021, Lane & Kay 2021, Kay et al. 2021a, Kay et al. 2022a).

The climate projection-driven river flow and soil moisture datasets suggest potential future decreases in summer flows, annual minimum 7-day flows, and summer/autumn soil moisture, along with possible future increases in winter flows and annual maximum flows. More detailed analyses, presented elsewhere, illustrate the variation in these general trends, both spatially and by ensemble member (Kay 2021, Lane & Kay 2021, Kay et al. 2021a, Kay et al. 2022a). These changes are consistent with the climate projections, which give wetter winters and drier and hotter summers (Murphy et al. Fig. 5.2), and increased summer PE (Robinson et al. 2022).

A study of trends in historical gauged flows from the UK Benchmark Network (Harrigan et al. 2017) shows a tendency for an increase in winter mean flows and high flow indices over the past 50 years, although with significant natural decadal variability (clear so-called flood-rich and flood-poor periods). The datasets here suggest that this overall trend could continue into the future, and they could potentially be used to further investigate natural variability. The analysis of Harrigan et al. (2017) shows less consistent changes in summer mean flows or low flow indices, with catchments in the south/east often showing decreases, but catchments in the north/west typically showing increases. The datasets here suggest that more consistent decreases could be seen everywhere in future.

However, the fact that the UKCP18 Regional climate projections applied here only use one GCM/RCM needs to be borne in mind. Other climate models tend to give smaller decreases (or increases) in summer precipitation than the UKCP18 Regional projections (Murphy et al. 2018 Fig. 5.2), so are likely to give lower reductions in summer flows and soil moisture. Similarly, other climate models give a wider range of changes in winter precipitation than the UKCP18 Regional projections (Murphy et al. 2018 Fig. 5.2), so could give larger or smaller increases in winter flows. The UKCP Local projections, produced by nesting a ~2.2km convection-permitting model in each RCM PPE member (Kendon et al. 2021), also give some differences in climatic changes compared to the RCM (Kendon et al. 2021), and consequently some differences in hydrological impacts (Kay 2022). In addition, the use of a high emissions scenario (RCP8.5) for the UKCP18 Regional projections is likely to lead to more extreme changes than would occur for lower emissions (e.g. Arnell et al. 2014), although RCP8.5 should not be considered implausible (Schwalm et al. 2020).

Further sources of uncertainty in the datasets include the observation-based PE and the calculation of RCM PE. MORECS 40km monthly PE data are used for the observation-based hydrological model runs; lower spatial and temporal resolution than the other driving data (Section 2.2). A dataset of 1km daily PE has since been derived (Brown et al. 2022) using HadUK-Grid data (Met Office 2019), although some the variables required had to be interpolated from monthly to daily. The RCM PE used here includes the effect of stomatal closure under higher CO_2 concentrations but does not include a potential leaf area increase due to carbon fertilisation (Rudd and Kay 2016; Robinson et al.2022).

Potential future changes in land cover are also excluded, as are any artificial influences on river flows. Also, only one hydrological model has been applied; a catchment-based dataset of simulated river flows from the ‘Enhanced future Flows and Groundwater’ (eFlaG) project (Hannaford et al. 2022b) uses similar driving data from the UKCP18 Regional projections for three hydrological models (including G2G), so could be used to look at potential uncertainty from hydrological model structure (Hannaford et al. 2022a). Note that eFlaG used HadUK-Grid rainfall, both for observation-based runs and for bias correction of UKCP18 RCM data, whereas CEH-GEAR rainfall were used here since data are included for the parts of the Republic of Ireland draining into Northern Ireland, enabling gridded flow simulation across Northern Ireland. The ability to provide full and coherent coverage, of gauged and ungauged locations~~,~~ is a particular strength of national-scale grid-based models like G2G, in contrast to catchment-based models.

5 Conclusions

The datasets presented here provide consistent spatial simulations of river flows and soil moisture for the whole of the UK, driven by both observed data and by an ensemble of regional climate model data from the latest UK climate projections, UKCP18. These enable direct studies of historical and potential future river flows and soil moisture, but they can also be used to provide inputs for further studies, for example to simulate water quality (e.g. Hutchins et al. 2016), crop yields (e.g. Cai et al. 2009), irrigated agriculture economic risk (Salmoral et al. 2019), or ecological impacts (e.g. Bussi et al. 2016).

An online (anonymous) stakeholder survey was carried out for UK-SCAPE WP2.2 in late 2021 (Kay et al. 2022e). This asked a set of questions divided into three broad classes; ‘job role and level of experience’, ‘data of interest’, and ‘data format/access preferences’. The responses on ‘data of interest’ showed that there is a lot of interest in water quantity, including both river flows and soil moisture, and a lot of interest in potential future changes in river flows, although slightly less so for changes in soil moisture. Furthermore, the responses on ‘data format/access preferences’ showed that the greatest 1st preference was for grids covering sub-regions or the whole country, although perhaps unsurprising this varied by job role (Academic, Government/Regulator, Practitioner/ Consultant), which likely influences how data are used. A large proportion of respondents were also happy downloading the full dataset as NetCDF files from the EIDC. The datasets described here thus provide for a significant stakeholder demand, although there is always more that could be done. Further developments could include a web-tool allowing interactive data exploration and plotting.

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Data Availability

The six datasets described in this manuscript are available from the Environmental Information Data Centre (EIDC); see Table 1.

References

Arnell NW, Charlton MB, Lowe JA (2014). The effect of climate policy on the impacts of climate change on river flows in the UK. J Hydrol, 510, 424-435.

Bell VA, Kay AL, Davies HN, Jones RG (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 VA, Kay AL et al. (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 VA, Kay AL et al. (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.

Bell VA, Rudd AC, Kay AL, Davies HN (2018a). Grid-to-Grid model estimates of monthly mean flow and soil moisture for Great Britain (1960 to 2015): observed driving data [MaRIUS-G2G-MORECS-monthly]. NERC Environmental Information Data Centre. doi:10.5285/e911196a-b371-47b1-968c-661eb600d83b.

Bell VA, Rudd AC, Kay AL, Davies HN (2018b). Grid-to-Grid model estimates of monthly mean flow and soil moisture for Great Britain: weather@home2 (climate model) driving data [MaRIUS-G2G-WAH2-monthly]. NERC Environmental Information Data Centre. doi:10.5285/3b90962e-6fc8-4251-853e-b9683e37f790.

Brown, M.J., Robinson, E.L., Kay, A.L., Chapman, R., Bell, V.A., Blyth, E.M. (2022). Potential evapotranspiration derived from HadUK-Grid 1km gridded climate observations 1969-2021 (Hydro-PE HadUK-Grid). NERC EDS Environmental Information Data Centre. doi:10.5285/9275ab7e-6e93-42bc-8e72-59c98d409deb.

Bussi G, Whitehead PG, Bowes MJ et al. (2016). Impacts of climate change, land-use change and phosphorus reduction on phytoplankton in the River Thames (UK), Sci Total Environ, 572, 1507-1519.

Cai X, Wang D, Laurent R (2009). Impact of Climate Change on Crop Yield: A Case Study of Rainfed Corn in Central Illinois. J Appl Meteorol Climatol, 4(9), 1868–1881.

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.

Guillod BP, Jones RG, Dadson SJ et al. (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.

Guillod BP, Jones RG, Kay AL et al. (2017). Managing the Risks, Impacts and Uncertainties of drought and water Scarcity (MaRIUS) project: Large set of potential past and future climate time series for the UK from the weather@home2 model. Centre for Environmental Data Analysis. doi:10.5285/0cea8d7aca57427fae92241348ae9b03.

Hannaford J, Mackay JD, Ascot M et al. (2022a). eFLaG: enhanced future FLows and Groundwater. A national dataset of hydrological projections based on UKCP18. Earth Syst Sci Data Discuss, doi:10.5194/essd-2022-40.

Hannaford J, Mackay J, Ascot M, et al. (2022b). Hydrological projections for the UK, based on UK Climate Projections 2018 (UKCP18) data, from the Enhanced Future Flows and Groundwater (eFLaG) project. NERC EDS Environmental Information Data Centre. doi:10.5285/1bb90673-ad37-4679-90b9-0126109639a9.

Harrigan S, Hannaford J et al. (2018). Designation and trend analysis of the updated UK Benchmark Network of river flow stations: the UKBN2 dataset. Hydrology Research, 49, 552–567.

Hough M, Jones RJA (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.

Hutchins MG, Williams RJ, Prudhomme C et al. (2016). Projections of future deterioration in UK river quality are hampered by climatic uncertainty under extreme conditions, Hydrological Sciences Journal, 61:16, 2818-2833.

Kay AL (2021). Simulation of river flow in Britain under climate change: baseline performance and future seasonal changes. Hydrol Process. 35(4), e14137, doi: 10.1002/hyp.14137.

Kay, A.L. (2022). Differences in hydrological impacts using regional climate model and nested convection-permitting model data. Climatic Change, 173(1-2), 11, doi:10.1007/s10584-022-03405-z.

Kay AL, Crooks SM (2014). An investigation of the effect of transient climate change on snowmelt, flood frequency and timing in northern Britain. International Journal of Climatology, 34(12), 3368–3381.

Kay AL, Davies HN, Lane RA, Rudd AC, Bell VA (2021a). Grid-based simulation of river flows in Northern Ireland: model performance and future flow changes. Journal of Hydrology: Regional Studies, 38, 100967.

Kay AL, Griffin A, Rudd AC, Chapman RM, Bell VA, Arnell NW (2021b). Climate change effects on indicators of high and low river flow across Great Britain. Advances in Water Resources, 151, 103909.

Kay AL, Lane RA, Bell VA (2022a). Grid-based simulation of soil moisture in the UK: future changes in extremes and wetting and drying dates. Environmental Research Letters, 17(7), 074029.

Kay AL, Rudd AC, Davies HN, Lane RA, Bell VA (2021c). Grid-to-Grid model estimates of river flow for Great Britain driven by observed data (1980 to 2011). NERC Environmental Information Data Centre. doi:10.5285/2f835517-253e-4697-b774-ab6ff2c0d3da.

Kay AL, Rudd AC, Davies HN, Lane RA, Bell VA (2021d). Grid-to-Grid model estimates of river flow for Northern Ireland driven by observed data (1980 to 2011). NERC Environmental Information Data Centre. doi:10.5285/f5fc1041-e284-4763-b8b7-8643c319b2d0.

Kay AL, Rudd AC, Davies HN, Lane RA, Bell VA (2021e). Grid-to-Grid model estimates of soil moisture for Great Britain and Northern Ireland driven by observed data (1980 to 2011). NERC Environmental Information Data Centre. doi:10.5285/c9a85f7c-45e2-4201-af82-4c833b3f2c5f.

Kay AL, Rudd AC, Davies HN, Lane RA, Bell VA (2022b). Grid-to-Grid model estimates of river flow for Great Britain driven by UK Climate Projections 2018 (UKCP18) Regional (12km) data (1980 to 2080) v2. NERC Environmental Information Data Centre. doi:10.5285/18be3704-0a6d-4917-aa2e-bf38927321c5.

Kay AL, Rudd AC, Davies HN, Lane RA, Bell VA (2022c). Grid-to-Grid model estimates of river flow for Northern Ireland driven by UK Climate Projections 2018 (UKCP18) Regional (12km) data (1980 to 2080) v2. NERC Environmental Information Data Centre. doi:10.5285/76057b0a-b18f-496f-891c-d5b22bd0b291.

Kay AL, Rudd AC, Davies HN, Lane RA, Bell VA (2022d). Grid-to-Grid model estimates of soil moisture for Great Britain and Northern Ireland driven by UK Climate Projections 2018 (UKCP18) Regional (12km) data (1980 to 2080). NERC Environmental Information Data Centre. doi:10.5285/f7142ced-f6ff-486b-af33-44fb8f763cde.

Kay AL, Spencer M, Bell VA (2022e). UK-SCAPE WP2.2: Water Futures. Stakeholder questionnaire results. Wallingford, UK Centre for Ecology & Hydrology, 14pp. nora.nerc.ac.uk/id/eprint/531705/

Kendon E, Short C, Pope J, Chan S, Wilkinson J, Tucker S, Bett P, Harris G (2021). Update to UKCP Local (2.2km) projections. Met Office Hadley Centre, Exeter, UK.

Lane RA, Kay AL (2021). Climate change impact on the magnitude and timing of hydrological extremes across Great Britain. Frontiers in Water, 3:684982, doi:10.3389/frwa.2021.684982.

Lowe JA, Bernie D, Bett P et al. (2018). UKCP18 Science Overview report. Exeter, UK: Met Office Hadley Centre.

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

Rameshwaran P, Bell VA, Brown MJ, Davies HN, Kay AL, Rudd AC, Sefton C (2022). Use of abstraction and discharge data to improve the performance of a national-scale hydrological model. Water Resources Research, 5(1), e2021WR029787.

Riahi K, Krey V et al. (2011). RCP-8.5: exploring the consequence of high emission trajectories. Clim Change, 109, 33–57.

Robinson EL, Kay AL, Brown M, Chapman R, Bell V, Blyth EM (2021). Potential evapotranspiration derived from the UK Climate Projections 2018 Regional Climate Model ensemble 1980-2080 (Hydro-PE UKCP18 RCM). NERC Environmental Information Data Centre. doi:10.5285/eb5d9dc4-13bb-44c7-9bf8-c5980fcf52a4.

Robinson EL, Kay AL, Brown M, Chapman R, Bell V, Blyth E (2022). Hydro-PE: gridded datasets of historical and future Penman-Monteith potential evaporation for the United Kingdom. Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2022-288.

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

Rudd AC, Bell VA, Kay AL (2017). National-scale analysis of simulated hydrological droughts (1891-2015). J Hydrol, 550, 368-385.

Rudd AC, Kay AL (2016). Use of very high resolution climate model data for hydrological modelling: estimation of potential evaporation. Hydrology Research, 47(3), 660–670, doi:10.2166/nh.2015.028.

Salmoral, G., Rey, D. Rudd, A., de Margon, P., Holman I. (2019). A Probabilistic Risk Assessment of the National Economic Impacts of Regulatory Drought Management on Irrigated Agriculture. Earth's Future, 7(2), 178-196.

Schwalm, C.R., Glendon, S., Duffy, P.B. (2020). RCP8.5 tracks cumulative CO2 emissions. Proc Nat Acad. Sci, 117, 19656-19657.

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. doi:10.5285/33604ea0-c238-4488-813d-0ad9ab7c51ca.