UK Hydrological Outlook

Technical description of the seasonal hydrological forecasts produced using the G2G-WBM model

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Authors

Victoria Bell, Helen Davies, Mark Rhodes-Smith, Alison Rudd and Rhian Chapman, UK Centre for Ecology & Hydrology

Publication Address

UK Centre for Ecology & Hydrology
Maclean Building
Benson Lane
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB
UK

General and business enquiries: +44 (0)1491 692562
E-mail: enquiries@ceh.ac.uk

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Contents

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 which 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 rainfall forecasts from the Met Office GloSea6 seasonal prediction system. The method used to make these forecasts is summarised in Section 7.

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

The G2G hydrological model is run continuously over several years to produce an estimate of the most recent hydrological conditions across Britain, from which estimates are made of the current depth of total subsurface water storage (S, mm), consisting of the sum of the unsaturated soil (V) and the groundwater stores (V_g) (mm), i.e. $S = V + V_g$, and of the unsaturated soil store, which are both provided in the Outlook as storage anomaly maps. An 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".

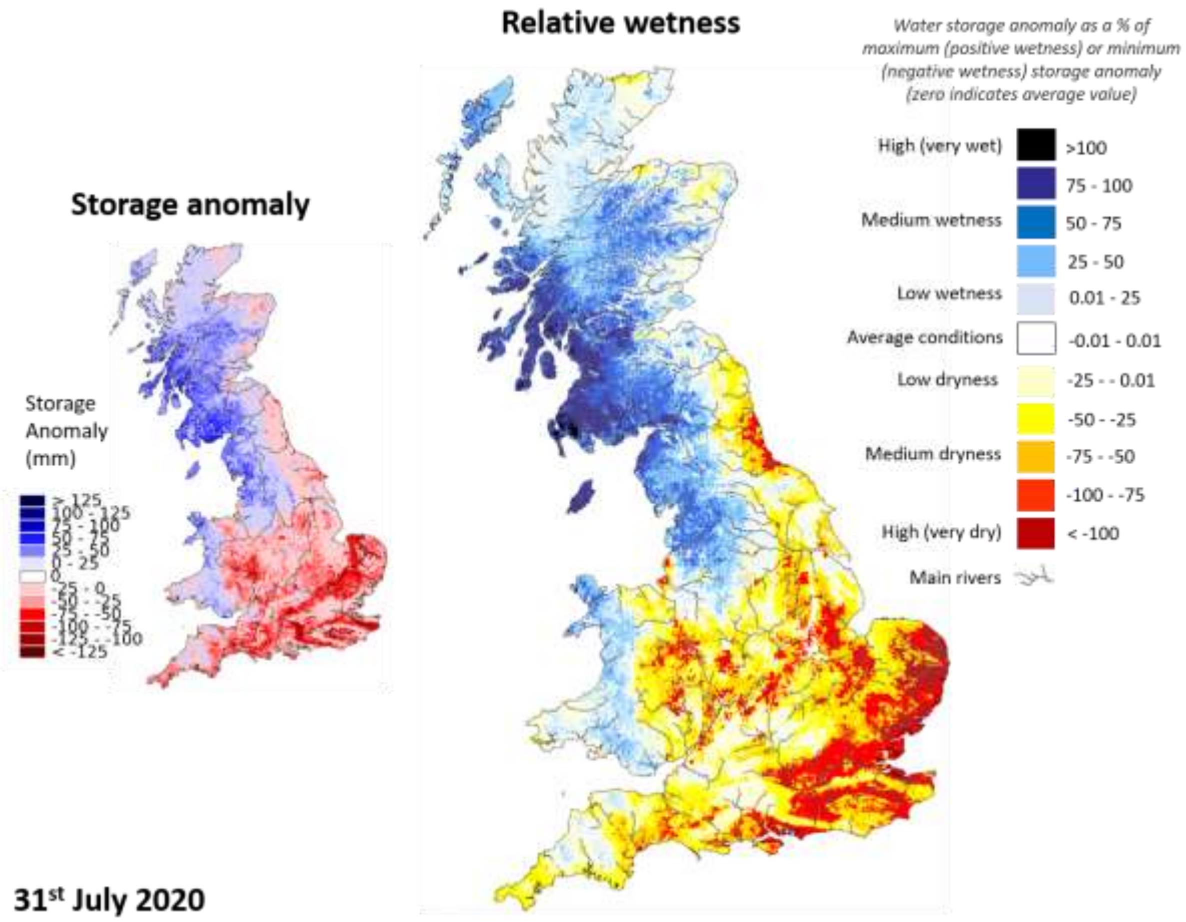


Figure 1. Subsurface storage anomaly and relative wetness for 31st July 2020.

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:

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

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.

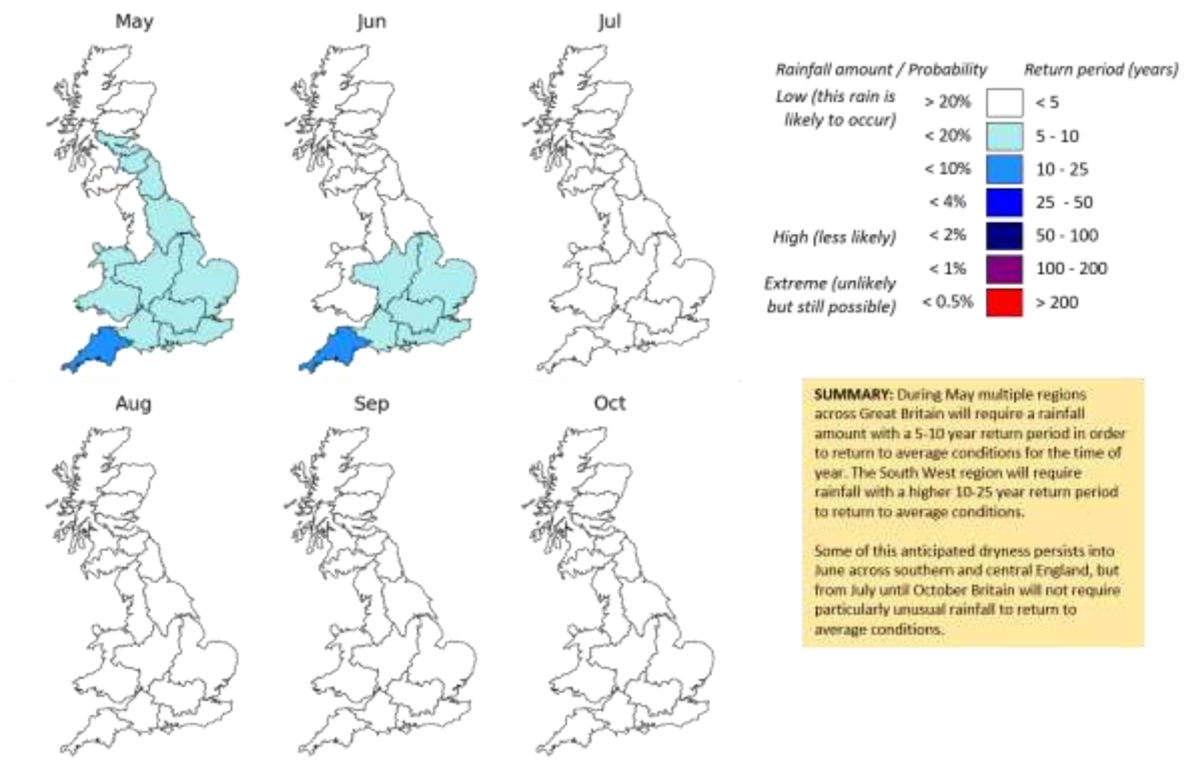


Figure 2. Return period of rainfall required to overcome the dry conditions (May-Oct 2021).

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 publicly 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%).

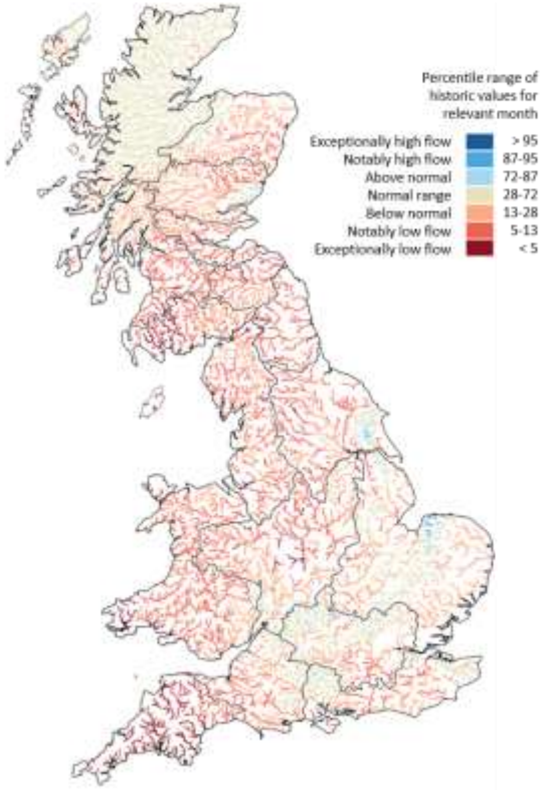


Figure 3. Monthly mean river flows simulated by the Grid-to-Grid hydrological model (April 2021).

7 Technical description: Seasonal hydrological forecasts

For the Hydrological Outlook, the G2G model provides an estimate of subsurface water in storage across the UK, derived using the most recent observations of rainfall and PE (as described in Section 3). These estimated stores are the initial conditions (the starting point) from which estimates of water storage and river flows for 1-3 months ahead can be produced. These forecasts are driven by rainfall forecasts from the Met Office.

Previously (before December 2023), the Met Office provided an ensemble consisting of total monthly rainfall values averaged across the whole of the UK (MacLachlan *et al*. 2015, Scaife *et al.* 2014). These have recently been improved to provide much larger ensembles of spatially-distributed forecasts, based on Atmospheric Circulation Analogues (hereafter ACA; Stringer *et al.* 2020), which are described in detail elsewhere in the HOUK documentation. Rhodes-Smith *et al.* (in prep.) provide a greater discussion of the performance of these forecasts, while here we give only a brief description of how these rainfall forecasts are used.

In the ACA rainfall forecast scheme, each ensemble member consists of a simulated rainfall sequence constructed from those observed in years with similar atmospheric conditions to those forecast. At each forecast period (one-month or three-months ahead), the simulated rainfall sequence consists of three sub-sequences drawn from the corresponding period of three analogue years, such that a one-month forecast consists of two ten-day sub-sequences and one sub-sequence that completes the month, while a three-month forecast consists of three one-month sub-sequences. The forecast rainfall sequences are detrended to correct for climatological variation between the year in which they occurred and the present.

Although a hydrological modeller would typically prefer higher temporal resolution, the individual sequences of daily rainfall do not contain meaningful forecast information at that resolution, and thus are aggregated to monthly totals, which are used as an input to the water balance model described below. 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 inputs 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 ACA rainfall forecast ensemble members and climatological PE as inputs (Bell *et al.* 2013, 2017).

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

5. 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. This is done for each 1km grid cell, for every member of the forecast ensemble. Thus the output from the model consists of (~400) 1km-resolution maps, with each grid cell assigned a value between 1 and 7 describing its river flows (1=exceptionally low flow, 4=normal flow, 7=exceptionally high flow).

6. Displaying spatially-distributed probability density functions in any 2D map is challenging, therefore we produce summary products tailored to different use cases. The G2G/WBM contribution to the monthly Hydrological Outlook publication consists of three products:

    a. **Probabilities of extreme conditions:** Maps of either England and Wales or Scotland that indicate the probability that each region experiences widespread extreme conditions, as described below.

    b. **Histograms of regional flow distributions:** A histogram for each region showing the distribution of the regionally-averaged forecast ensemble.

    c. **Table of regional flow distributions**: The data shown in the histogram, provided in a tabular format.

7. In addition to the published summaries, some further products are provided on the Hydrological Outlooks portal. These are:

a. **Histograms of 1km flow distributions:** A histogram for every grid cell, showing the distribution of forecast ensemble members.

b. **Histograms of regional flow distributions**: As described for the written publication.

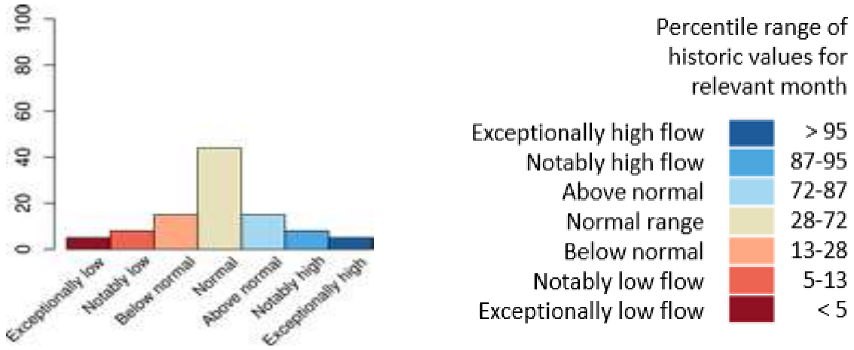


Figure 4. Flow categories used in the Hydrological Outlook with the historical (expected) distribution shown as a histogram.

8 Standard forecast products

The WBM-based forecast products published as standard in the Outlook are described below.

8.1 Probability of extreme river flows

- Use this page if you are making decisions on a national or multi-regional scale and require an alert of forecast extremes (floods and droughts) and how widespread they may be.

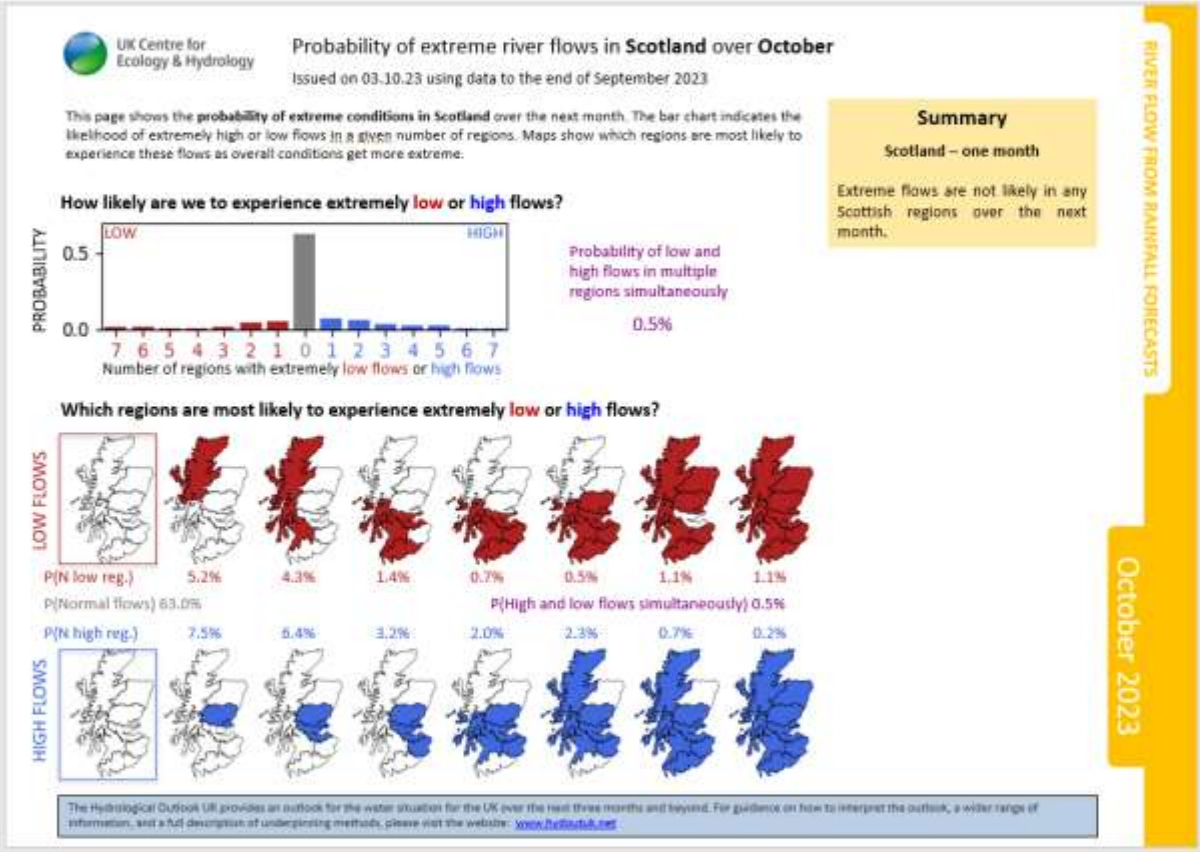


Figure 5. Page showing the probability of extreme conditions in Scotland over the next month (October 2023), taken from the unpublished prototype Outlook for that month.

The four pages in this format show the probability that extreme conditions are observed in either Scotland or England & Wales over the next one or three month periods. These serve as a 'national' perspective on flow forecasts. They are designed to help identify regions where high or low flows are more probable, and thus summarise the full model outputs at these scales. They are unlikely to be useful if you want to know about risks at more localised scales, where the 1km outputs provided through the Portal are recommended.

The "Probability of extreme river flows" product consists of three elements: a summary, a histogram and a 'ribbon' of maps. These are explained below.

Summary:

Figure 6: Example summary box, as appears on many pages. This is completed by UKCEH staff.

The summary box provides a top-level overview and interpretation of what this page is telling us this month. It is written each month by the UKCEH staff member who has run the model. There are separate summaries provided for each page.

Histogram:

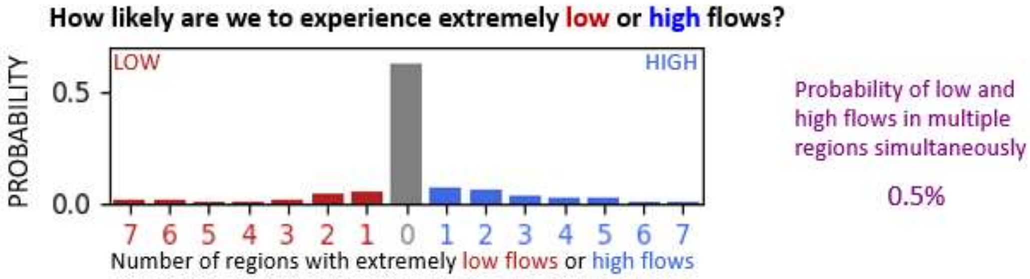


Figure 7: Histogram from the extreme river flows page, this extracted from the page shown in Figure 5.

The histogram shows the probability distribution for extremely high or low flows being observed in each number of regions over the forecast period. 'Extremely' high or low flows are defined as being in the most extreme 13% of flows observed over the historical period used to calibrate the model, currently 1963-2016. This definition corresponds to the 'Exceptionally high/low' and 'Notably high/low' categories used elsewhere in the Outlook.

It is produced by calculating the regional average of the 1km flow fraction (forecast flow / monthly mean flow over the historical period) and then ranking this regional flow fraction according to those observed over the historical period. For each member of the forecast ensemble, the number of regions with extremely high and low flows are counted and the ensemble member is then assigned to one of the 15 (21 for England & Wales) histogram bins. Ensemble members that exhibit at least one region with extremely high flows *and* at least one region with extremely low flows are not added to the histogram, but are noted in the purple text alongside the map. If this comprises a significant part of the probability distribution, the summary box will describe how to interpret this information.

In a 'normal' month, a relatively small number of regions are likely to experience extreme flows (typically of order 1-2). However, if the histogram shows a high probability that a large number of regions are likely to experience extreme flows, it may be appropriate to consider whether any preparatory action is needed. It should be noted that these are probabilistic forecasts, and thus extreme conditions are expected to occur occasionally even when the model predicts a low probability of occurrence.

'Ribbon' plots

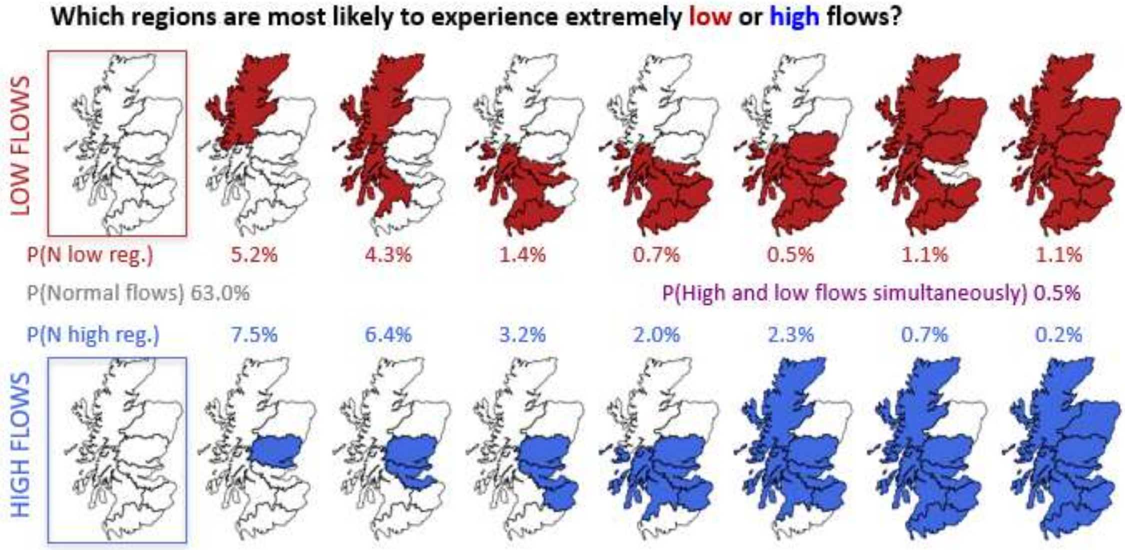


Figure 8: Example ribbon plot, this extracted from the page shown in Figure 5.

The 'ribbon' plot summarises which regions are more likely to experience extremely high or low flows. Regions that appear blue/red in lots of the maps are more likely to experience high/low flows than regions that appear in only a few maps. The ribbon also shows the overall forecast distribution again using the percentages below/above each map. Note that the percentage does not show the probability that the exact combination of regions shown on the corresponding map experience high/low flows, but only the probability that that *number* of regions experience extremely high/low flows. Thus, in the example above (October 2023), the probability that exactly 1 region in Scotland experiences extremely low flows is 5.2%, but this does not imply that the Highlands have a probability of 5.2% of experiencing extremely low flows.

The red/blue box drawn around some maps indicates the central 50% confidence interval. In this case, it suggests that the central 50% encompasses non-extreme flows in all regions and up to one region experiencing extremely high flows. Note that since the box is drawn around entire maps, the total probability encompassed in this range may not sum to 50% due to rounding errors. In the above (extreme) case, the box actually encompasses the range from the 14.3rd percentile to the 77.7th percentile, which is the nearest to the 50th percentile that can be drawn given the distribution. We reiterate that as these are probabilistic forecasts, we only expect 50% of real months to fall within this confidence interval, such that 50% of months show more extreme conditions.

The regions coloured on each map are those thought most likely to experience the extremely high/low flows in the case in which at least that many regions experience extreme flows. Technically, for the n^{th} map, the subset of the ensemble in which at least n regions experience extreme flows are selected. Within this subset, each region is given a probability that it experiences extreme flows, corresponding to the number of ensemble members in which it appears divided by the size of the subset. The corresponding map is then generated by colouring in the n most probable regions. This shows greater sequential coherence between adjacent maps than simply taking the subset with exactly n regions with extreme flows, which suffers from the small size of each subset. Tests over 2023 have shown that this approach is generally successful in indicating which regions experience extreme flows.

8.2 Histograms of regional flow distributions

- Use this page if you are making decisions for only one region.

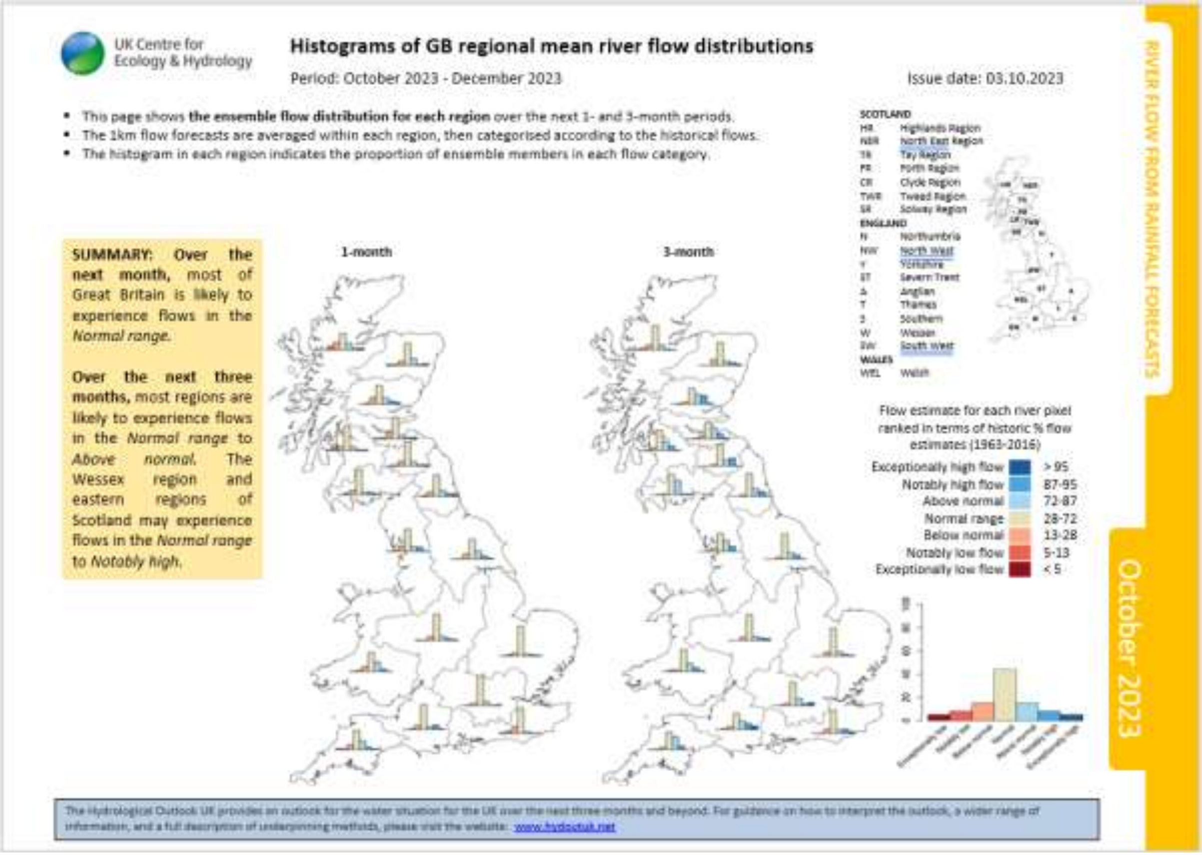


Figure 6. Regional histograms illustrating the full range of ensemble forecasts (left: 1-month forecast for October 2023; right: 3-month forecast for October-November-December 2023).

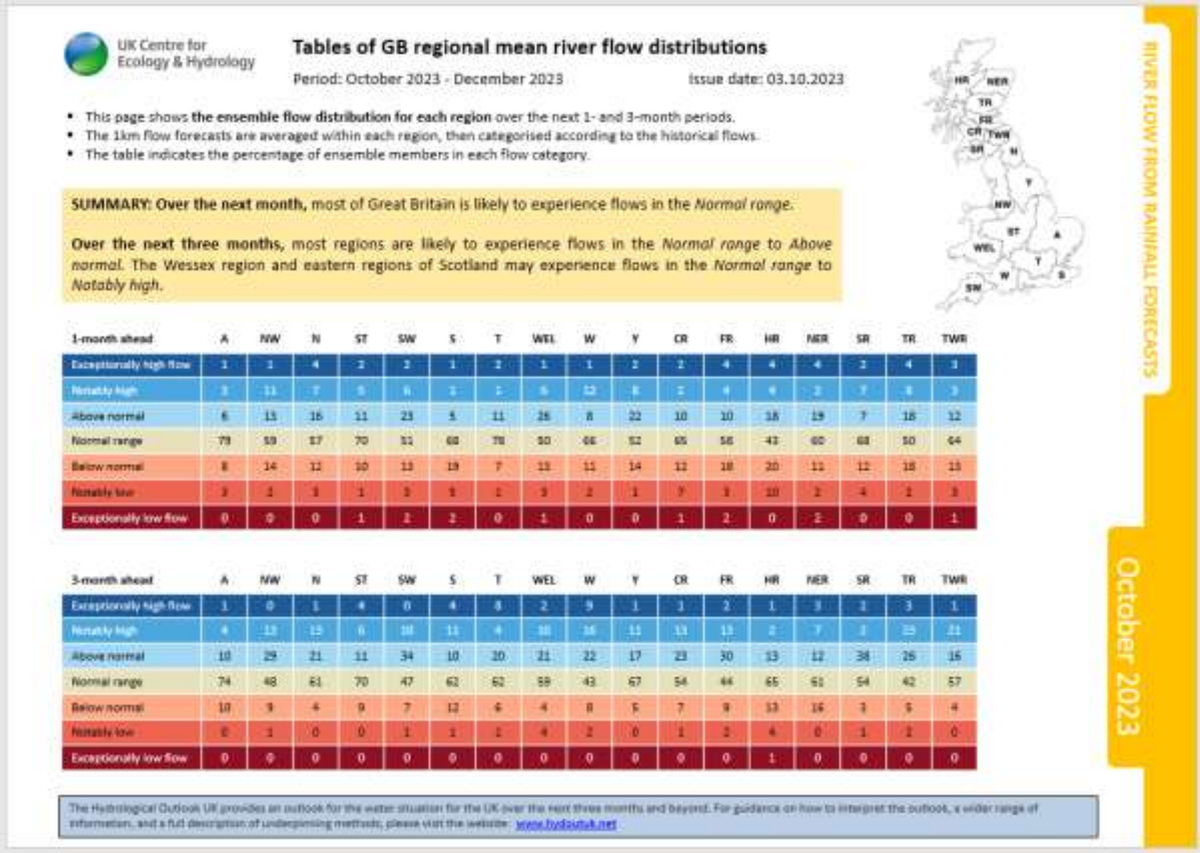
This page shows the distribution of ensemble members for each region. Formally, for each ensemble member, the 1-km flow fractions (forecast flow/observed flow over the historic reference period, currently 1963-2016) are averaged within the region, and then ranked according to the historical distribution of the same quantity. The histogram drawn over each region then shows the distribution of these ranked regional averages. The expected (historical) distribution is shown on the left of the page. A summary is provided by UKCEH staff in the yellow box.

This page, from the October 2023 forecast, for instance, indicates that over the next month most regions are likely to see normal distributions of river flows, with greater confidence that southern England will see normal flows (indicated by the more central probability distribution). Over the next three months, however, high flows become more likely (indicated by the longer tail into the above normal ranges). This might be interpreted as suggesting that October is likely to see normal flows, which are likely to increase in November and December by a larger change than would be expected historically. In turn, this might be taken to indicate a wetter than average winter, especially for the eastern parts of Scotland where notably high flows are possibles.

It should again be emphasised that these are probabilistic forecasts, and that rare events do happen. Please also remember that this model simulates natural flows at monthly timescales, and thus ‘flash’ events are not captured.

8.3 Table of regional flow distributions

- Use this page if you are making decisions for one region *and* you want access to the raw numbers.



- This page shows **the ensemble flow distribution for each region** over the next 1- and 3-month periods.
- The 1km flow forecasts are averaged within each region, then categorised according to the historical flows.
- The table indicates the percentage of ensemble members in each flow category.

SUMMARY: Over the next month, most of Great Britain is likely to experience flows in the *Normal range*.

Over the next three months, most regions are likely to experience flows in the *Normal range* to *Above normal*. The Wessex region and eastern regions of Scotland may experience flows in the *Normal range* to *Notably high*.

1-month ahead	A	NW	N	ST	SW	S	T	WEL	W	Y	CR	FR	HR	NER	SR	TR	TWR
Exceptionally high flow	1	1	4	2	2	1	2	1	1	2	2	4	4	4	2	4	3
Notably high	3	11	7	5	6	1	1	5	12	8	2	4	4	2	7	3	3
Above normal	6	13	16	11	23	5	11	26	8	22	10	10	18	19	7	18	12
Normal range	79	59	57	70	51	68	78	50	66	52	65	56	43	60	68	50	64
Below normal	8	14	12	10	13	19	7	13	11	14	12	18	20	11	12	18	13
Notably low	3	2	3	1	3	5	1	3	2	1	7	3	10	2	4	2	3
Exceptionally low flow	0	0	0	1	2	2	0	1	0	0	1	2	0	2	0	0	1

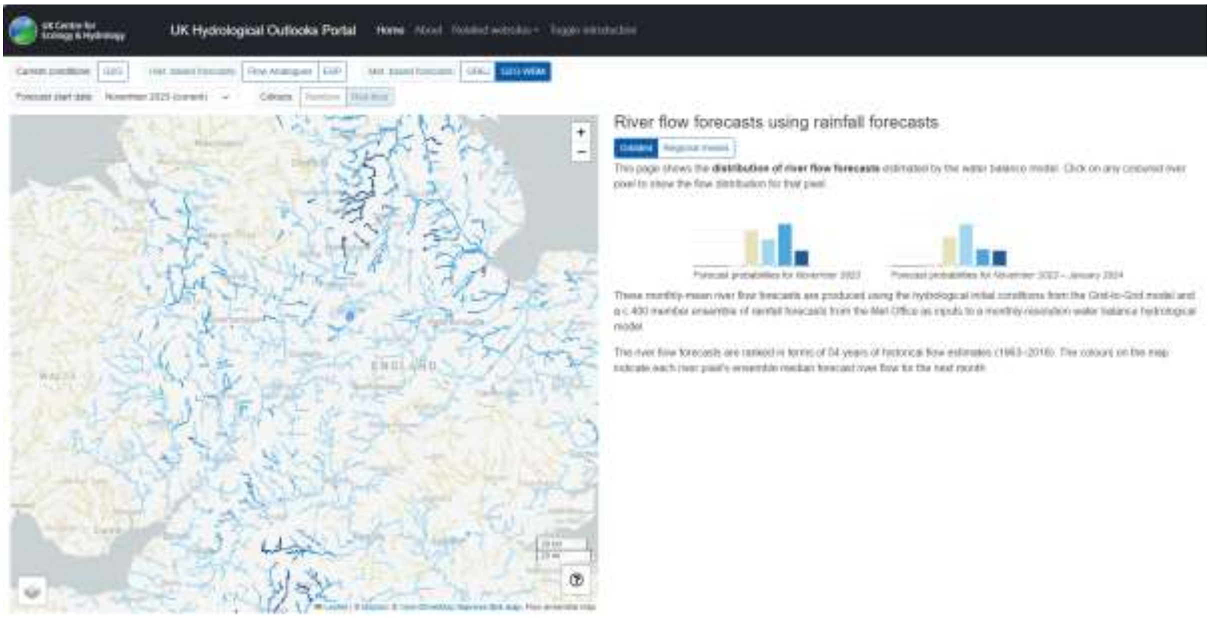
3-month ahead	A	NW	N	ST	SW	S	T	WEL	W	Y	CR	FR	HR	NER	SR	TR	TWR
Exceptionally high flow	1	0	1	4	0	4	8	2	9	1	1	2	1	3	2	3	1
Notably high	4	13	15	6	10	11	4	10	16	11	13	13	2	7	2	15	21
Above normal	10	29	21	11	34	10	20	21	22	17	23	30	13	12	38	26	16
Normal range	74	48	61	70	47	62	62	59	43	67	54	44	65	61	54	42	57
Below normal	10	9	4	9	7	12	6	4	8	5	7	9	13	16	3	5	4
Notably low	0	1	0	0	1	1	1	4	2	0	1	2	4	0	1	2	0
Exceptionally low flow	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

The Hydrological Outlook UK provides an outlook for the water situation for the UK over the next three months and beyond. For guidance on how to interpret the outlook, a wider range of information, and a full description of underpinning methods, please visit the website: www.hydoutuk.net

The information on this page mirrors the regional histograms on the previous page. The yellow summary box is written by UKCEH staff and will be identical to the previous page. The table shows the percentage of ensemble members in each flow band (rows) for each region (column). Thus each column should sum to 100%, to within rounding errors. A probability of 0 suggests that a particular condition is unlikely, but does not mean that it is impossible. More formally, it suggests that the probability is less than about 0.25%. This means that it is likely to occur about once every 400 months (about every 30 years).

8.4 Histograms of 1km flow distributions (Portal only)

- Use this product if you are making decisions at a local (1km) scale.



This product is only made available via the Hydrological Outlooks portal. It comprises a map showing the median 1-month forecast flow scenario for each river pixel. Note that this is a pixel-by-pixel ensemble median, and thus the map does not show a spatially coherent scenario. There are also two histograms that show the distribution of flows for the selected pixel.

To use this product, click on any river pixel (one that is coloured in). The histograms will automatically update to show the probability distributions of flows in this pixel.

9 Interpretation of results

Hindcast analyses have been performed by Bell *et al.* (2017), using the older spatially-invariant rainfall forecasts, wherein most of the skill was derived from the hydrological initial conditions rather than the rainfall forecasts. The subsequent analysis by Rhodes-Smith *et al.* (in prep) shows that the improved rainfall forecasts described in Section 7 show improved skill along the west coast of England, Wales and Scotland in Autumn and Winter.

The hindcast analyses of Bell *et al.* (2017) and Rhodes-Smith *et al.* (in prep) show that the model shows limited skill in spring and summer, with skill mainly derived from the hydrological initial conditions, and thus better performance in regions that are more responsive to stored water than to rainfall. However, autumn and winter flows can be reasonably well forecast, particularly for 3-months ahead.

10 References

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