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# Developing a large-scale water-balance approach to seasonal forecasting: application to the 2012 drought in Britain

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## Abstract:

Seasonal hydrological forecasts, or outlooks, can potentially provide water managers with estimates of river flows and water resources for a lead-time of several months ahead. An experimental modelling tool for national hydrological outlooks has been developed which combines a hydrological model estimate of subsurface water storage across Britain with a range of seasonal rainfall forecasts to provide estimates of area-wide hydrological conditions up to a few months ahead. The link is 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. The new scheme is assessed over a recent period which includes the termination of the drought that affected much of Britain in the first few months of 2012. An illustration is provided of its use to obtain return-period estimates of the "rainfall required" to ease drought conditions; these are well in excess of 200 years for several regions of the country, for termination within a month of 1 April 2012, and still exceed 40 years for termination within three months. National maps of subsurface water storage anomaly show for the first time the current spatial variability of drought severity. They can also be used to provide an indication of how a drought situation might develop in the next few months given a range of possible future rainfall scenarios.

## INTRODUCTION

The drought that affected much of Britain during the early months of 2012 followed a two year period during which the synoptic patterns that usually bring rain-bearing low pressure systems to southern Britain from the Atlantic followed a different, more northerly course. Rainfall for England over the 27 months from January 2010 was the lowest (in this timeframe) in a rainfall series from 1910, and greatly accentuated the normal north-west to south-east rainfall gradient across the UK. By the spring of 2012 drought conditions were exceptionally severe: overall runoff from England & Wales for March was the lowest in a series from 1961, estimated storage in the Chalk aquifer (the major water supply source in much of the drought-afflicted region) was lower than during the extreme drought of 1976 and stocks in some reservoirs in southern England were below half of capacity. With lowland soils at their driest for late March on record, the drought also impacted severely on agriculture, the environment and wildlife (reflecting the desiccation of wetlands and the seasonally extreme contraction in the stream network).

Late spring heralded a major and sustained change in weather conditions as the jet stream adopted a more southerly track. The April-July rainfall total for England & Wales exceeded the previous maximum in the 113-year national series by a considerable margin (CEH and BGS, 2012). As a consequence, the normal seasonal decline in spring river flows was dramatically reversed and the focus of hydrological stress switched rapidly from drought to the risk of widespread flooding. Such a transformation during the late spring and early summer is at the extreme range of variability captured in the instrumented era, and has no close modern parallel in the UK.

The fragile water resources outlook in the early spring of 2012 triggered a series of measures to moderate the drought's effects (e.g. additional water transfers, augmentation of low flows, fish rescues and public appeal to moderate water usage). In early April these were supplemented by hosepipe bans affecting around 20 million consumers in eastern, central and southern England. It is possible that some of these measures might not have been needed had an effective seasonal hydrological forecast been available, as such forecasts can potentially provide an estimate of river flows and water resources for a lead-time of several months ahead. A number of authors have explored the potential for seasonal hydrological forecasting in the UK, with many investigating statistical relationships between large-scale North Atlantic climate indices (such as the North Atlantic Oscillation) and seasonal rainfall or river flow anomalies (Lavers *et al.*, 2010a,b; Macgregor and Phillips, 2004; Svensson and Prudhomme, 2005; Wedgebrow *et al.*, 2002; Wilby, 2007). Lavers (2010) is one of the few to have explored direct use of coupled ocean-atmosphere model output with hydrological models for seasonal hydrological forecasting in the UK, perhaps because of the perceived lack of skill in seasonal weather forecasts in extratropical regions beyond a lead time of 1 month (Lavers *et al.*, 2009).

For many areas, particularly those with a long "hydrological memory", such as lakes and aquifers, hydrological forecasts can potentially be considered an initial value problem, where 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 (HIC), or "initial state", from which future simulations will depart following changes in boundary conditions, consisting primarily of the weather and water consumption. The relative importance of initial conditions and boundary forcing (the meteorological forecast) on the skill of seasonal hydrological prediction has been examined recently by a number of authors. In one of the few such comparison studies to include the UK, Bierkens and van Beek (2009) concluded that much of the skill in forecasting mean seasonal river flows across Europe (out to 6-months ahead) could be attributed to correct hydrological initial conditions, rather than particular skill in the weather forecast. A number of studies in the USA also conclude that knowledge of the initial condition is key to forecast accuracy, particularly for forecasting at a lead time of one month (Shukla and Lettenmaier, 2011), but that the relative importance of the HIC persists for longer in regions where interannual variation in surface and soil-moisture water storage is large compared to precipitation (Mahanama *et al.*, 2012) and in particular regimes where baseflow or the timing of snowmelt are important (Wood and Lettenmaier, 2008). Sinha and Sankarasubramanian (2012) investigated the benefits of using both climatological ensemble and forecast precipitation anomalies with a good HIC for a large catchment in the USA. While they were able to quantify the additional skill that came from using precipitation forecasts, they stressed the importance of focussing future effort on use of a forecast ensemble to provide a probabilistic hydrological forecast ensemble. The Hydrologic Ensemble Prediction Experiment (HEPEX) represents an international effort in this area that embraces seasonal forecasting for water resource management (http://www.hepex.org/).

Given the perceived importance of the HIC in seasonal hydrological forecasting, particularly in catchments/regions with a longer hydrological memory, the question arises as to how much useful information can be gained from a good quality estimate of the most recent hydrological condition. The drought that affected southern Britain during the early months of 2012, and its dramatic conclusion following several months of heavy rainfall, has provided a suitable platform to test these ideas using a countrywide hydrological model (Grid-to-Grid, or G2G) driven by up-to-date daily rainfall data and monthly estimates of potential evaporation (PE). Here, the 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. The approach is similar to the drought monitoring index used by Luo and Wood (2007) to estimate anomalies in soil-moisture, but here the anomaly is estimated for total column water storage, which additionally includes unsaturated and saturated-zone storage. During extended periods of rainfall deficit, resulting storage anomalies can provide an estimate of the additional rainfall required over subsequent months to enable subsurface stores and river flows to return to mean monthly values. These estimates of "required rainfall" can be compared to historical records to determine a likelihood (or return period) of occurrence. Such an analysis would lend itself more to a qualitative 'outlook' than a quantitative forecast in the first instance, but could also be combined with (an ensemble of) seasonal weather forecasts or historical analogues to provide a more traditional seasonal hydrological forecast.

The next section provides a summary of the G2G hydrological model, followed by a description of how it can be used to estimate the anomalies in total water stored below the surface of the landscape.

This is followed by a temporal and spatial assessment of the "water-balance anomaly" approach to seasonal forecasting for a period including the drought that affected southern Britain in the first few months of 2012. It serves to illustrate the use of the methodology to provide return-period estimates of "rainfall required" to ease drought conditions back to normal. An ensemble of seasonal rainfall forecasts is also used to illustrate the potential of the water-balance anomaly approach to provide a hydrological outlook up to a few months ahead.

## METHODOLOGY

### 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*., 2007b, 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 across the UK, with a 15-minute time-step, and is underpinned by digital spatial datasets on topography, soil/geology and land cover. Gridded time-series of precipitation and 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. 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.

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 $\Delta x$. 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). Soil water storage capacity within each cell is assumed to vary from point to point according to a probability distribution function, following Moore (1985): this ensures that a cell generates realistic quantities of saturation-excess surface runoff even when not fully saturated. 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 (Hydrology of Soil Types; Boorman *et al*., 1995) dataset. These data underpin the ability of the model to represent the spatial heterogeneity of sub-surface 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 historical mean levels. For use in the water-balance anomaly approach, the water depths of unsaturated soil and groundwater storages is combined to provide a single estimate of change in "sub-surface water storage". Thus during a drought period, a recovery in G2G modelled subsurface storage provides an indication of recovery in both groundwater and in water in transit through the unsaturated zone, thus potentially providing advanced warning of whether the landscape has already received sufficient excess rainfall to recover from drought, even if the water has not yet replenished groundwater levels.

Split sample calibration and assessment of the G2G model for 42 UK catchments was undertaken by Bell *et al.* (2009), where the G2G model formulation used here was referred to as "Soil-G2G". When model-simulated river flows were compared to daily observed river flows, the median $R^2$ Efficiency performance measure - sometimes referred to as the ''Nash–Sutcliffe Efficiency" (Nash and Sutcliffe, 1970) - was 0.7 (a value of 1 indicates perfect agreement, 0 indicates the model simulation is only as good as using the mean flow value for the whole period whilst negative values arise if the flow simulations are worse than that provided by the mean flow). Overall, the model simulates river flows well for a wide range of catchments, and very well for many catchments having a natural flow regime and for which the flow record is believed to be accurate. A model assessment specifically focussing on periods of drought is in preparation, as is a paper validating G2G estimates of soil moisture against observational data.

**Data and study area**

The G2G Model employs as input gridded time-series of precipitation and PE. Precipitation data in this case were daily totals on a 5km grid, derived from raingauge data by the Met Office for the period 1958 to present. PE data were monthly totals on a 40 km grid, obtained from the Met Office Rainfall and Evaporation Calculation System (MORECS; Hough and Jones, 1997). Rainfall data are downscaled to the 1km G2G grid using information on Standard Average Annual Rainfall, to incorporate more topographic variability (Bell et al. 2007a); 40km PE data are simply copied down to the 1km grid, as PE is less spatially variable than rainfall. Both daily rainfall and monthly PE are spread equally over the 15-minute G2G time-step required for model stability, but model output of river flow is averaged and assessed at a daily time-step.

A temporal assessment of the water-balance approach to seasonal forecasting, reported later, has been undertaken for three contrasting catchments in England: the Kennet at Theale (39016), a 1033 km$^2$ catchment for which the flow-regime is groundwater-dominated; the Eden at Sheepmount (76007), a 2287 km$^2$ catchment with variable geology including carboniferous limestone in the headwaters and boulder-clay over sandstone in the lowlands; and the Avon at Evesham (54002), a 2210 km$^2$ catchment of low relief underpinned by sedimentary (argillaceous) geology. Assessment of the methodology is also demonstrated spatially by comparing maps of G2G modelled water storage anomaly obtained using observed rainfall and PE as input, with those produced by combining information from the G2G initial condition at the forecast time-origin with a range of 1-month ahead rainfall forecasts, including using observed rainfall as a surrogate for a perfect rainfall forecast. A UK-scale seasonal meteorological forecast (Arribas et al., 2011) has also been used, provided by the UK Met Office. This consists of a 42-member ensemble of UK-average (i.e. spatially uniform) monthly total rainfall forecast for the next month, available at the start of each month.

**Hydrological outlooks from storage anomalies**

Expressing the continuity equation in terms of water depth (mm) over a model grid-cell, any change in total subsurface water storage, $S=(V+V_g)/\Delta x^2$, must be due to the balance between input precipitation $P$ and outputs through actual evaporation $E$ and net outflow per unit area $Q$, so $\mathrm{d}S/\mathrm{d}t = P-E-Q$. In terms of discrete months, for month $m$ then $\Delta S_m = S_{m+1}-S_m$, so $S_{m+1} \approx S_m + P_m - E_m - Q_m$. Similarly, taking monthly mean values over a number of years, $\bar{S}_{m+1} \approx \bar{S}_m + \bar{P}_m - \bar{E}_m - \bar{Q}_m$. We can thus express the anomaly in a subsequent month's storage as $S'_{m+1} \approx S_{m+1} - \bar{S}_{m+1} \approx S'_m + P'_m - E'_m - Q'_m$, where the anomaly for an arbitrary model variable $X_m$ in month $m$ is $X'_m = X_m - \bar{X}_m$. Thus the storage anomaly at the end of a month can be estimated from that at the start of the month plus the anomalies in the monthly total rainfall, actual evaporation and net flow. Similarly, the storage anomaly after $n$-months can be estimated from the initial storage anomaly plus the anomalies in $n$-month total rainfall, actual evaporation and net flow as: $S'_{m+n} \approx S'_m + \sum_{i=m}^{m+n-1}(P'_i - E'_i - Q'_i)$, at least for relatively small $n$. A storage anomaly will thus persist from month to month if $P$, $E$ and $Q$ take their mean values.

The high spatial heterogeneity of the climate and landscape in Britain leads to considerable variation in the relative sizes of the key variable anomalies: $S'_m$, $P'_m$, $E'_m$ and $Q'_m$. Although the water-balance methodology has been developed for individual 1km pixels, a discussion of catchment mean values of the key variables can more easily illustrate the temporal development of storage anomalies from year to year. Note that at a catchment scale, the monthly water-balance anomaly equations are only approximate as water in transit across the catchment is neglected; this potential source of error is most likely to occur in very large or groundwater-dominated catchments where changes in sub-surface storage affect river flows at time-scales longer than one month. (The relatively small size, by global standards, of British catchments means this is less of issue than it would be in continental-scale catchments). Catchments in the south of Britain are more likely to have large aquifers, stores and storage anomalies and lower flow than many northern catchments, which tend to have higher relief, shallower soils and larger volumes of rainfall. Figure 1a presents time-series of catchment-average anomalies of monthly total rainfall and actual evaporation, subsurface water storage at the start of the month and mean monthly river flow at the catchment outlet, for a 4½-year period from 2008 to June 2012, for the three example catchments. The figure illustrates three typical types of relationship between the key variables $S'_m$, $P'_m$, $E'_m$ and $Q'_m$:

(i) For catchments with a high proportion of large subsurface stores, such as those whose response is dominated by groundwater from a chalk aquifer, {$E'_m$, $Q'_m$}<<{$S'_m$, $P'_m$} and $S'_{m+1} \approx S'_m + P'_m$. The Kennet at Theale (39016) provides an example of such a catchment.

(ii) For catchments located in high rainfall areas, the soil/subsurface is often saturated and typically {$E'_m$, $S'_m$}<<{$Q'_m$, $P'_m$}. In this case, $Q'_m \approx P'_m$ and although in general $S'_{m+1} \approx S'_m + P'_m - Q'_m$, during periods of drought recovery $S'_{m+1} \approx S'_m + P'_m$. The Eden at Sheepmount (76007) is a good example. Any change in $S'_m$ is primarily due to the balance between rainfall and river flow, but will also be influenced by other factors such as the intensity and location of rainfall with respect to areas of deep or shallow subsurface water storage.

(iii) For catchments with variable geology and a range of store depths, including both deep and shallow stores, any change in $S'_m$ is highly dependent on $P'_m$ but $Q'_m$ and $E'_m$ can also influence the month-by-month water balance. The Avon at Evesham (54002) is an example of such a catchment. In practice, any large storage deficit will only be overcome through an increase in mean monthly rainfall, but during dry periods when subsurface water stores are low, decreases in $Q'_m$ (and to a lesser extent, $E'_m$) will to some extent mitigate against the impact of reduced rainfall on storage deficits. Thus $S'_{m+1} \approx S'_m + P'_m - Q'_m$, but during periods of drought recovery $S'_{m+1} \approx S'_m + P'_m$.

Thus as a first approximation, $S'_{m+n} \approx S'_m + \sum_{i=m}^{m+n-1} P'_i$ for 1≤$n$≤3. This expression will be particularly appropriate during periods of recovery from a deficit, which are most likely to arise from above average rainfall for subsequent months ($P'_i$>0), rather than from decreased evaporation ($E'_i$<0). Additionally, limits on the water storage anomaly, $(S'_m)_{\min}$ and $(S'_m)_{\max}$, are required to take into account the minimum and maximum storage respectively of each 1km pixel's sub-surface water store. Since $S'_m = S_m - \bar{S}_m$, if the minimum storage capacity is zero, it follows that $(S'_m)_{\min} = -\bar{S}_m$. Conversely, assuming each pixel has a maximum possible monthly mean storage, $S_{\max}$, $(S'_m)_{\max} = S_{\max} - \bar{S}_m$. Although each 1km pixel is associated with a saturated soil-moisture content which provides a local maximum value of soil-moisture storage, there is no pre-defined maximum for groundwater storage. Thus $S_{\max}$ has been estimated as the maximum modelled value of $S_m$ for each pixel over the period 1962 to 2012. Further analysis/discussion is provided in a later section ('Assessment of method using observed rainfall').

Changes to factors such as land-cover, abstraction/effluent returns or climate will affect catchment water-balances and their recovery from drought periods. However, assuming stationarity in current conditions, this water-balance approach provides a spatially-distributed tool to compare an ongoing drought with similar historical periods. This approximation can be exploited in two ways to obtain simple measures of the hydrological outlook a month or so ahead:

(i) **Regional rainfall return periods.** Estimate the return period of the rainfall required to return the stores to normal levels at a regional/local scale. That is, if $S'_{m+n} = 0$ then $\sum_{i=m}^{m+n-1} P'_i \approx -S'_m$ or $\sum_{i=m}^{m+n-1} P_i \approx \sum_{i=m}^{m+n-1} \overline{P}_i - S'_m$. Comparing this value (calculated regionally) with estimates of rainfall return period - such as those based on the assumption of log-normally-distributed monthly rainfall accumulations (Tabony, 1977) - for a given starting month *m* and for various *n*-months ahead, provides the estimated return period of the required rainfall in each case. This gives an indication of the severity of the current situation, and the likelihood of returning to normal over a range of time-scales. However, it should be noted that such return period estimates (based here on observed rainfall data for 1910-2010) are sensitive to non-stationarity, both from natural climate variability and climate change.

(ii) **Seasonal rainfall forecasts.** Combine the current storage anomaly with seasonal rainfall forecasts, to produce seasonal storage forecasts. That is, given a rainfall forecast $P_f$ for months *m* to *m+n-1*, estimate $S'_{m+n}$ as $S'_m + P_f - \sum_{i=m}^{m+n-1} \overline{P}_i$. By using an ensemble of rainfall forecasts, an ensemble of water storage forecasts can be quickly and easily produced, enabling an assessment of the range of possible situations *n*-months ahead. 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.

During periods of recovery from drought, additional rainfall causes sub-surface stores which are in deficit to fill and change from a negative to positive storage anomaly. During this period, river flow anomalies will also typically change from negative to positive because, during a recovery from drought, the fast component of river flow is generated when stores, or a proportion of stores, are close to saturation. Thus, as subsurface stores approach their climatological mean, $S'_{m+1} \to 0$, monthly mean flows will tend to approach theirs, $Q_m \to \overline{Q}_m$.

The next section provides an example application of this methodology for estimating water storage anomalies a month or so ahead, using the recent drought in England as a case study. An assessment of the method is provided for three contrasting catchments in England and nationally, followed by a demonstration of national application of the two alternative forms of hydrological outlook based on regional return periods and seasonal forecasts.

## AN EXAMPLE APPLICATION: THE 2012 DROUGHT IN BRITAIN

The drought of 2010-2012 and its termination following three months of above-average rainfall provides a perfect case study for assessing the large-scale water-balance approach to seasonal forecasting. In the two years prior to Spring 2012, England and Wales experienced 88% of normal (1971-2000 average) rainfall, while Scotland experienced 112% of its normal rainfall. By the end of March 2012 drought warnings were in force and a recovery during spring/summer 2012 seemed highly unlikely. Figure 2a presents a left-hand column of time-series maps of rainfall anomaly (mm), first over the preceding two year period, and then as monthly values from March to June 2012. The corresponding time-series maps of G2G-estimated month-end subsurface storage anomaly (mm) are presented in Figure 2b (second column) for the months of February through to June 2012. By the end of March, subsurface water storages across the whole of Britain are in deficit (red shading) with the highest deficits located in parts of the south and east overlying chalk geology such as the Chiltern Hills and Berkshire Downs. The next three months saw a dramatic change as Britain experienced the wettest April on record over the last 100 years, followed by near-average May rainfall and the wettest June since 1910, resulting in an almost complete termination of drought conditions. The maps in Figure 2b show the G2G-estimated water storage anomalies changing from red (deficit) in March to blue (excess) in June as the spatially-variable subsurface storage capacities across the landscape are replenished by the high rainfalls (deeper sub-surface storages take longer to recover).

**Assessment of method using observed rainfall**

***Catchment-based assessment***

The capability of this water-balance anomaly procedure to estimate subsurface water storage and river flows across Britain in future months can be assessed by hindcasting water storage anomalies, under the assumption of perfect foreknowledge of rainfall (i.e. using observed rainfall) used as input to the G2G model. Figure 1b shows 1- and 2-month ahead forecasts of storage anomalies for the three case-study catchments (Kennet, Eden and Avon). The catchment-average monthly water storage anomaly, $S'_m$, is estimated by the G2G model run continuously over the period 2008 to 2012, following an initialisation period of two years, using observed rainfall and PE as input (as shown in Figure 1a). Time-series of 1- and 2-month ahead forecast water storage anomalies, shown with broken lines, are estimated using the G2G estimate of $S'_m$ at the forecast origin, with the addition of the next 1- and 2-month total monthly rainfall anomaly, i.e. $S'_{m+1} \approx S'_m + P'_m$ and $S'_{m+2} \approx S'_m + P'_m + P'_{m+1}$.

The results for the example catchments are broadly in line with expectations following the analysis of the relative sizes of anomalies above. For the groundwater-dominated catchment (Kennet), the relationship between change in water storage anomaly and rainfall is clear for a 1-month ahead forecast, and to a slightly lesser extent, the 2-month ahead forecast. The hydrological response of the higher relief Eden catchment is dominated primarily by rainfall rather than subsurface water storage. Estimating the 1-month ahead water storage anomaly (bold red line) from rainfall and current storage alone (dashed line) is of particular value during periods following a water storage deficit when rainfall provides the dominant driver of recovery. For the lowland Avon catchment which has a more spatially variable hydrological response it is possible to achieve a reasonably good estimate of the water storage anomaly for 1- and 2-months ahead using a perfect forecast of the next month's rainfall alone, particularly for positive anomalies. Both forecasts of water storage anomaly estimate the timing of recovery from a deficit reasonably well, shown by the time at which the forecasts cross the time-axis. Peak water storage anomalies for both the Eden and Avon catchments arising from high rainfall anomalies are limited by the maximum monthly mean storage anomaly, $(S'_m)_{\max}$, which stops them becoming physically unrealistic. In contrast, the minimum storage anomaly $(S'_m)_{\min}$, representing a minimum storage of zero (see Section 'Hydrological outlooks from storage anomalies'), corresponds to such a theoretically low value that it is never invoked. The time-series for the Eden and Avon catchments in Figure 1b indicate that this can lead to larger errors in estimated water storage anomaly for negative (deficit) than positive (surplus) values. Further work will investigate whether the assumption of zero minimum storage is realistic, perhaps leading to derivation of a more useful lower bound.

***Spatial assessment***

Figure 2c (third column) provides a time-series of maps showing the spatial variation in the 1-month ahead forecast water storage anomaly estimated using the G2G estimate of $S'_m$ at the forecast origin, with the addition of the next 1-month total rainfall anomaly which is assumed to be a perfect rainfall forecast. Visual comparison with the G2G estimated anomaly maps in Figure 2b (second column) suggests that the 1-month ahead forecast compares reasonably well with a full G2G model estimate that takes into account incremental sub-daily changes in rainfall and responses of flow and evaporation. However, there is a tendency to overestimate deficits (red shading) in the 1-month ahead water storage anomaly maps for areas with smaller sub-surface storages, such as parts of Wales, Northern England and Scotland where the mitigating effects of reduced evaporation $E'_i$ and flow $Q_i'$

in subsequent months have been neglected. The currently low minimum water storage anomaly limit will contribute to the underestimate, as this value is seldom invoked.

**National hydrological outlooks**

***Regional rainfall return periods from 1 April 2012***

Estimates of the return period of the rainfall required to return the subsurface water storages to normal levels can be provided at a regional/local scale by assuming that a storage deficit will primarily be overcome through the addition of higher than normal rainfall values. Table 1 presents regional-average water storage anomalies for 1 April 2012 and return periods of rainfall required over 1, 3 and 6 month periods to return water storages to normal for 10 regions across England and Wales (see the region key in Figure 2 for locations). As expected, the return period falls rapidly as the period over which rainfall can occur is increased: for example for Thames Region the likelihood of rainfall occurring drops from 1 in 539 years to 1 in 7 years as the period increases from one to six months. Clearly, receiving all the rainfall required to overcome such a large drought-induced water storage deficit in one month is much less likely and would be associated with significant flooding. Despite the low probability (high return period) of experiencing sufficient rainfall to end the drought in the three months following 1 April 2012, that is almost exactly what happened; the rainfall received over this 3-month period had a return period in excess of 100 years for many regions of the country (CEH and BGS, 2012). A continuation of the unusual southerly track of the jet stream led to record April to June rainfall and an almost complete termination of drought conditions (apart from north-west Scotland).

***Seasonal forecasts***

The monthly time-series maps of water storage anomaly in Figures 2d and 2e have been estimated using G2G estimates of $S'_m$ at the start of the month, with the addition of the 1-month-ahead UK-scale forecast rainfall anomaly, $P'_f$. Specifically, $S'_{m+1} \approx S'_m + P'_f$, where $P'_f = P_f - \overline{P_m}$ and $\overline{P_m}$ is UK mean monthly rainfall (i.e. $P'_f$ is spatially uniform). To illustrate the range of possible forecasts, the water storage anomaly maps have been obtained using only the ensemble minimum (Figure 2d) and maximum (Figure 2e) total monthly rainfall anomaly to provide an indicative envelope of behaviour. The difference in the regional-scale anomalies between the two sets of maps in columns (d) and (e) is apparent, particularly in areas with smaller anomalies such as the north and west of Britain. For April 2012, the maximum rainfall forecast of 124 mm was closest to the observed UK mean of 127 mm, and the water storage anomaly obtained using the maximum forecast (Figure 2e) is closest to the anomalies derived using observed rainfall data (Figures 2b and 2c). Differences are due, in part, to the use of the UK spatially-averaged rainfall forecast ensemble instead of the spatially-distributed (observed) rainfall data; use of downscaling techniques to convert UK-wide forecasts to regional/local scales could provide a better indication of the likelihood of drought recovery in a specific region. The water storage anomaly maps derived using the minimum member of each ensemble forecast provides an indication of how severe the drought could have become if extremely low rainfall conditions had persisted. This example provides a simple illustration, or ‘proof-of-concept’, of how meteorological rainfall forecasts could be combined with the hydrological water-balance anomaly procedure. Use of the full range of ensemble rainfall forecasts in combination with current water storage anomaly estimates could potentially provide a range of 1- to 3-month ahead hydrological outlooks with associated probabilities.

## SUMMARY

A water-balance anomaly procedure has been developed to track monthly changes in the water stored in the landscape in order to estimate how much effective rainfall would be required to return stores to “normal” hydrological conditions (e.g. under drought conditions). Here, “normal” is taken to be the modelled 30-year mean depth of water stored in soil and groundwater. The new scheme has been implemented for the UK and tested with reference to the widespread drought that affected much of Southern Britain in the early months of 2012. The scheme uses a countrywide hydrological model (Grid-to-Grid, or G2G) - with inputs provided by up-to-date daily rainfall data and monthly estimates of potential evaporation - to produce spatially-distributed estimates of the anomaly in subsurface water storage on a 1km resolution across the UK. These anomalies can also be spatially averaged to provide estimates in different regions, catchments or for different flow regimes (for example chalk aquifers). Note that working with anomalies from modelled "climatological" mean monthly storage is likely to reduce the influence of uncertainty from the hydrological model, although this could still be a factor. During periods of recovery from a water storage deficit, the methodology can provide an indication of when river flows might return to mean monthly values, a measure often used to indicate the end of a drought. Such an estimate might provide additional information to enable water managers to implement short- or medium-term water-saving measures, or perhaps to delay planned measures if a recovery in a particular part of the country looks likely.

The capability of this water-balance procedure to estimate UK subsurface water storages and river flows in future months has been tested over a 4½-year period by hindcasting water storage anomalies while assuming perfect foreknowledge of rainfall (i.e. using observed rainfall). Also the feasibility to combine the estimate of current UK water storage anomalies with a rainfall forecast ensemble to produce outlook forecasts has been demonstrated. Clearly these initial tests are not sufficient to quantify the true skill of the modelling procedure; this will be determined with reference to a more extensive historical record and a wider range of hydrological extremes in a subsequent manuscript. However, initial results presented here indicate that the modelling procedure could potentially be run operationally on a month-by-month basis, linked to either an ensemble of rainfall forecasts or to historical rainfall records treated as alternative future rainfall scenarios, for estimating the likelihood of recovery from a drought anomaly. The direct use of monthly rainfall anomalies removes any immediate requirement for temporal downscaling of seasonal rainfall forecasts, often provided as monthly totals. Further work will examine the sensitivity of the hydrological outlook to the spatial and temporal distribution of the rainfall forecast, and ongoing work to improve the accuracy and spatial resolution of seasonal meteorological forecasts would potentially improve the skill of the outlook. Data assimilation of the most recent sub-monthly observation estimates of rainfall, potential evaporation and river flow could also potentially improve the accuracy of predictions of water storage anomaly and time to recover from drought. During conditions of wetter than normal water storage anomaly the water-balance procedure could also potentially provide an indication of flood susceptibility in areas of high subsurface water storage, such as chalk aquifers, up to a few weeks or months ahead. Future work will aim to provide a more comprehensive assessment of the methodology introduced here, over the full historical record, and highlight areas which can benefit the most from seasonal hydrological outlooks produced in this way.

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**References**

Arribas A, Glover M, Maidens A, Peterson K, Gordon M, MacLachlan C, Graham R, Fereday D, Camp J, Scaife AA, Xavier P, McLean A, Colman A, Cusack S. 2011. The GloSea4 ensemble prediction system for seasonal forecasting. *Monthly Weather Review*, **139**(6): 1891-1910.

CEH and BGS. 2012. Hydrological Summary for June 2012. Centre for Ecology & Hydrology/British Geological Survey, 12pp.http://www.ceh.ac.uk/data/nrfa/nhmp/hs/pdf/HS_201206.pdf

Bell VA, Kay AL, Jones RG, Moore RJ. 2007a. Development of a high resolution grid-based river flow model for use with regional climate model output. *Hydrology and Earth System Sciences*, **11**: 532-549.

Bell VA, Kay AL, Jones RG, Moore RJ. 2007b. Use of a grid-based hydrological model and regional climate model outputs to assess changing flood risk. *Int. J. Climatol.*, **27**: 1657-1671. DOI:10.1002/joc.1539.

Bell VA, Kay AL, Jones RG, Moore RJ, Reynard NS. 2009. Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. *Journal of Hydrol*ogy **377**(3–4): 335–350.

Bierkens MFP, van Beek LPH. 2009. Seasonal predictability of European discharge: NAO and hydrological response time. *Journal of Hydrometeorology*, **10**: 953–968. DOI: 10.1175/2009JHM1034.1.

Boorman DB, Hollis JM, Lilly A. 1995. Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. *IH Report No. 126*, Institute of Hydrology, Wallingford, UK, 137pp.

Cole SJ, Moore RJ. 2009. Distributed hydrological modelling using weather radar in gauged and ungauged basins. *Advances in Water Resources* **32**(7): 1107-1120. DOI: 10.1016/j.advwatres.2009.01.006.

Lavers D, Luo L, and Wood EF. 2009. A multiple model assessment of seasonal climate forecast skill for applications. Geophys. Res. Lett., 36, L23711, doi:10.1029/2009GL041365.

Lavers DA, Prudhomme C, Hannah DM. 2010a. Large-scale climate, precipitation and British river flows: identifying hydroclimatological connections and dynamics. *Journal of Hydrology*, **395**, 242-255. DOI:10.1016/j.jhydrol.2010.10.036.

Lavers DA, Prudhomme C, Hannah DM. 2010b. Large-scale climatic influences on precipitation and discharge for a British river basin. *Hydrological Process*es **24** (18), 2555–2563. DOI:10.1002/hyp.7668.

Lavers D. 2010. Seasonal hydrological prediction in Great Britain - an assessment. Ph.D. thesis, University of Birmingham.

Luo L**,** Wood EF. 2007. Monitoring and predicting the 2007 U.S. drought. *Geophys. Res. Lett.*, **34**, L22702. DOI: 10.1029/2007GL031673.

McGregor GR, Phillips ID. 2004. Specification and prediction of monthly and seasonal rainfall over the south-west peninsula of England. *Quarterly Journal of the Royal Meteorological Society*, 130: 193-210. DOI: 10.1256/qj.03.10.

Mahanama S, Livneh B, Koster R, Lettenmaier DP, Reichle R. 2012. Soil moisture, snow and seasonal streamflow forecasts in the United States. *Journal of Hydrometeorol*ogy **13**: 189–203.

Moore RJ. 1985. The probability-distributed principle and runoff production at point and basin scales. *Hydrological Sciences Journal* **30**(2): 273-297.

Moore RJ, Cole SJ, Bell VA, Jones DA. 2006. Issues in flood forecasting: ungauged basins, extreme floods and uncertainty. In: I Tchiguirinskaia, KNN Thein & P Hubert (eds.), Frontiers in Flood Research, 8th Kovacs Colloquium, UNESCO, Paris, June/July 2006, *IAHS Publ. 305*, 103-122.

Shukla S, Lettenmaier DP. 2011. Seasonal hydrologic prediction in the United States: understanding the role of initial hydrologic conditions and seasonal climate forecast skill. *Hydrology and Earth System Sciences* **15**: 3529-3538. DOI: 10.5194/hess-15-3529-2011.

Sinha T, Sankarasubramanian A. 2012. Role of climate forecasts and initial land-surface conditions in developing operational streamflow and soil moisture forecasts in a rainfall-runoff regime: skill assessment. *Hydrology and Earth System Sciences Discussions* **9**(4): 5225-5260.

Svensson C, Prudhomme C. 2005. Prediction of British summer river flows using winter predictors. *Theoretical and Applied Climatology,* **82** (1-2)**,** 1-15. DOI: 10.1007/s00704-005-0124-5.

Tabony RC. 1977. The variability of long duration rainfall over Great Britain. *Met. Office Scientific Paper No. 37*.

Wedgbrow CS, Wilby RL, Fox HR, O'Hare G. 2002. Prospects for seasonal forecasting of summer drought and low river flow anomalies in England and Wales. *International Journal of Climatology,* **22,** 219-236. DOI: 10.1002/joc.735.

Wilby RL. 2001. Seasonal forecasting of river flows in the British Isles using North Atlantic pressure patterns. *Journal of the Chartered Institution of Water and Environmental Management,* 15**,** 56-63.

Wood AW, Lettenmaier DP. 2008. An ensemble approach for attribution of hydrologic prediction uncertainty. *Geophysical Research Letters* **35**: L14401. DOI:10.1029/2008GL034648.

**Table 1. Region-average water storage anomaly on 1 April 2012 and return period of rainfall required over the subsequent 1, 3 and 6 months to return the anomaly to zero.**

| Region (abbreviation) | Region-average storage anomaly on 1 April (mm) | Approximate return period (years) of rainfall required to return water storage to normal in: | | |
|---|---|---|---|---|
| | | 1 month (i.e. 1 May) | 3 months (i.e. 1 July) | 6 months (i.e. 1 October) |
| Anglian (A) | -72 | 454 | 41 | 6 |
| Northumbria (N) | -29 | 8 | 4 | 2 |
| North West (NW) | -30 | 6 | 3 | 0 |
| Thames (T) | -90 | 539 | 47 | 7 |
| Severn-Trent (ST) | -61 | 66 | 12 | 4 |
| Southern (S) | -91 | 2480 | 47 | 7 |
| South West (SW) | -48 | 11 | 6 | 3 |
| Wales (Wa) | -47 | 9 | 4 | 2 |
| Wessex (W) | -88 | 309 | 27 | 5 |
| Yorkshire (Y) | -45 | 18 | 7 | 3 |

**Figure captions**

Figure 1. (a) Time-series of catchment-average anomalies (mm) of monthly total precipitation *P'*, evaporation *E'*, subsurface water storage at the start of the month *S'*, and mean monthly flow at the catchment outlet *Q'*, for a 4½-year period from 2008 to June 2012 for the three example catchments; (b) 1- and 2-month ahead forecasts of water storage anomaly *S'* (mm) assuming perfect rainfall forecasts.

Figure 2. Column (a): time-series maps showing the rainfall anomaly (mm) in the preceding two year period, followed by the monthly rainfall anomaly (mm) for March to June 2012; Column (b): corresponding time-series maps of G2G-estimated month-end subsurface water storage anomaly (mm); Columns (c),(d),(e): 1-month ahead forecasts of water storage anomaly (mm) obtained using the G2G estimate of *S'* at the end of the previous month (i.e. column b in previous row), with the addition of (c) the 1-month ahead total observed rainfall anomaly (assumed to be a perfect forecast); (d) the minimum and (e) maximum from the ensemble of 1-month ahead total forecast rainfall anomalies.

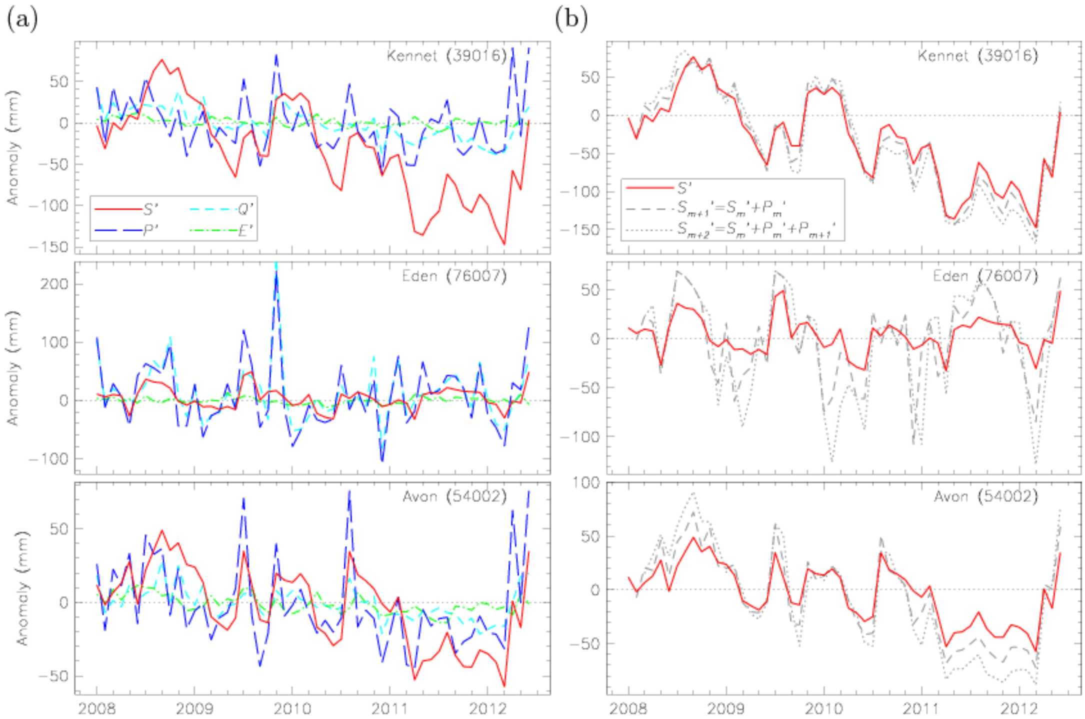
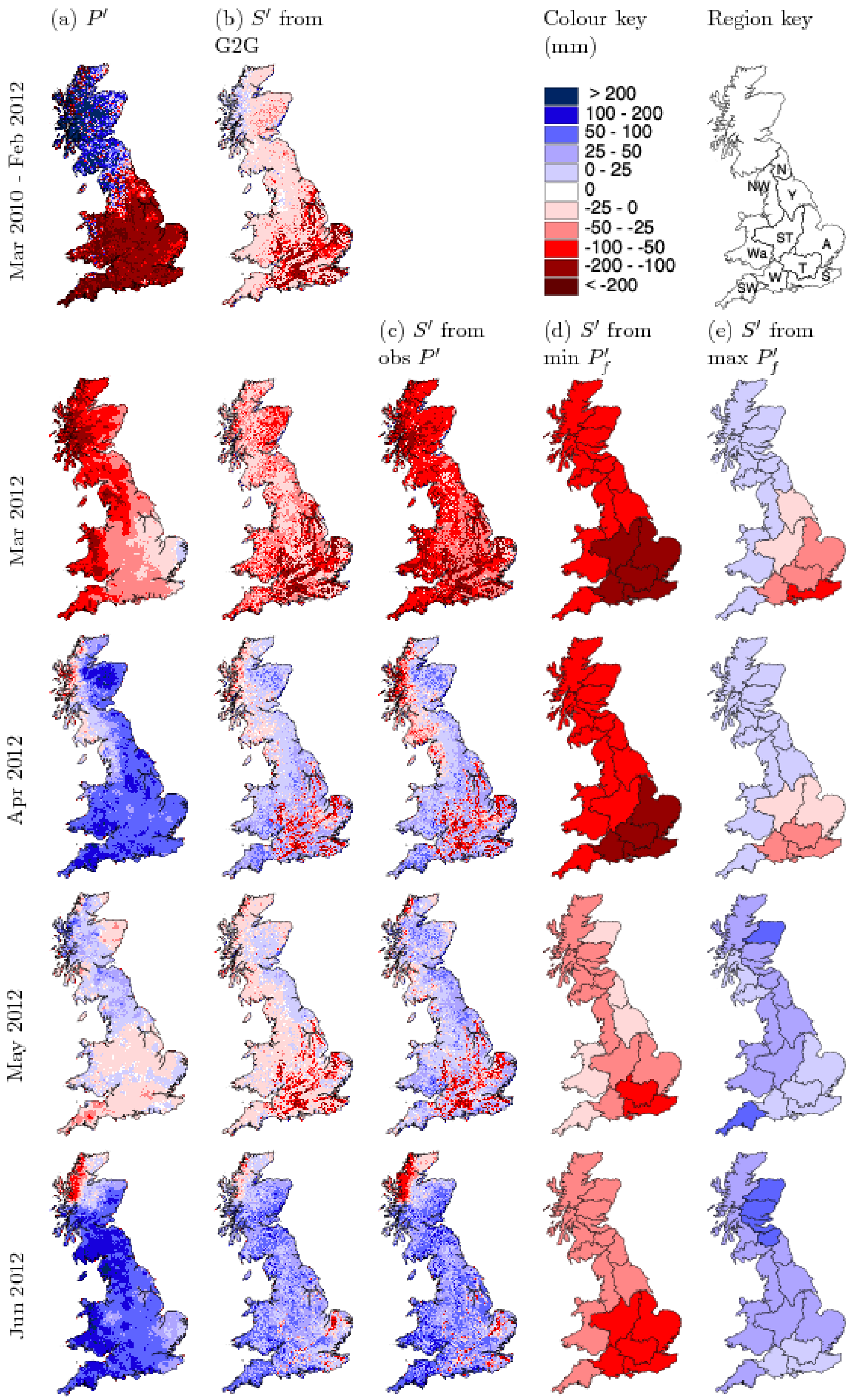

(a)
(b)
Kennet (39016)
Eden (76007)
Avon (54002)
Anomaly (mm)
S'
P'
Q'
E'
$S_{m+1}'=S_m'+P_m'$
$S_{m+2}'=S_m'+P_m'+P_{m+1}'$
2008
2009
2010
2011
2012

Fig.1.



(a) $P'$
(b) $S'$ from G2G
Colour key (mm)
Region key
Mar 2010 - Feb 2012
> 200
100 - 200
50 - 100
25 - 50
0 - 25
0
-25 - 0
-50 - -25
-100 - -50
-200 - -100
< -200
N
NW
Y
ST
A
Wa
W
T
S
SW
(c) $S'$ from obs $P'$
(d) $S'$ from min $P'_f$
(e) $S'$ from max $P'_f$
Mar 2012
Apr 2012
May 2012
Jun 2012


Fig.2.