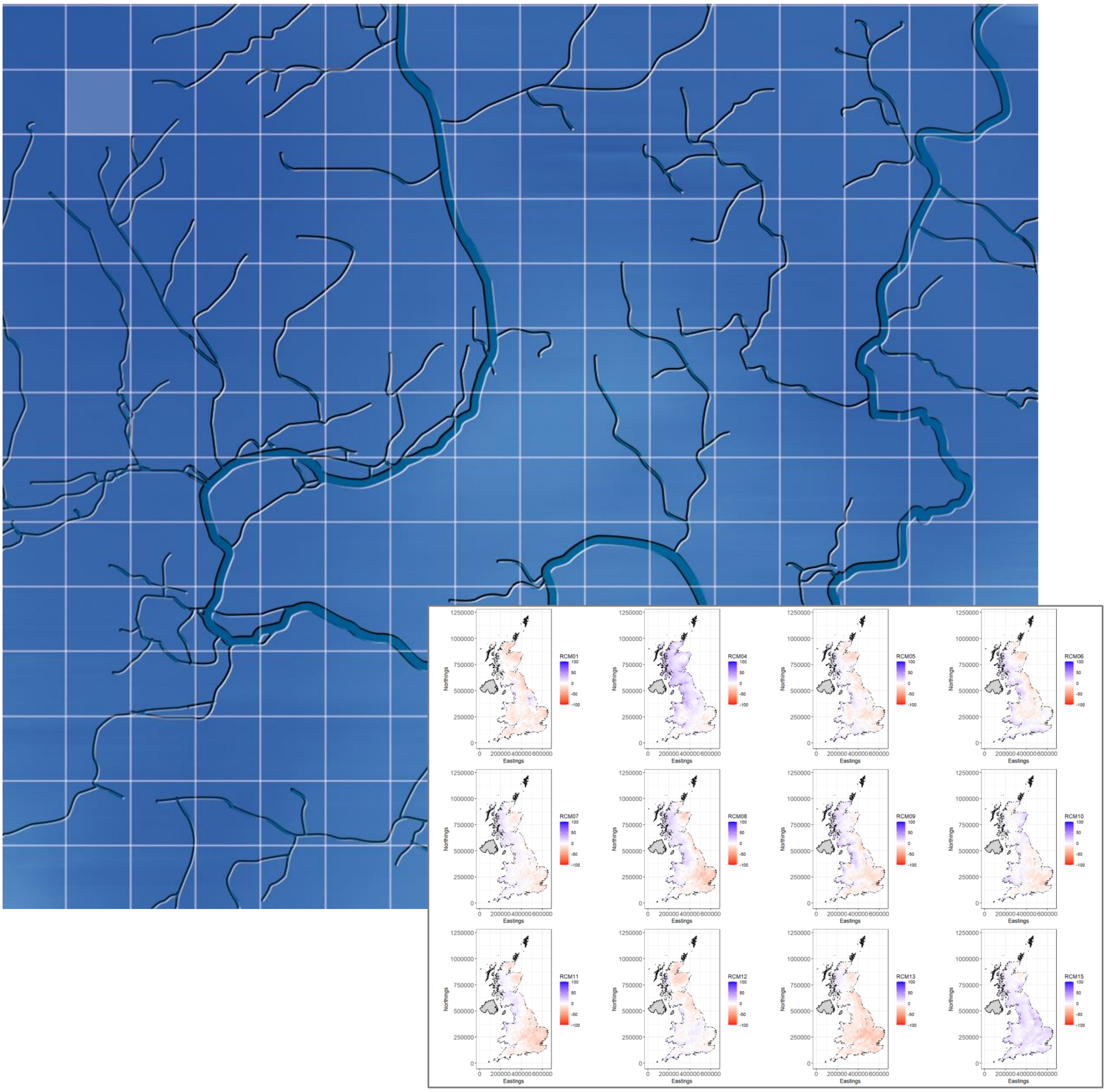
EA, NRW and SEPA

April 2024

Development of climate change adjusted flow statistics in Qube



Development of climate change adjusted flow statistics in Qube

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For and on behalf of Wallingford HydroSolutions Ltd.

The WHS Quality & Environmental Management system is certified as meeting the requirements of ISO 9001:2015 and ISO 14001:2015 providing environmental consultancy (including monitoring and surveying), the development of hydrological software and associated training.

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Contents

1 Executive summary

Qube is a web-based water resource model that can be used to estimate natural and influenced flow durations curves (FDCs) and time series for ungauged sites throughout the UK and Ireland. Within an ungauged catchment, a natural FDC can be estimated based on the catchment characteristics (runoff and soil properties) within the catchment.

There is a need for many users to be able to estimate the impact that climate change may have on water resources; this includes GB regulators (SEPA, NRW and the EA) as well as water companies and the wider hydrological community. This report details the development of datasets estimating the climate change impacts on the FDC and annual and monthly mean flows. This data has been subsequently incorporated within Qube to allow users ready access to this information for ungauged catchments.

In the past few years, a number of UK wide gridded datasets have been produced by the Met Office (MO) and UK Centre for Ecology and Hydrology (UKCEH). The MO have developed the HadUK observed meteorological datasets[1], which UKCEH have subsequently used to produce potential evaporation (PE, PET and PETI) datasets[2]. The MO UKCP18 climate change, RCP8.5 pathway datasets have also been downscaled and bias corrected by UKCEH as part of the eFLaG project to produce 1km gridded time series of precipitation and PE datasets.

The CERF (Continuous Estimation of River Flows)[3] rainfall-runoff model has been redeveloped using the HadUK precipitation and UKCEH PETI datasets and calibrated using flow data from 472 gauges. The CERF2-HadUK model development is documented within the 'Development of CERF2-HadUK rainfall-runoff model' science report. The CERF2-HadUK model has then been used to produce a daily time series of flow percentiles for ~11,000 TSEP (Time Series Exceedence Percentiles) catchments within Great Britain (GB). In application, Qube selects the most similar TSEP catchment to the ungauged location and scales the time series to the natural FDC; this ensures that the time series and FDCs within Qube are internally consistent.

This report details the development of the climate change datasets used within Qube, using the CERF2-HadUK model and the UKCP18 downscaled and bias corrected datasets produced as part of eFLaG[4,5]. CERF2-HadUK has been run for the TSEP catchments, using these climate change meteorological datasets and the resulting changes in the FDC and annual and monthly mean flows have been calculated. Similar to the times series estimation, through the selection of donor 'similar' catchments (based on distance and catchment characteristics), the change factors can be transferred to ungauged sites. This has been applied within Qube to allow users to generate estimates of climate change FDCs and annual and monthly mean flows for the near and far future epochs for ungauged sites throughout the UK.

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[1] Hollis, D.; McCarthy, M.; Kendon, M.; Legg, T.; Simpson, I. (2018): HadUK-Grid gridded and regional average climate observations for the UK

[2] https://catalogue.ceh.ac.uk/documents/9275ab7e-6e93-42bc-8e72-59c98d409deb

[3] Griffiths, J., Keller, V., Morris, D., Young, A.R. 2008. Continuous estimation of River Flows (CERF). Environment Agency. SC030240

[4] https://www.ceh.ac.uk/our-science/projects/eflag-enhanced-future-flows-and-groundwater

[5] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023

2 Introduction

There is a requirement for regulators such as the EA, NRW and SEPA, as well as the wider hydrological community, to be able to estimate climate change adjusted natural flow duration curves (FDCs) and annual and monthly mean flows for the near and far future within any catchment, gauged or ungauged.

A scoping project recommended using the forcing dataset from the UKCP18 eFLaG[6,7] gridded meteorological datasets, with the CERF (Continuous Estimation of River Flows)[8] daily rainfall-runoff model, to produce the climate adjusted natural flow, which can be subsequently implemented within Qube. Priorities included an agreement that the model outputs should utilise the latest Met Office (MO) projections in UKCP18 near and far future, be consistent with other national assessments, and should include extensive coverage of catchments across Great Britian (GB).

The CERF rainfall-runoff model has been redeveloped and calibrated using the MO HadUK precipitation[9] and UKCEH HadUK potential evaporation (PETI) datasets[10]. This is detailed within the 'Development of CERF2-HadUK rainfall-runoff model' science report. An advantage of using this data is that the metadata structures of the HadUK datasets were constructed to follow the UKCP18 project outputs ensuring consistency between the historical and climate change forcing datasets.

The UKCP18 eFLaG[11,12] gridded meteorological datasets are used in combination with the CERF2-HadUK rainfall-runoff model to generate climate change daily time series datasets for ~11,000 donor TSEP catchments for use in Qube. Percentage changes at the TSEP catchments between current and future flows at key percentiles and annual and monthly mean flows have been computed. Interpolation and extrapolation have been used to estimate the full climate adjusted FDCs. In application within Qube, the percentage change factors are transferred to ungauged sites through the selection of donor 'similar' catchments (based on distance and catchment characteristics) and applied to the Qube natural FDC and mean flows.

Figure 1 presents a summary of the datasets and models used to develop the climate change datasets for Qube.

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[6] https://www.ceh.ac.uk/our-science/projects/eflag-enhanced-future-flows-and-groundwater
[7] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023
[8] Griffiths, J., Keller, V., Morris, D., Young, A.R. 2008. Continuous estimation of River Flows (CERF). Environment Agency. SC030240
[9] Hollis, D.; McCarthy, M.; Kendon, M.; Legg, T.; Simpson, I. (2018): HadUK-Grid gridded and regional average climate observations for the UK
[10] https://catalogue.ceh.ac.uk/documents/9275ab7e-6e93-42bc-8e72-59c98d409deb
[11] https://www.ceh.ac.uk/our-science/projects/eflag-enhanced-future-flows-and-groundwater
[12] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023

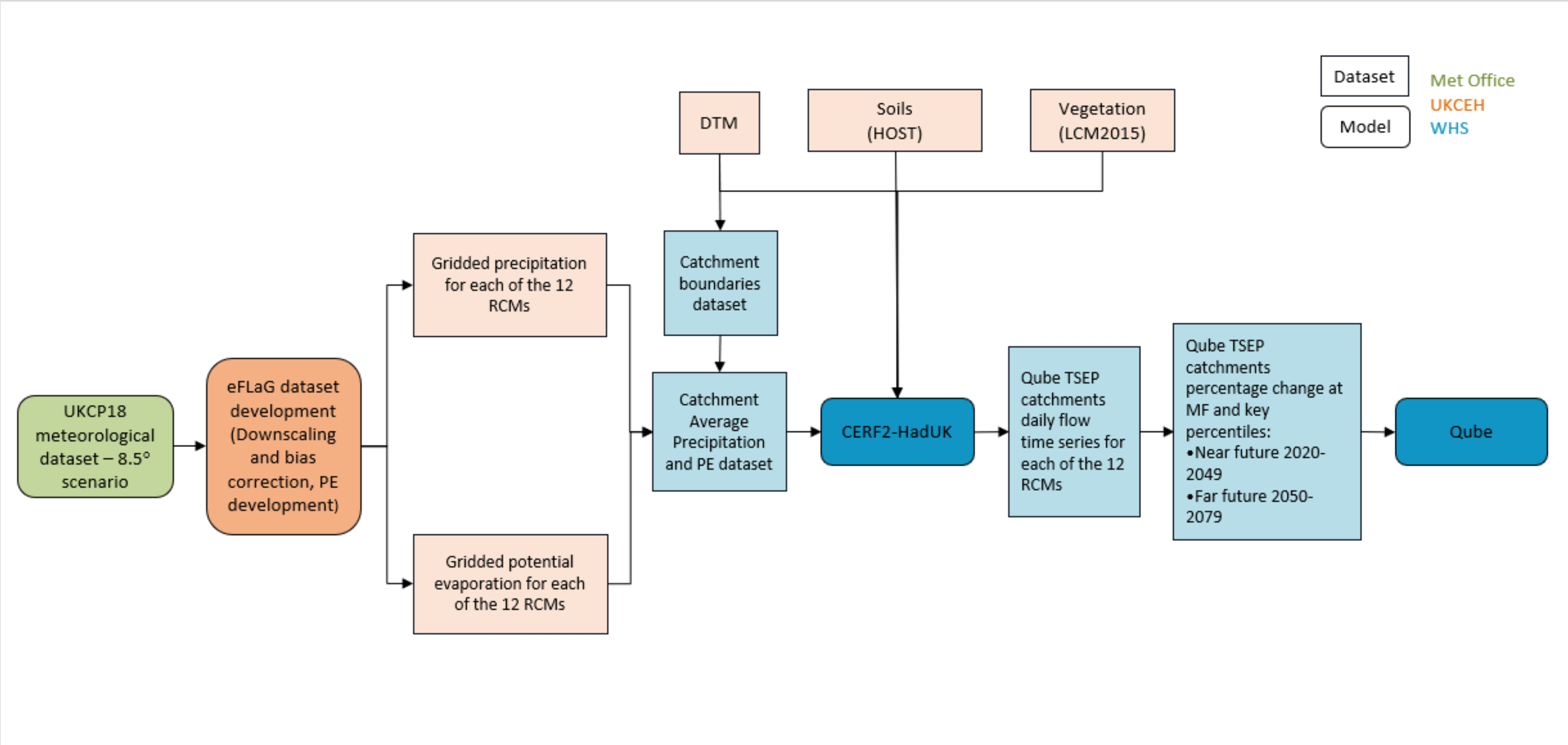

Figure 1. Summary diagram of the datasets and models used to develop the climate change datasets for Qube.

This document provides details on the development of climate change adjusted FDCs and annual and monthly mean flows presenting the datasets (section 3) and the methodology applied (section 4). Section 5 presents the results and discussion, while section 6 provides a conclusion and interpretation of the results. Acknowledgements are found in section 7.

3 Datasets

The CERF2-HadUK rainfall-runoff model requires meteorological forcing data in the form of precipitation and potential evaporation (PE). CERF2-HadUK also requires spatial datasets including a digital terrain model (DTM), soils data and vegetation datasets. The spatial datasets remain consistent for the observed historical time series modelling and climate change modelling.

3.1 Meteorological forcing datasets: eFLaG

The UKCP18 eFLaG gridded meteorological datasets were used as the source of the meteorological forcing data. The meteorological datasets are based on the UKCP18 12 km resolution RCM (regional climate model) using RCP (Representative Concentration Pathway) 8.5 with a 12-member perturbed parameter ensemble (PPE) for the period December 1980 to November 2080. RCP8.5 is a pathway where greenhouse gas emissions continue to grow unmitigated, leading to a best estimate global average temperature rise of 4.3°C by 2100.

Note that ensemble members are sourced from only one climate model and one emissions scenario, where the 12 ensemble members represent a range of boundary conditions for the climate model and are considered equally plausible scenarios.

3.1.1 Precipitation dataset

The "Gridded simulations of available precipitation (rainfall + snowmelt) for Great Britain, developed from observed data (1961-2018) and climate projections (1980-2080)"[13] was used as the precipitation dataset.

This dataset includes simulations driven by observational data (January 1961-December 2018) and simulations driven by Regional Climate Model (RCM) projections (December 1980-November 2080) on a 1 km grid. Only the data driven by the RCM projections have been used in this project.

The dataset provides available precipitation (rainfall and snowmelt) using the 12-members perturbed parameter ensemble from the UK Climate Projections 2018 (UKCP18) precipitation and temperature data. The UKCP18 precipitation data was bias corrected and downscaled from 12 km to a 1 km grid based on patterns of average annual rainfall. UKCP18 temperature data was downscaled based on lapse rate and elevation. The downscaled RCM data were then input into a snowmelt module to provide the available precipitation. The dataset is held by the EIDC (Environmental Information Data Centre).

3.1.2 Potential evaporation dataset

The "Potential evapotranspiration derived from the UK Climate Projections 2018 Regional Climate Model ensemble 1980-2080 (Hydro-PE UKCP18 RCM)"[14] was used as PE dataset in the project.

[13] https://catalogue.ceh.ac.uk/documents/755e0369-f8db-4550-aabe-3f9c9fbcb93d
[14] https://catalogue.ceh.ac.uk/documents/eb5d9dc4-13bb-44c7-9bf8-c5980fcf52a4

This dataset is based on different variables in the UKCP18 dataset (12 RCMs) and provides daily total potential evapotranspiration (PET) and daily total potential evapotranspiration with interception correction (PETI) at a 12 km resolution, of which the PETI variable has been used. For consistency with the precipitation data, the 12 km PE dataset developed by UKCEH has been sampled on the 1 km grid as part of the project. The dataset is held by the EIDC.

3.2 Spatial datasets

CERF2-HadUK requires a soils dataset and a land cover dataset, as well as a Digital Terrain Model (DTM) to describe elevation.

These datasets are consistent with those used in the development of the historical time series dataset within Qube. The UKCEH Hydrology of Soil Types (HOST)[15] dataset was used to described soil and the UKCEH Land Cover Map 2015 (LCM2015)[16] was used to describe vegetation. For further details on these datasets, please see the 'Development of CERF2-HadUK rainfall-runoff model' science report.

4 Methodology

Catchment average rainfall and PE were generated for each of the ~11,000 donor TSEP catchments for each of the 12 RCMs. The full available period in the data from December 1980 to November 2080 was considered. CERF2-HadUK was then run for each catchment to generate a daily flow time series.

The following flow duration curves were then computed for each of the TSEP sites for each RCM:

- RCM baseline: January 1989 – December 2018
- Near future: January 2020 – December 2049
- Far future: January 2050 – December 2079.

Key percentiles (Q10, Q20, Q30, Q40, Q50, Q60, Q70, Q80, Q90 and Q95), and annual and monthly mean flows were then extracted from the time series for each TSEP site and the percentage changes between baseline and future flow at each percentile and for the annual and monthly mean flows were computed:

$$Percentage\ Change_{Q,future} = (Q_{future} - Q_{baseline})/Q_{baseline} * 100$$

These data are then imported into Qube at each TSEP site.

Qube then computes the absolute values of climate change using the percentage changes as follows:

$$Q_{future} = Q_{Qube} + Q_{Qube} * \frac{Percentage\ Change_{Q,future}}{100}$$

Where Q_{Qube} is the Qube natural flow (m^3/s) for the full period of record (1969-2021).

For the FDC, Qube then uses the climate change adjusted flows at the key percentiles to log normally interpolate and linear normally extrapolate additional percentiles across the full FDC.

[15] Boorman, D.B., Hollis, J.M. and Lilly, A. 1995. Hydrology of Soil types: a hydrologically-based classification of the soils of the United Kingdom. Institute of Hydrology Report No. 126. Wallingford, UK.
[16] Rowland, C.S.; Morton, R.D.; Carrasco, L.; McShane, G.; O'Neil, A.W.; Wood, C.M. (2017). Land Cover Map 2015 (1km dominant target class, GB). NERC Environmental Information Data Centre. https://doi.org/10.5285/c4035f3d-d93e-4d63-a8f3-b00096f597f5

The following diagrams summarise the above methodology. Figure 2 illustrates the processes from the CERF2-HadUK time series to the computation of the percentage changes. Figure 3 shows the computations that Qube carried out to estimate the climate change adjusted flows at any gauged or ungauged location.

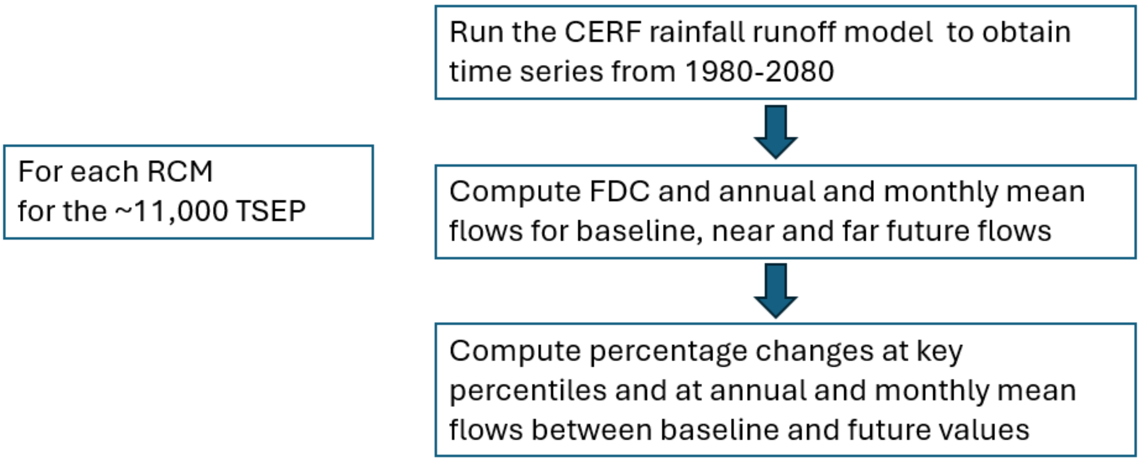

Figure 2. Processes from the CERF2-HadUK time series to the computation of the percentage changes at the key percentiles and mean flows for each of the 12 RCMs at the ~11,000 TSEP sites

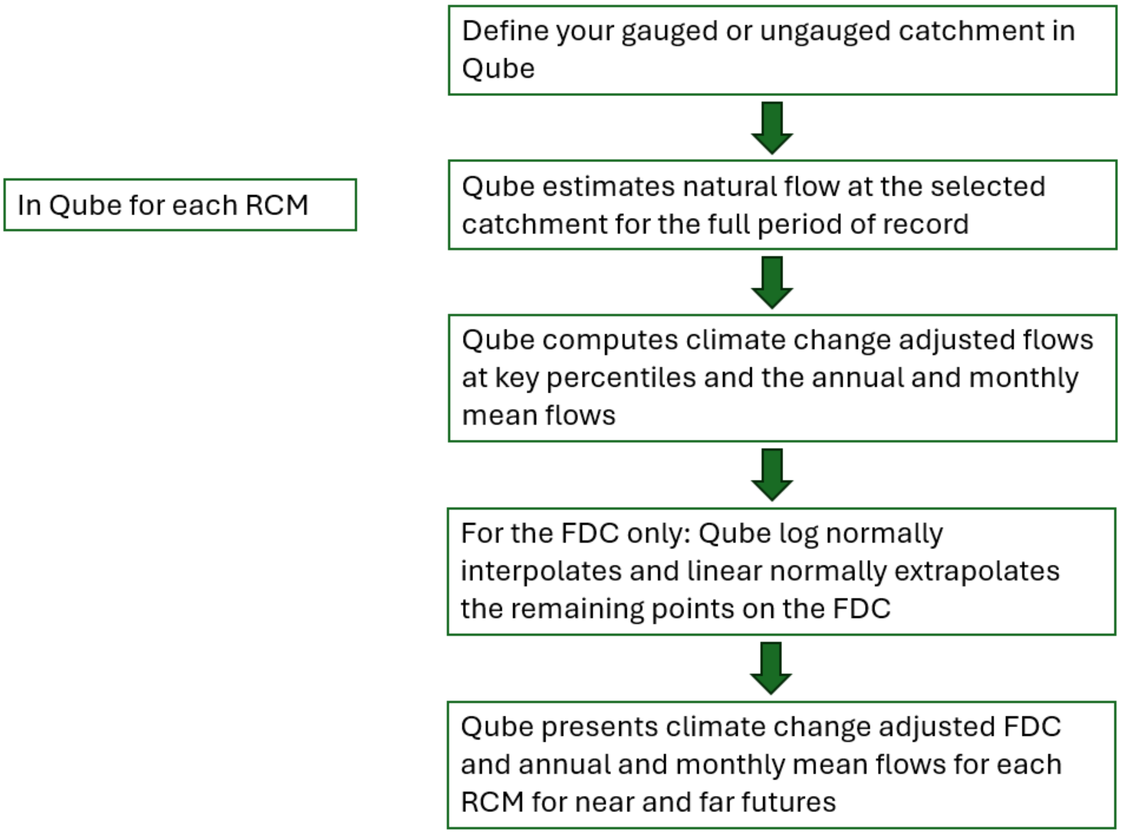

Figure 3. Computations that Qube carries out to estimate the climate change adjusted FDCs and mean flows for each of the 12 RCMs.

5 Results and discussion

A comparison of the baseline and observed mean flow for each RCM run is presented first. To provide confidence in the climate change results, the mean flows from the historical observed model and climate change baseline should be similar.

Within Qube both the climate adjusted annual and monthly mean flows and the adjusted FDCs will be presented. This report focusses on the percentage changes in FDC as, generally, these are most commonly used within water resource management, and this data is available for comparisons with other studies.

The percentage changes in the FDC for a number of strategic percentiles is first presented for the TSEP catchments. A high-level comparison of these results with those from the eFLaG project is then completed.

The main eFLaG project and other studies that utilised the eFLaG datasets (Parry et al., 2024[17], Aitkin et al., 2023[18]) present outputs from ~200 gauging stations only. CERF2-HadUK has been used to generate outputs for ~11,000 catchments (including a large number of gauged catchments) throughout GB. The comparison and discussion are therefore largely limited to gauged catchments. They are intended to provide context for the present model outputs, particularly in relation to other hydrological outputs using the eFLaG dataset and are not intended to represent a full literature review of the issues associated with climate change modelling and the resulting impacts on water resources across GB.

5.1 Comparison between HadUK and RCMs baseline

A comparison between the historical HadUK and the RCMs baseline period has been carried out to assess the consistency of the datasets. Only the overlapping time series from January 1989 to December 2018 has been considered in the comparison. Figure 4 shows the mean flow percentage bias between these datasets.

[17] Parry, S., Mackay. J. D., Chitson. T.,Hannaford. J., Magee. E, Tanguy. M., Bell. B. A., Facer-Childs. K., Kay. A., Lane. R., Moore. R. J., Turner.S., Wallbank. J. 2024. Divergent future drought projections in UK river flows and groundwater levels. Hydrology and Earth System Sciences, Volume 28, issue 3. HESS, 28, 417–440, 2024 https://doi.org/10.5194/hess-28-417-2024

[18] Aitken, G., Beevers, L., Parry, S. et al. Partitioning model uncertainty in multi-model ensemble river flow projections. Climatic Change 176, 153 (2023). https://doi.org/10.1007/s10584-023-03621-1

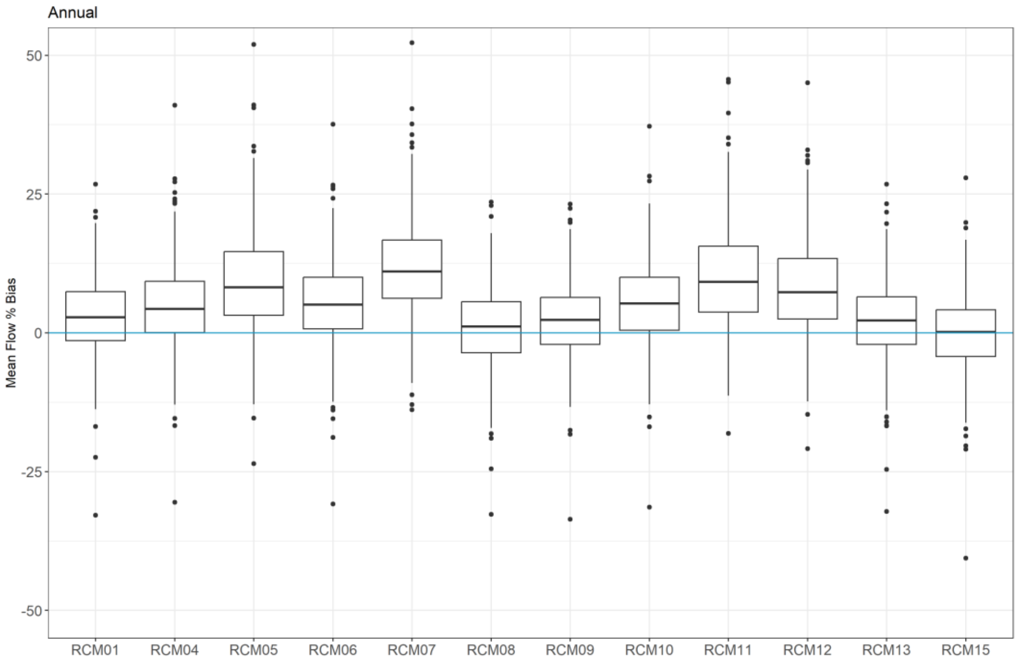

Figure 4. Annual percent bias between HadUK and RCMs baseline time series at mean flow

From Figure 4, it is possible to observe that almost all RCMs show a positive median bias with respect to the mean flow. For RCM01, RCM08, RCM09, RCM13 and RCM15 the central part of the box plot overlaps with zero indicating smaller biases within these RCMs. Further analysis indicates that the general positive bias is spatially consistent across England, Wales, and Scotland. Analysis of the underlying meteorological variables indicates that the precipitation shows little overall bias, whilst there is generally a negative bias in the PETI data, i.e. the PETI within the baseline period for the climate change dataset is generally lower than that used within the historical CERF2-HadUK PETI dataset.

The HadUK dataset is derived from station observations of meteorological variables. Within the RCM development for eFLaG, only the precipitation was bias corrected as part of the PETI calculation, and differences between UKCP18 and HadUK meteorology remain for the other variables. Consultation with UKCEH indicates that it is possible that the lack of bias correction within the PETI dataset may explain some of the differences between the two datasets when comparing the observed PETI and the RCM PETI (for the baseline period)[19].

The percentage changes subsequently utilised within Qube, are calculated from an internally consistent dataset (the climate change transient series) and the average median bias is still low (4.92%) therefore it is considered that the datasets and methodology are appropriate for estimating the impact of climate change on flows within GB.

[19] Robinson, E. L., Brown, M. J., Kay, A. L., Lane, R. A., Chapman, R., Bell, V. A., and Blyth, E. M.: Hydro-PE: gridded datasets of historical and future Penman–Monteith potential evaporation for the United Kingdom, Earth Syst. Sci. Data, 15, 4433–4461, https://doi.org/10.5194/essd-15-4433-2023, 2023.

5.2 Climate change percentage changes at TSEP

The following figures show the median of the RCMs percentage changes at the TSEP sites for the near and far future. The percentiles considered are Q10 (Figure 5), Q30 (Figure 6), Q50 (Figure 7), Q70 (Figure 8), Q90 (Figure 9) and Q95 (Figure 10).

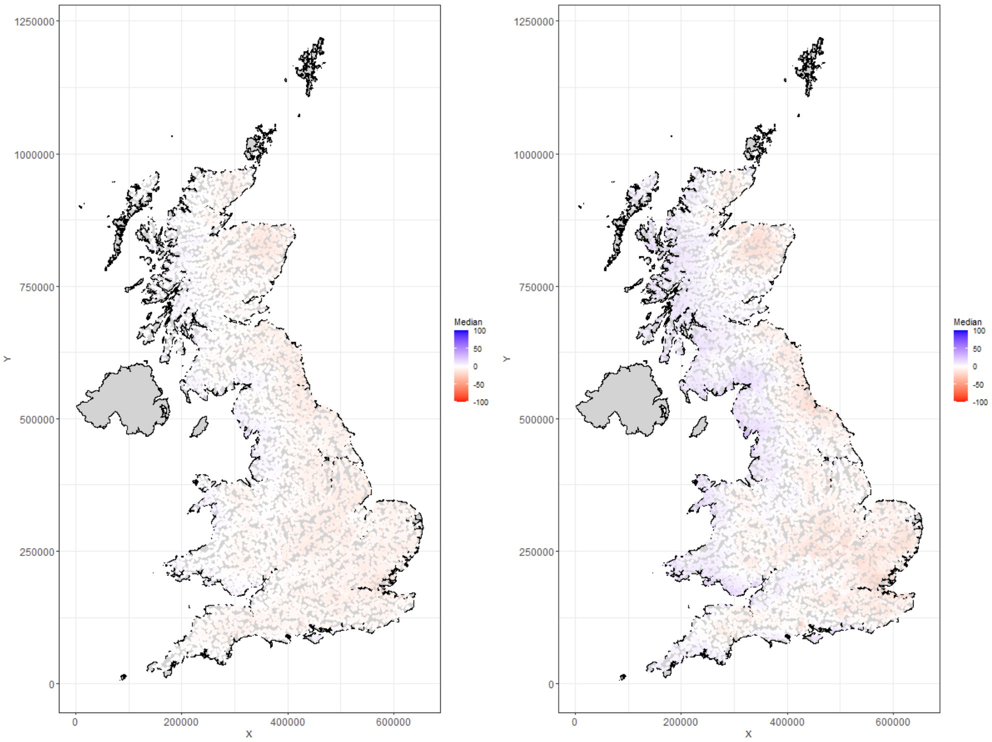

Figure 5. Median of the RCMs' percentage changes at Q10 for the near future (left) and the far future (right)

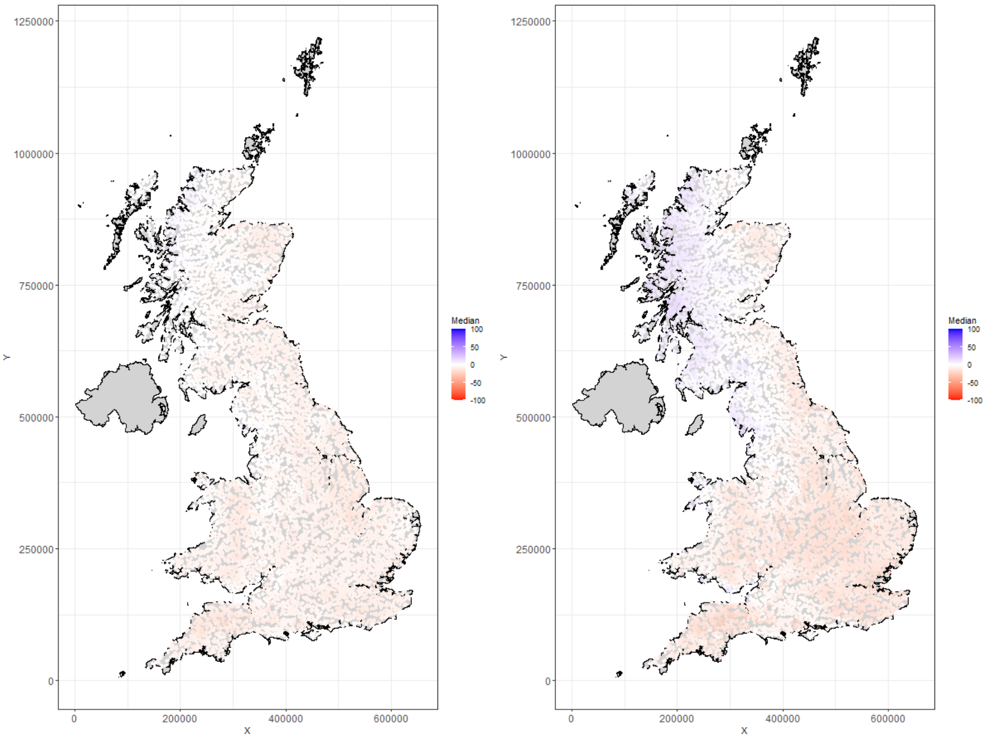

Figure 6. Median of the RCMs' percentage changes at Q30 for the near future (left) and the far future (right)

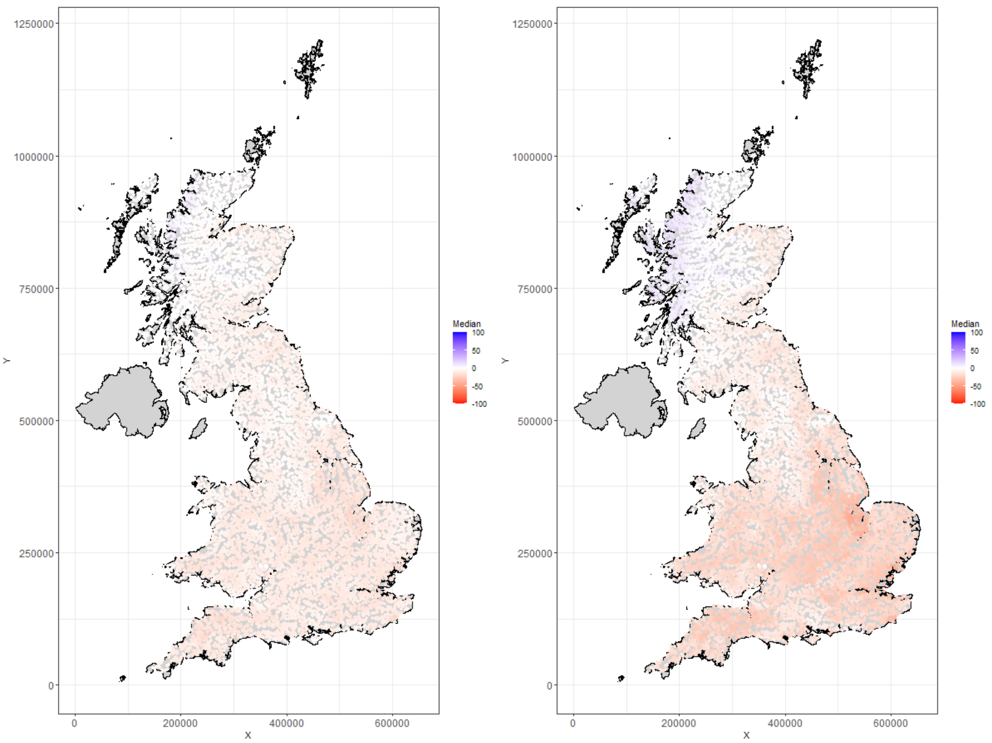

Figure 7. Median of the RCMs' percentage changes at Q50 for the near future (left) and the far future (right)

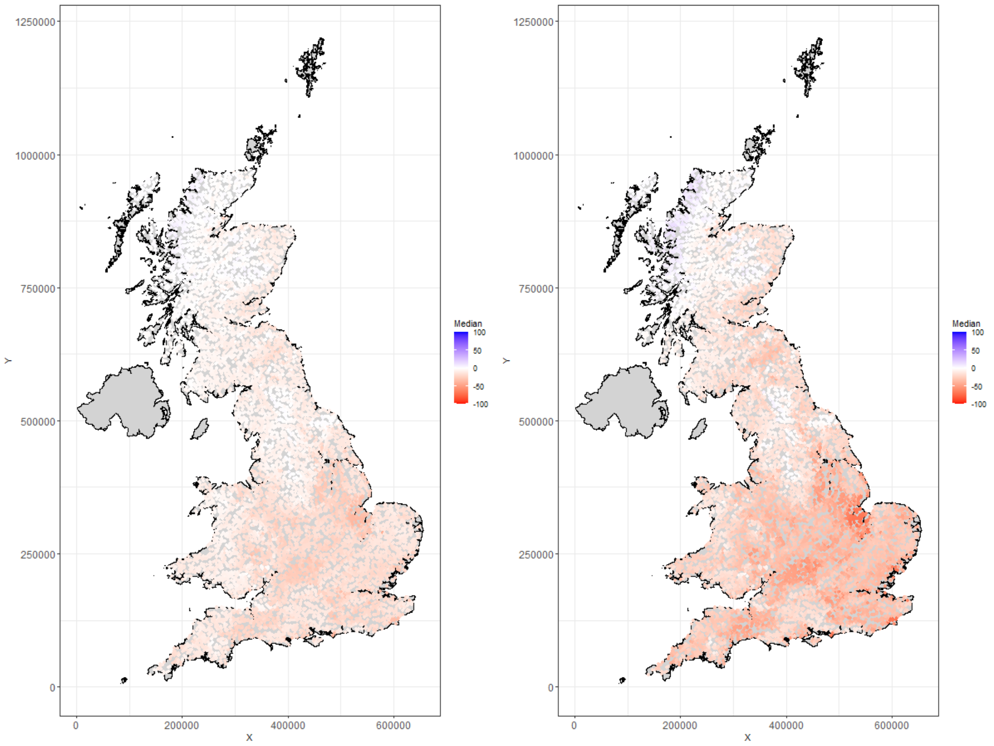

Figure 8. Median of the RCMs' percentage changes at Q70 for the near future (left) and the far future (right)

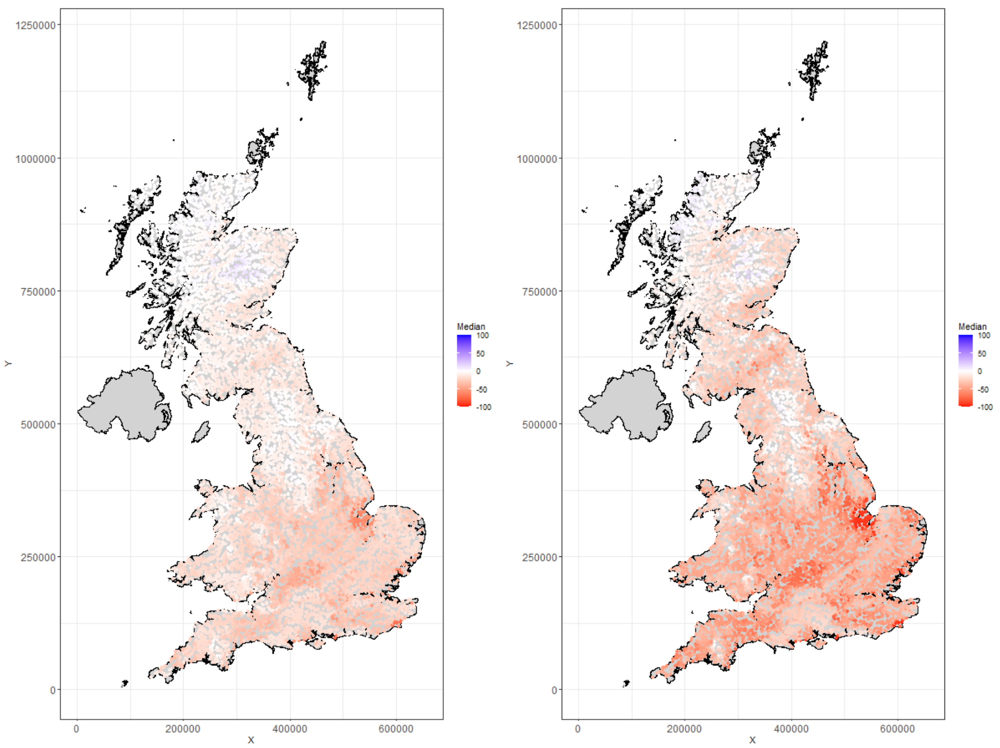

Figure 9. Median of the RCMs' percentage changes at Q90 for the near future (left) and the far future (right). Please note that one outlier TSEP has been removed from the maps for presentation purposes.

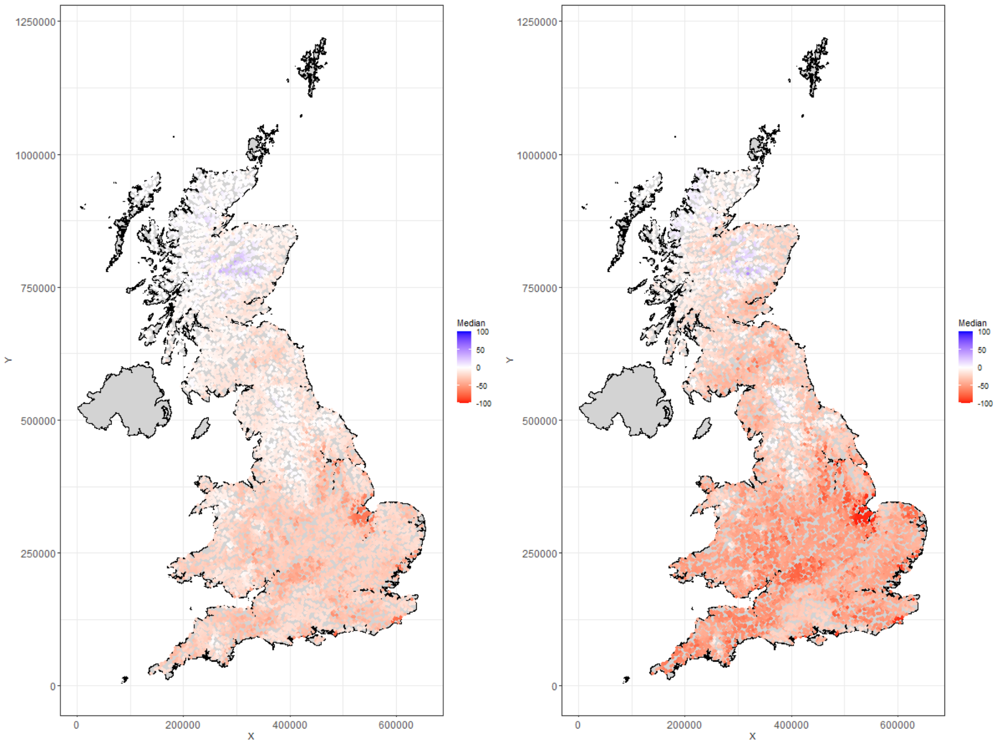

Figure 10. Median of the RCMs' percentage changes at Q95 for the near future (left) and the far future (right). Please note that one outlier TSEP has been removed from the maps for presentation purposes.

At high and median flows (Q10, Q30 and Q50) in the near future (left map on Figure 5 to Figure 7), there are negative percentage changes in the central and eastern part of GB indicating a general decrease in high and median flows in these areas. Positive percentage changes can be seen in the western and northern parts of GB indicating an increase in high and median flow values in these areas. The percentage changes for the far future follow similar patterns as the near future's percentage changes with a higher degree of change, where negative and positive changes become larger.

At low flows (Q70, Q90 and Q95), the percentage changes are generally negative throughout GB with the southeast exhibiting the highest percentage changes. The exceptions to this are a number of small catchments in higher altitude areas in central and northwest Scotland, and northern England, where positive percentage changes can be seen. Note that, while the percentage changes are significant, the flow changes tend to be small. Please additionally note that one outlier TSEP has been removed from the maps for presentation purposes.

Further analysis within these TSEP catchments indicate that this may be due to the changing impact of the process of snow accumulation and melt within these catchments. For the more extreme catchments, the lowest flows during the current period are in early spring, as there is little runoff within the catchment as most precipitation falls as snow and is stored a such. Under climate change conditions, the low flows are more evenly distributed between spring and summer. This might be related to smaller fractions of snow cover within the near and far future epochs. Whilst Bell et al., 2016[20], investigating the impact of the snow module on climate change projections (UKCP09), found little change in peak flows for the catchments investigated, they did note that there could be a significant reduction of snow days in some areas due to climate change. They state that snowmelt processes were shown to be important for upland parts of GB, mainly in eastern Scotland, and that the reduced presence of snow in the future could have a large impact on river flows. Parry et al., 2024[21] additionally notes the impact of changes in the extent of snow accumulation and melt, highlighting the importance of including these aspects within forcing data.

There are considerable uncertainties within the modelling process, due to the uncertainties within the cascade of models (from the UKCP18 outputs to the final CERF modelled flows) which should be taken into account when analysing these particular results. It is also important to note that whilst snowmelt was found to have an impact on some of the flow regimes within the gauged development dataset for CERF2-HadUK, there were no small catchments where these processes dominated the low flows within the gauged dataset (nor was the impact of snowmelt included within the development precipitation dataset). These results must therefore be interpreted in the context of the uncertainties associated with the forcing datasets and hydrological model.

The high negative percentage changes in East Anglia are, similarly, associated with changes of flow in catchments that are very small. In this case, they also have low baseline rainfall and a highly variable flow regime, resulting in very low baseline Q95 flow values, e.g. at one TSEP catchment a value of 0.0079 m^3/s for current Q95 and 0.00027 m^3/s for Q95 in the far future. There were also no gauged catchments included within the CERF2-HadUK gauging station development dataset which were similarly small, with low baseline rainfall and dominated by the same soil type.

5.2.2 Percentage change variability among RCMs

Figure 5 to Figure 10 present the median RCM percentage changes. The variability of the individual RCMs can be seen within Figure 11 and Figure 12 respectively for Q10 and Q95 for the far future. These illustrate that there can be significant differences between the RCM runs, with some being consistently 'wet' (e.g. RCM15) whilst others represent a 'drier' (e.g. RCM01) possible future. There is also considerable spatial variability. For high flows there is a general pattern of higher flows in the north and east of Scotland, but this can be spatially variable with RCM06 and RCM12 both exhibiting higher flows in the east. RCM15 shows higher flows throughout GB whereas RCM01 indicates that lower flows will occur throughout GB. There is a more consistent pattern of lower flows throughout GB, but with large differences in magnitude. A number of RCM runs also show the positive changes in the high altitude areas of Scotland. RCM15 additionally shows an increase in flows in the groundwater dominated catchments of the south and east.

All RCM runs are available in Qube to allow an assessment of the variability of these results.

[20] 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. Climatic Change, 136 (3). 539-553. 10.1007/s10584-016-1637-x
[21] Parry, S., Mackay. J. D., Chitson. T.,Hannaford. J., Magee. E, Tanguy. M., Bell. B. A., Facer-Childs. K., Kay. A., Lane. R., Moore. R. J., Turner.S., Wallbank. J. 2024. Divergent future drought projections in UK river flows and groundwater levels. Hydrology and Earth System Sciences, Volume 28, issue 3. HESS, 28, 417–440, 2024 https://doi.org/10.5194/hess-28-417-2024

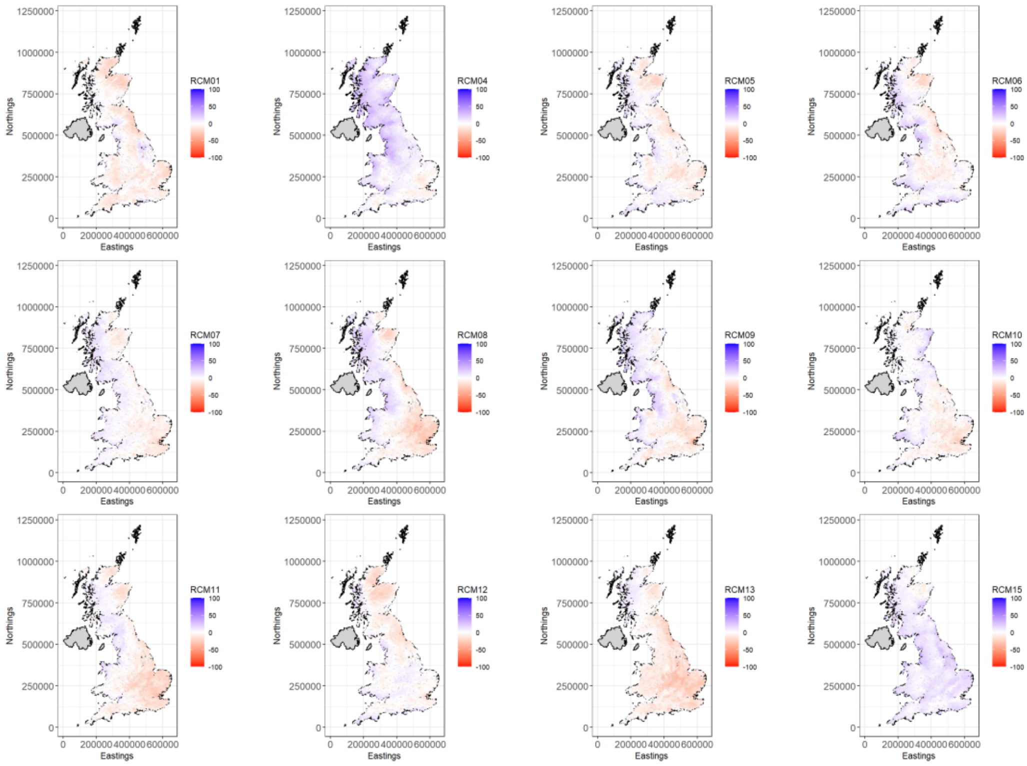

Figure 11. Variability within RCMs runs at Q10 for the far future

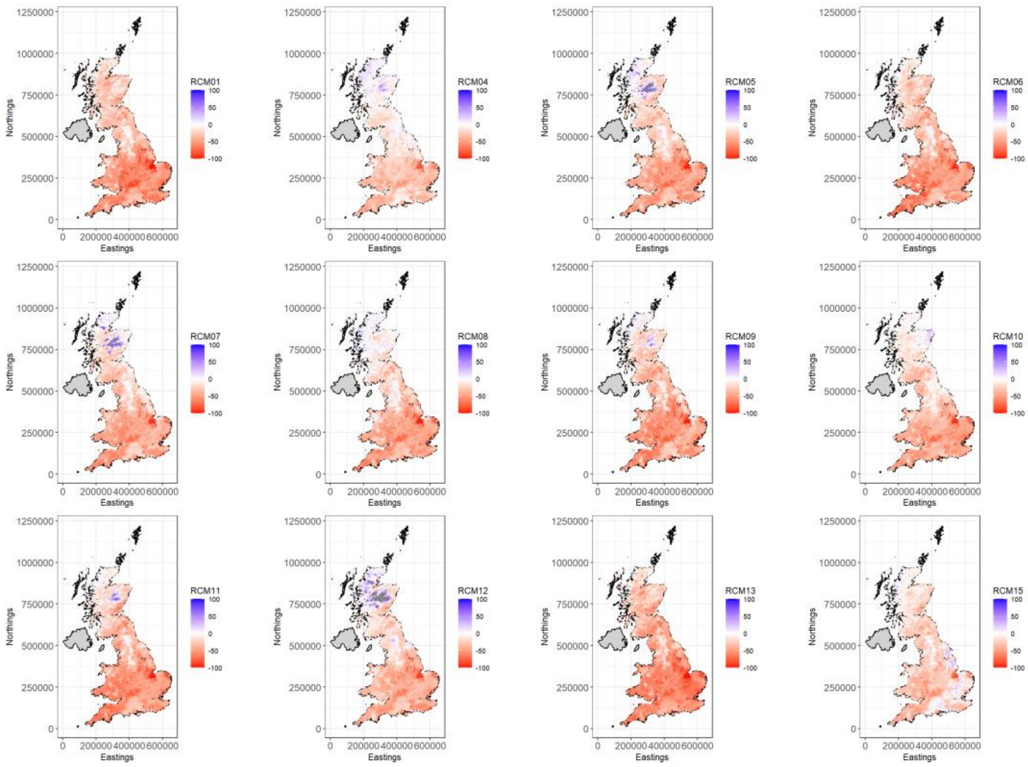

Figure 12. Variability within RCMs runs at Q95 for the far future

5.3 Comparison with UKCP18 and eFLaG outputs

5.3.1 Summary of eFLaG outputs

eFLaG provides a valuable downscaled and bias corrected gridded climate change meteorological forcing dataset that can be used to assess the implication of climate change on water resource. The eFLaG project utilised these meteorological forcing datasets within 4 different hydrological models and the resulting percentage changes at a selection of gauging stations can be viewed via the eFLaG Portal[22].

The G2G (Grid to Grid), PDM, GR4J and GR6J hydrological models were those used within the eFLaG project. These are described in Hannaford et al., 2023[23], but can generally be separated into 3 lumped hydrological models; GR4J, GR6J and PDM, and a semi-distributed model; G2G. The lumped models were calibrated to individual gauged flow data, whilst the G2G model is a generalised model with a fixed national parameter set that can be run for gauged and ungauged catchments.

5.3.2 Comparison with the CERF2-HadUK hydrological model outputs

A comparison between the CERF2-HadUK and eFLaG hydrological model outputs indicates that whilst the general spatial patterns, and direction of changes for low and high flows are similar for all hydrological models (for individual RCM runs and the median), there can be significant differences in the magnitude of the changes, particularly at low flows. This was also noted within the four eFLaG hydrological models using the eFLaG dataset by Parry et al.,2024[26].

At higher flows, the percentage changes from CERF2-HadUK and the eFLaG hydrological models are similar, with less variability between the hydrological models and considerable variability between RCM runs, supporting the findings within Aitkin et al.,[24]. Spatial patterns are also similar with lower flows in the central and eastern part of the country and higher flows in the north and west within eFLaG outputs. This pattern was also reported by Lane et. al., 2022[25]; another study using the UKCP18 datasets and the DECIPHeR hydrological model.

At low flows, the differences between the hydrological models becomes more noticeable and CERF2-HadUK has more similar percentage changes to the PDM and GR6J models, whilst the outputs from G2G and GR4J exhibited more negative percentage changes. These differences also highlight the generally higher uncertainty at low flows noted by Aitkin et al., 2023[24].

Lower negative percentage changes can be found both in the CERF2-HadUK results and the gauging stations in eFLaG hydrological models for catchments which are more groundwater dominated in the south. As noted by Parry et al., 2024[26], this may be related to the way in which the wetter winters

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[22] https://eip.ceh.ac.uk/hydrology/eflag

[23] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023

[24] Aitken, G., Beevers, L., Parry, S. et al. Partitioning model uncertainty in multi-model ensemble river flow projections. Climatic Change 176, 153 (2023). https://doi.org/10.1007/s10584-023-03621-1

[25] Lane. R. A., Coxon. G., Freer. J., Seibert. J., Wagener. T. 2022. A large-sample investigation into uncertain climate change impacts on high flows across Great Britain Hydrol. Earth Syst. Sci., 26, 5535–5554, 2022 https://doi.org/10.5194/hess-26-5535-2022

[26] Parry, S., Mackay. J. D., Chitson. T.,Hannaford. J., Magee. E, Tanguy. M., Bell. B. A., Facer-Childs. K., Kay. A., Lane. R., Moore. R. J., Turner.S., Wallbank. J. 2024. Divergent future drought projections in UK river flows

provide enhanced recharge to aquifers that can limit the impact of the increased dryness of the summers.

The increase in Q95 within small, high altitude catchments in Scotland presented in Figure 10 is not found within the wider literature from studies using the eFLaG dataset. This might be due to the fact that there are few gauging stations in this area, and those that tend to be larger and do not have high proportions of snow cover, thus these catchment types are not included in the results of the wider studies discussed.

5.4 Uncertainties in the dataset

There are many sources of uncertainty within the climate change adjusted FDC computed in Qube; starting from the eFLaG input datasets which were produced using only one climate model, one emissions scenario, and one downscaling and bias correction approach. The limitations of the approach are more fully discussed within Hannaford et al.,[27], Parry et al., 2024[28], and Aitkin et al., 2024[29].

It is important to remember that the climate change adjusted FDC implemented within Qube are the realisation of a single hydrological model (CERF2-HadUK) and, for this reason, carry the uncertainties related to it. Aitkin et al., 2023[29] assessed the relative levels of uncertainty associated with the outputs separating these into hydrological model and RCM uncertainty. The results suggested that the RCM uncertainty is larger for high flows, whilst at lower flows the hydrological model has a greater contribution. This is exhibited in the results through the greater consistency in model outputs at high flows between hydrological models whereas at low flows there is a larger variability between hydrological models than between RCM runs.

The extreme examples analysed in section 5.2 (at lower flows the flow increased in high altitude areas in Scotland and flow decreased in the East Anglia region) illustrate both the value of high spatial resolution results, where combinations of climate and spatial datasets result in changes that are not found within gauged catchments, but also the current limitations in the assessment for the performance of the hydrological models in these locations/catchments types due to the sparsity of appropriate gauging stations. Both examples also illustrate the fact that, as flows at high percentiles are often very low, the percentage changes can appear large even whilst the changes in flows are very small; a point also noted by Aitkin et al. 2023[29].

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and groundwater levels. Hydrology and Earth System Sciences, Volume 28, issue 3. HESS, 28, 417–440, 2024 https://doi.org/10.5194/hess-28-417-2024

[27] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023

[28] Parry, S., Mackay. J. D., Chitson. T.,Hannaford. J., Magee. E, Tanguy. M., Bell. B. A., Facer-Childs. K., Kay. A., Lane. R., Moore. R. J., Turner.S., Wallbank. J. 2024. Divergent future drought projections in UK river flows and groundwater levels. Hydrology and Earth System Sciences, Volume 28, issue 3. HESS, 28, 417–440, 2024 https://doi.org/10.5194/hess-28-417-2024

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6 Conclusion and interpretation of results

Natural climate change adjusted flow duration curves and mean flows were developed and implemented in Qube as part of this project. The CERF2-HadUK rainfall-runoff model was run from December 1980 to November 2080. Percentage changes were computed between baseline and near and far future at key flow statistics, with the full FDC percentiles derived using log normal interpolation and linear normal extrapolation.

Liaison with the eFLaG team at UKCEH has been carried out during the project to ensure consistency in the input data and the methodologies. The percentage changes resulting from the eFLaG models were compared with the percentage changes from CERF2-HadUK. As within the eFLaG project's models, general spatial and temporal patterns were found to be similar, whilst the magnitude, particularly at low flows could vary between models. In general, the percentage changes in flows from CERF2-HadUK, implemented within Qube, are more comparable with those from the PDM and GR6J hydrological models.

When interpreting the climate change adjusted flows, it is important to note the limitations and uncertainties associated with the generation of the datasets. As noted previously, the outputs from eFLaG represent only one climate model, using one emissions scenario and one bias corrected and downscaling method. Some of the uncertainty is represented by the RCM runs, which illustrate the variability relating to the parameterisation of the model, and these are shown to provide widely varying possible outcomes. The results from Qube, generated through CERF2-HadUK, represent results from one hydrological model and it is noted that, particularly at low flows, there can be large differences between the magnitudes of the changes using different hydrological models.

However, the results presented in Qube are shown to be comparable to those from other hydrological models at common gauging stations. Implementation within Qube allows users, from a wide variety of backgrounds, to readily access possible scenarios of climate change impact on flows at both gauged and ungauged locations throughout GB thus provides a valuable tool for furthering our understanding of the possible impact of climate change on river flows and providing information that can be used as part of adaptation and future management strategies.

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