UK Hydrological Outlook

Brief description of river flow forecasts using seasonal weather forecasts

2021

UKRI Natural Environment Research Council

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Revision date: 25th August 2021

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1 Foreword

This document describes one method of generating a seasonal river flow forecast that is used to inform the UK Hydrological Outlook (Prudhomme *et al.* 2017).

2 General methodology

A methodology for national hydrological outlooks has been developed which combines a hydrological model (Grid-to-Grid or "G2G") estimate of total subsurface water storage (in both soil and groundwater) across Britain with a range of Met Office seasonal rainfall forecasts to provide estimates of area-wide hydrological conditions up to a few months ahead. Bell *et al.* (2013) and Bell *et al.* (2017) provide a summary of the methodology, which is summarised in the technical description below.

For many areas, hydrological forecasts up to a few weeks or months ahead are dependent on accurate knowledge of the current storage of water in the landscape. This information provides the hydrological initial condition, or "initial state", from which future simulations will depart following changes in boundary conditions, consisting primarily of the weather and water consumption. For the Hydrological Outlook UK, the G2G estimate of subsurface water storage provides an initial condition of subsurface water in storage across the UK, derived using the most recent observations of rainfall and potential evaporation (PE).

This current G2G estimate of subsurface water storage not only provides an initial condition for forecasts, it can also provide up-to-date information about how wet or dry the landscape is. Based on this information, maps of "relative wetness and dryness" can be derived (Section 4) indicating areas where subsurface water storage is particularly high or low, and may be prone to flood or drought conditions in the coming days/weeks. During periods of drought, the link can be made between a deficit in subsurface water storage and a requirement for additional rainfall over subsequent months to enable subsurface water storage and river flow to return to mean monthly values (Section 4).

The G2G estimated hydrological initial condition provides a starting point from which estimates of water storage and river flows for 1-3 months ahead can be produced as perturbations from the initial state, driven by an ensemble of Met Office rainfall forecasts from the GloSea5 seasonal prediction system. The method used to make these forecasts is summarised in Section 5.

3 Technical description: The Grid-to-Grid (G2G) Model

G2G is a spatially-distributed hydrological model, used in Britain for both continuous simulation of river flows in a changing climate (Bell *et al*., 2007, 2009) and for real-time flood forecasting (Moore *et al.*, 2006; Cole and Moore, 2009)**.** The model is generally configured to a 1km^2 grid, with a 15-minute time-step, and is underpinned by digital spatial datasets of topography, soil/geology and land cover. Gridded time-series of (daily) precipitation and (monthly) potential evaporation are used as model input and area-wide, gridded time-series of river flows, runoff and soil-moisture are output from the model. Note that the G2G Model simulates natural rather than influenced flows and thus can appear to over- or under-estimate flows for heavily influenced catchments (e.g. those affected by effluent returns or abstractions for public water supply). A detailed description of G2G is presented in Bell *et al*. (2009), with a brief overview of the model's subsurface (soil and groundwater) storage formulation provided below.

For the production of a hydrological outlook, the G2G Model is run continuously over several years to produce an estimate of the most recent hydrological conditions across Britain, from which an estimate is made of the current depth of subsurface water storage as an "anomaly" from climatological mean monthly storage. Here, the depth of subsurface water storage consists of the sum of the unsaturated soil and the groundwater stores.

The soil water state is the volume of available water, V, stored in the unsaturated layer of the soil column of a grid cell of side length Δx. From continuity, $dV/dt = \Delta x^2(P - E - Q)$, with P precipitation, E actual evaporation and Q net outflow per unit area (which includes inflow from upstream cells, lateral flow to the next downstream cell, downward drainage to the saturated zone and saturation-excess surface runoff). Drainage is represented as a simple power law function of V, with two parameters based on soil hydraulic properties derived from the 1km resolution HOST dataset (Hydrology of Soil Types; Boorman *et al*., 1995). These data underpin the ability of the model to represent the spatial heterogeneity of subsurface storage: Bell *et al.* (2009) provides more details.

The groundwater state is the volume of available water, V_g, stored in the saturated zone of a grid cell, with drainage from the unsaturated soil column above providing groundwater recharge. A nonlinear function relates groundwater outflow to V_g. Note that while the configuration of soil-storage capacity to the HOST dataset associates an effective maximum to the soil-water volume V in each 1km grid cell, V_g is not limited in this way and its size will reflect the balance between antecedent recharge and groundwater outflow from the cell. The depth of water in groundwater storage thus arises from the balance between recharge and groundwater outflow over long periods, and while it is unlikely to correspond directly to a groundwater level observation, it can provide an indication of whether storage in the saturated zone is greater or less than the long-term average.

4 Technical description: Relative Wetness (previously known separately as Relative 'Wetness' & Relative 'Dryness')

The G2G hydrological model is run continuously over several years to produce an estimate of the most recent hydrological conditions across Britain, from which an estimate is made of the current depth of subsurface water storage (S, mm), consisting of the sum of the unsaturated soil (V) and the groundwater stores (V_g) (mm), i.e. $S = V + V_g$. The example storage anomaly map in Figure 1 shows daily mean subsurface water storage, S, as an "anomaly" from the historical monthly mean ($\bar{S}$, mean monthly storage over the period 1981 – 2010). The example map is predominantly blue in the north and west indicating a positive anomaly, i.e. with total subsurface water storage greater than the historical monthly mean.

Each month, to highlight areas that are particularly wet or dry, the total daily mean subsurface water storage (S, mm) is presented using a colour scale showing water storage anomaly relative to the historical maximum or minimum anomaly. Figure 1 presents this relative wetness map, which combines maps previously shown separately as the “relative wetness” and “relative dryness”.

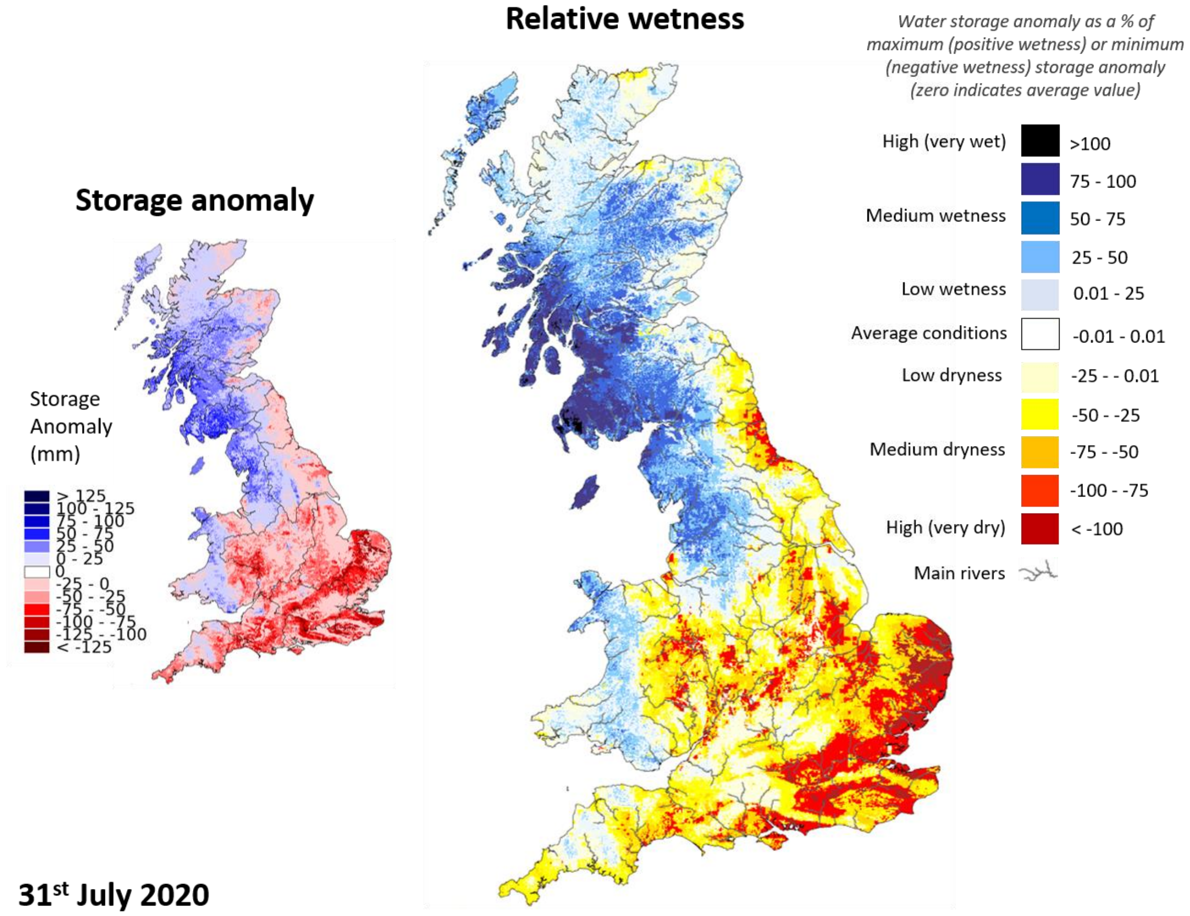

Figure 1. Subsurface storage anomaly and relative wetness for 31st July 2020.

Specifically: the relative wetness in the sub-surface, R_w (%), is expressed as an anomaly from the monthly mean (1981 – 2010) wetness at that location:

$$R_w = \begin{cases} (S - \bar{S}) / (S_{\max} - \bar{S}) * 100, & S \leq \bar{S} \\ (S - \bar{S})/(\bar{S} - S_{min}) * 100 & S > \bar{S} \end{cases}$$

A value of R_w = 0 indicates that the sub-surface water storage in the region matches the monthly average value. Places where R_w >0 and R_w <0 are wetter or drier, respectively, than is average for that month. Values where $|R_w|$>100 indicate the subsurface water storage is higher/lower than the previous maximum/minimum monthly mean storage estimated by the G2G over the period 1971 to 2010 (over all months), and is thus an unusually extreme value.

These maps do not provide a forecast, but the relative wetness can provide an indication of locations which are particularly wet or dry. Rainfall in areas with high positive relative wetness could result in flooding in the coming days/weeks. Areas of negative relative wetness provide an indication of locations which are particularly dry, and little or no rain in these areas could potentially lead to (or prolong) a drought.

5 Technical description: Products for dry/drought periods

For dry areas within a Hydrological Outlook region, i.e. where relative wetness <0, we estimate regional average subsurface water storage deficit (mm) from the last day of the most recent G2G model run. For each region we also estimate the regional monthly average rainfall total (mm) (for the period 1971-2000). These can be combined to provide an estimate of the return period of rainfall required to overcome any dry conditions (Figure 2). The procedure is outline below:

For each of the next 6 months, we estimate the rainfall total (including what is normally expected for each month) required to overcome the dry conditions.

- To overcome the dry conditions by the end of month 1:
  rainfall required (mm) = regional monthly average rainfall for month 1 + regional average storage deficit

- To overcome the dry conditions by the end of month 2 (more likely):
  rainfall required (mm) = regional monthly average rainfall for months 1 and 2 + regional average storage deficit

- To overcome the dry conditions by the end of month *n* (likely):
  rainfall required (mm) = regional monthly average rainfall for months 1 to *n* + regional average storage deficit

Using Tabony tables we estimate the return period of the rainfall required in each region and over the next 1 to 6 months to overcome the dry conditions. The return period results are displayed as regional maps (Figure 2) with the colour scale based on the return period (years) of the rainfall required to replenish subsurface stores over the next 1, 2, .., 6 months ahead. Note these maps do not provide a drought forecast. Instead they indicate the return period of rainfall required to overcome the dry conditions for the following 6 months based on current conditions.

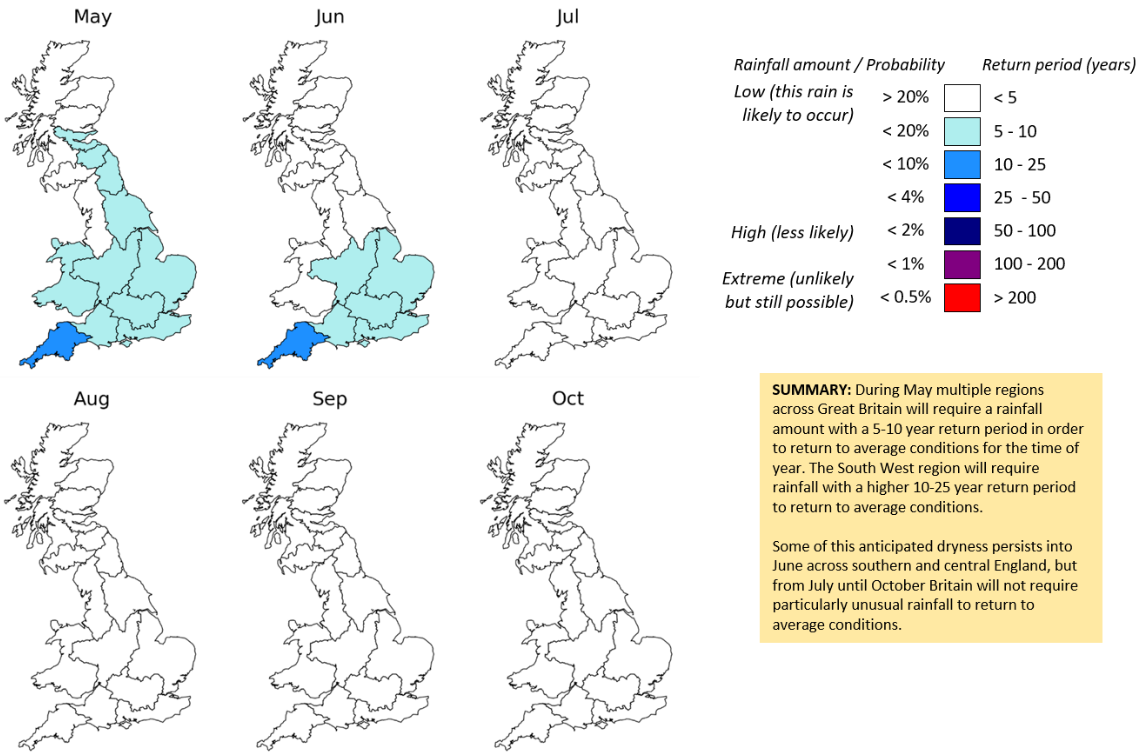

Figure 2. Return period of rainfall required to overcome the dry conditions (May-Oct 2021).

6 Technical description: G2G monthly mean flow estimates

The G2G Model estimates of monthly mean river flow for the most recent month (Figure 3) are also publically available on the Hydrological Outlooks website (https://hydoutuk.net/current-conditions). The flows are displayed on a 1km×1km grid in terms of percentile ranges of historical G2G flow estimates for that month. These provide bands of flows ranging from ‘Exceptionally high flow’ (>95%) to ‘Exceptionally low flows’ (<5%). Flows are considered ‘Normal’ if they are within a wide central percentile (28 to 72%).

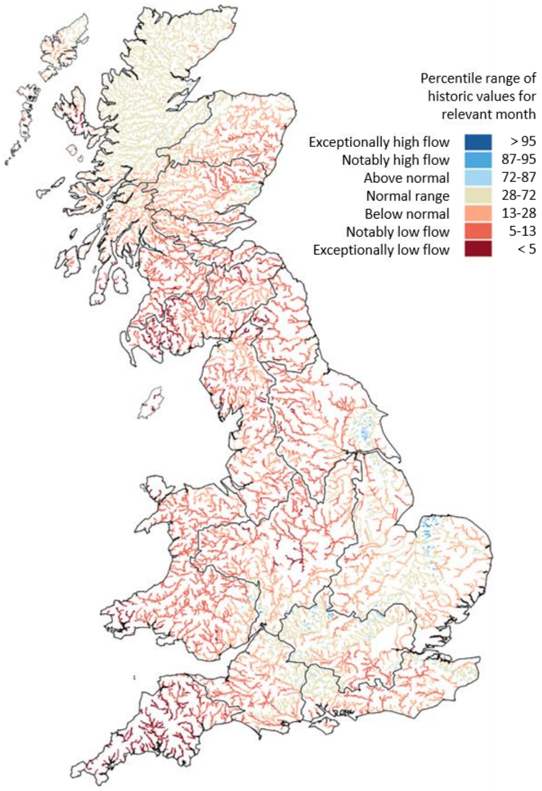

Figure 3. Monthly mean river flows simulated by the Grid-to-Grid hydrological model (April 2021).

7 Technical description: Seasonal hydrological forecasts

For the Hydrological Outlook, the G2G provides an initial condition estimate of subsurface water in storage across the UK, derived using the most recent observations of rainfall and PE. This initial condition is a starting point from which estimates of water storage and river flows for 1-3 months ahead can be produced as perturbations from the initial state, driven by Met Office rainfall forecasts.

At present the Met Office can provide an ensemble of weather variables at a seasonal (monthly) resolution (MacLachlan *et al.* 2015, Scaife *et al.* 2014) with a single value for each variable applicable to the whole of the UK. Thus, the high spatial and temporal variability observed in UK weather, particularly rainfall, is not represented. This presents a dilemma for hydrological modellers who typically require high spatial and temporal resolution weather information to estimate a water balance, and to represent the ephemeral nature of streamflow. An ensemble of mean UK rainfall forecasts provides no information on whether the rainfall is more likely to occur in the North or South, however, it does provide some indication of whether the rainfall totals will be higher or lower than the climatological mean (long-term average).

The current generation of Met Office monthly rainfall forecasts can only provide low-resolution temporal and spatial information (UK-scale and monthly). This has led to the development of 1- and 3- month ahead water-balance forecasts of subsurface storage (Bell *et al.* 2013, Bell *et al.* 2017) using UK-wide Met Office forecasts which have been expressed as a perturbation (or “anomaly”) from long-term monthly mean rainfall. The use of monthly rainfall anomalies in place of daily or sub-daily rainfall input removes any immediate requirement for temporal downscaling of seasonal rainfall forecasts, which are often provided as monthly totals.

The procedure used to prepare a UK hydrological forecast each month is summarised below:

1. The G2G has been run continuously from 1962 to the present day using observed weather data (daily, 1km precipitation and monthly PE data).

2. The G2G Model can be initialised by the end-states of a prior run (a scheme commonly used in flood forecasting). Thus the model can be kept up to date by running it forward every month, initialised with the end-states saved at the end of last month, and run forward using as input the latest month's rainfall and PE data.

3. The most recent end of month G2G subsurface storage estimate is used as the initial condition for a water-balance forecast of the next 1- and 3-months subsurface storage using Met Office rainfall forecast ensemble members and climatological PE as input (Bell *et al.* 2013, 2017).

4. The Met Office UK-scale monthly and 3-monthly resolution ensemble rainfall forecasts are converted to spatially uniform rainfall anomalies, a (mm) relative to Met Office model estimates of climatological mean rainfall. A spatially distributed UK monthly rainfall amount, P^* , is calculated as $P^* = \frac{P_{ij}}{\bar{P}}(\bar{P} + a)$, where $\bar{P}$ and P_{ij} are the UK-mean and the local (1km pixel) monthly mean rainfall (1981-2010) respectively.

5. Corresponding ensembles of regional river flow estimates for the next 1- and 3-months ahead can be estimated using a water balance hydrological model (Bell *et al.* 2017).

6. Forecast monthly and 3-monthly mean flows are scaled with reference to the long-term monthly mean flow (1981-2010), ranked in relation to 54 years of historical flow estimates (1963 – 2016) and coloured accordingly to one of seven bands, as shown in Figure 4.

7. In order to summarise the *(~40)*-member ensemble of equally-probably hydrological forecasts, 5 maps representing quartiles (4 bands of increasing magnitude) of rainfall (flow) forecasts are presented alongside the maximum and minimum forecasts.

8. This type of summary is similar to a box and whiskers summary plot of a distribution, and the resulting set of forecast maps illustrates the median, the inter-quartile range (1st to 3rd quartile) and the overall range (maximum and minimum) of the distribution of forecasts as shown in Figure 4.

9. There is a 25% chance of a forecast within each quartile and thus a 50% chance of a forecast within the 1st and 3rd quartiles, as shown in Figure 5.

10. Regional histograms (Figure 6) illustrate the full range of ensemble forecasts. They show the percentage of ensemble forecasts falling in each of the flow categories as generated by the monthly-resolution water-balance model. As before results are averaged by region then ranked in terms of 54 years of historical regional flow estimates (1963 – 2016).

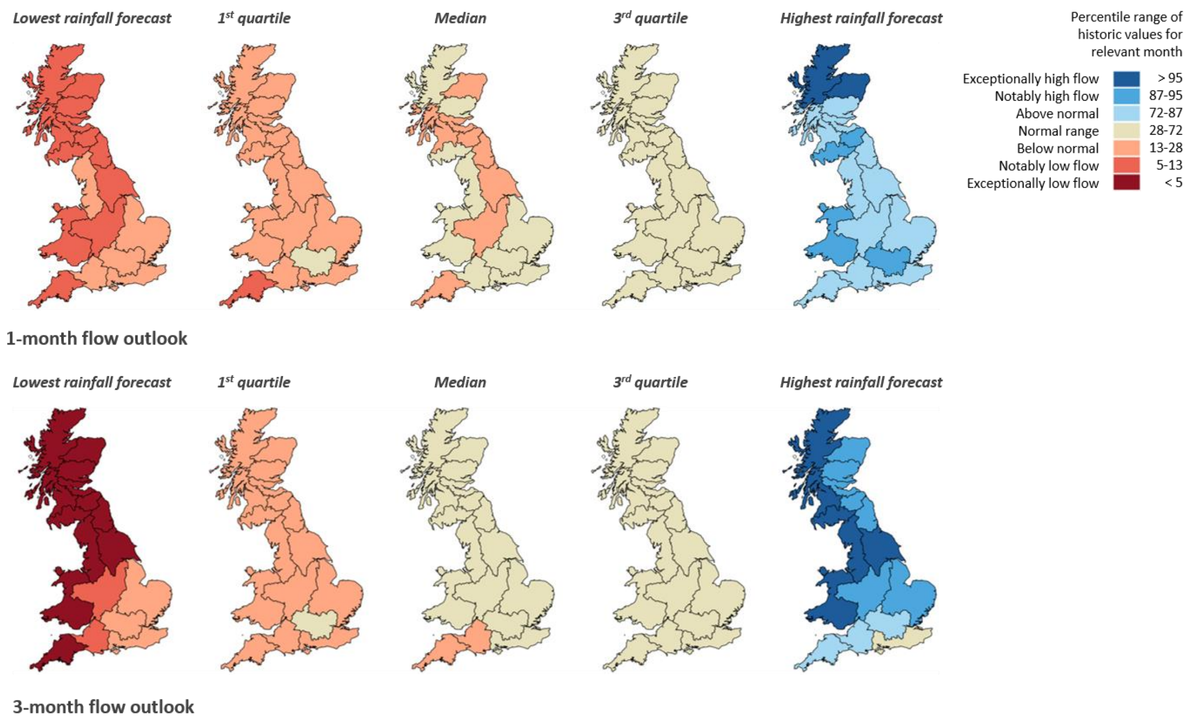

Figure 4. Regional river flow forecasts for May to July 2021 for five members of the Met Office ensemble of rainfall forecasts. The observed flows could be more extreme than the flows generated by either the lowest or highest members of the rainfall ensemble.

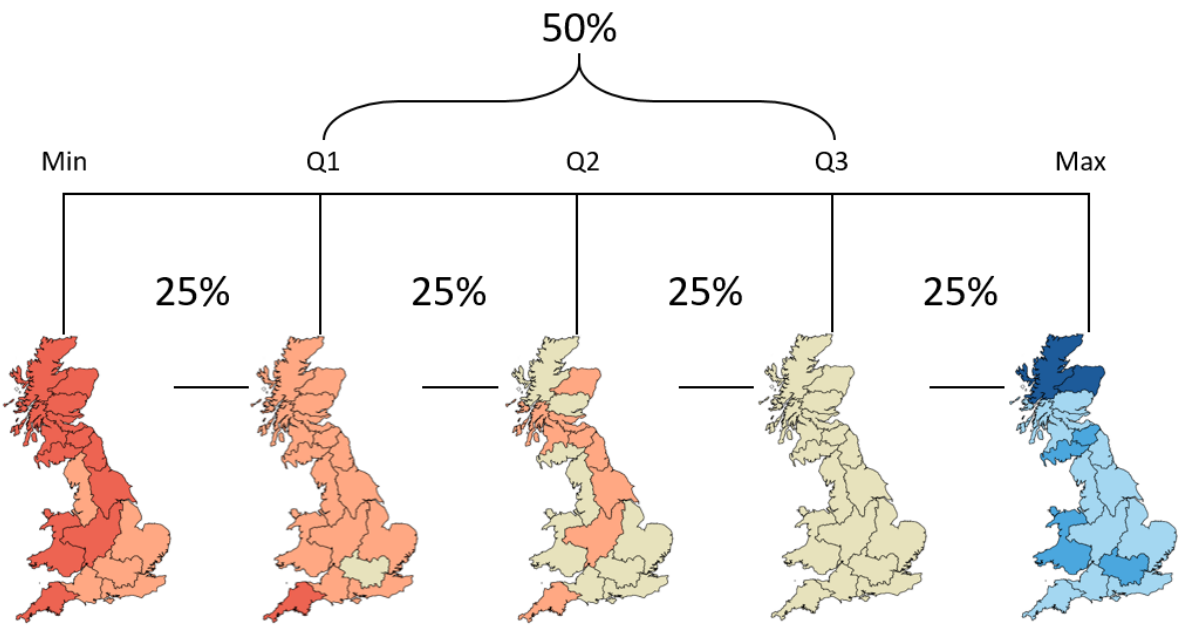

Figure 5. The probability of a forecast lying within the quartile bands.

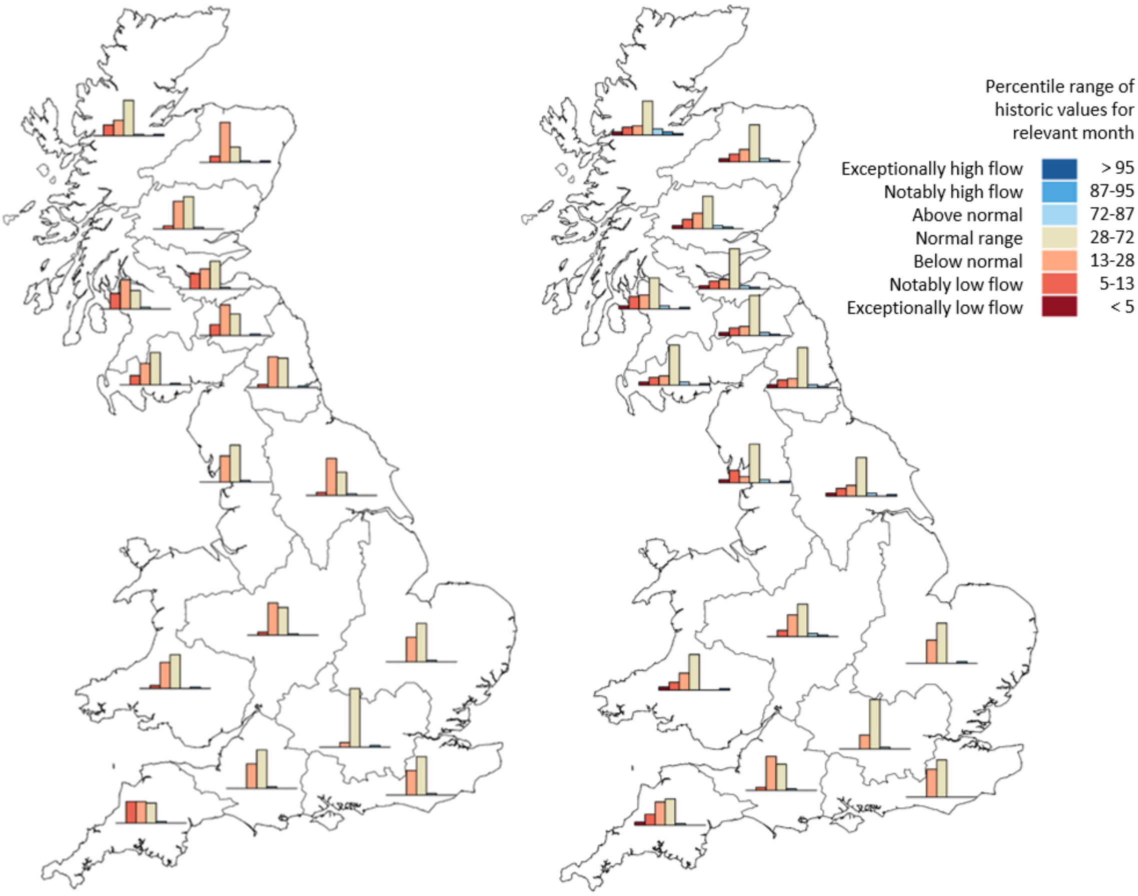

Figure 6. Regional histograms illustrating the full range of ensemble forecasts (1-month: May (left) and 3-month: May-June-July (right) 2021).

8 Interpretation of results

For the examples shown in Figures 4 to 6, the forecasts can be interpreted as follows:

SUMMARY: During May, river flows across the country are most likely to be in the *Normal range* or *Below normal.* Flows in the South West region are most likely to be in the *Normal range* to *Notably low.*

Over the next 3 months river flows across the country are most likely to be in the *Normal range* or below.

Typically, much of the spatial variability (~60%) in the 1-month ahead flow estimates arises from the hydrological initial condition at the start of the month as estimated by the G2G Model, combined with a model estimate of how much water the landscape can store (Bell *et al.,* 2017). For 3-month ahead forecasts, more of the forecast skill arises from the GloSea5 rainfall forecasts (~70%), particularly in the North and West of Britain. Note that any spatial variability arising from the use of the GloSea5 rainfall forecasts comes only from the imposed monthly mean UK rainfall distribution (Section 5, procedure item 4).

The hindcast analysis by Bell *et al.* (2017) also indicated that only very limited forecast skill is achievable for spring and summer seasonal hydrological forecasts driven by GloSea5 rainfall forecasts; however, autumn and winter flows can be reasonably well forecast using (ensemble mean) rainfall forecasts from GloSea5, particularly for 3-months ahead.

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