The impact of the variability and periodicity of rainfall on surface water supply systems in Scotland
Muhammad Afzal, Alexandre S. Gagnon and Martin G. Mansell

ABSTRACT

This paper analyses the impact of the variability and periodicity of rainfall on the reliability of water supply systems in Scotland. A conceptual rainfall-runoff model was used to simulate catchment runoff, and the reliability of 29 notional and six actual reservoirs was calculated using a simple storage model. The relationship between water supply reliability and the variability of rainfall was then investigated using different measures of variability. A strong correlation was found between reservoir reliability and measures representing the distribution of rainfall between the winter and summer seasons, as well as the cumulative sum (CUSUM) of annual precipitation, quantifying the variability of rainfall between years. In contrast, mainly the intra-annual CUSUM range and the variance of monthly precipitation influenced the reliability of river-intake schemes. The presence of periodic patterns in rainfall anomalies was found to be more prevalent in West Scotland, where reservoir reliability is on average lower than in the East. In addition, a sensitivity analysis revealed the small influence of evapotranspiration on reservoir reliability in comparison to rainfall variability. This study reveals the measures of variability most affecting the reliability of surface water supplies in Scotland, and could therefore help with their management in the context of future climate change.

Key words | climate variability, hydrological modelling, periodicity, reliability, Scotland, surface water supply

INTRODUCTION

Scotland receives approximately 1,400 mm of precipitation per year averaged over the period 1914–2004 (Barnett et al. 2006). Given this abundance of precipitation and that it has increased in recent decades (Werritty & Sugden 2012), particularly since the 1970s (Afzal et al. 2015), one would expect the reliability of water supplies not to be of concern. However, the increasing trend in annual precipitation is possibly the result of an increase in high intensity rainfall events (Fisher & Rubio 1997; Osborn & Hulme 2002), which have increased over the UK since the 1950s (Alexander et al. 2005). Since this increase in precipitation has taken place in winter when reservoirs are full (Osborn & Hulme 2002), it often does not contribute to reservoir recharge (Anderson 1997).

Moreover, there are regional variations in precipitation, resulting in an uneven distribution of water supplies across the country (Wright 1995). Although the overall yield of developed water resources in Scotland was 52% greater than total demand in 2005/2006 (Scottish Water, personal communication, June 2007), the majority of Scotland’s population live in the lowland belt where the yield to demand surplus is low (Adeloye & Low 1996), and with the demand exceeding the available yield in some localised areas (Scottish Water, personal communication, June 2007). Furthermore, in the drier areas of eastern Scotland irrigation is more common, creating further strains on water resources, with rivers occasionally drying up (Adeloye & Low 1996). An East–West asymmetry in water resources is
even widening, with the West becoming wetter and the East drier (Mayes 2000).

In addition to the regional variations in precipitation and demand levels there is evidence of an increase in rainfall variability, as expected with intensification of the hydrological cycle in a warming climate (Fisher & Rubio 1997). For example, the winter to summer (w/s) ratio and the intra-annual variance of precipitation have increased in Scotland during the period 1961–2000 (Afzal et al. 2015); the former is the result of winters becoming wetter and summers drier (Barnett et al. 2006). This increase in rainfall variability could outweigh the trends towards increasing total annual precipitation, as seasonal patterns revealed by the w/s ratio, for example, are hidden when precipitation trends are calculated at the annual timescale. In England and Wales, for instance, Jones & Conway (1997) reported no long-term trend in total annual precipitation as the increase in winter precipitation was nullified by a decreasing trend in summer rainfall. An increase in the variability of rainfall could potentially impact negatively on the reliability of water resources, especially if evapotranspiration increases in a warmer climate.

Evapotranspiration is another key component of the hydrological cycle influencing catchment runoff and consequently reservoir recharge. With a warming of the atmosphere, an increase in evaporation is expected (Fisher & Rubio 1997). Using the UK Met Office Rainfall and Evaporation Calculation System (MORECS), Kay et al. (2013) reported an increase in evapotranspiration during the period 1961–2012 across the UK, including Scotland, but noted that spatial and seasonal variations remain to be analysed. Nonetheless, climate models project an increase in evaporation in the summer under climate change (Wade et al. 2013). This increase in evaporation, combined with greater variations in rainfall between seasons and from year to year, as well as changes in extremes, will inevitably influence catchment runoff and consequently have implications for water resource systems.

In Scotland, approximately 93% of water resources originate from surface sources. This is in contrast to England and Wales, where groundwater provides about 35% of public water supplies (Wright 1993). The relatively low groundwater use in Scotland is because of its limited availability for geological reasons (Anderson 1997), with highly productive aquifers restricted to the South West and Fife (MacDonald et al. 2005) where they contribute significantly to water supply. For example, in the Dumfries and Galloway region of south-western Scotland, groundwater contributes up to 20% of the total available yield (Wright 1995). In terms of surface water supplies, there are large differences in the size of the developed resources, ranging from Loch Lomond with a yield of 455 ML per day (Jowitt & Hay-Smith 2002), to more than 100 operational sources each with a yield of less than 0.01 ML per day. Furthermore, more than 50% of these operational sources are from river-intake schemes that extract water directly from rivers and burns, with no storage capacity other than the catchment itself (i.e. soil moisture). Such schemes are particularly prevalent in the North of Scotland (i.e. Highland and Grampian regions) (Wright 1995).

Climate variability plays an important role in determining the availability of water resources (Brown & Ward 2013). The North Atlantic Oscillation (NAO) is a major source of inter-annual climate variability in Europe, especially during the boreal winter. It refers to the difference in atmospheric pressure at sea level between the Icelandic low and the Azores high (Hurrell 1995). Higher than normal pressure for the Azores high compared with lower than average pressure for the Icelandic low is called a positive NAO state. During such a state, the meridional pressure gradient is enhanced, thereby leading to a predominance of westerly winds and storm tracks passing over northern Europe (Hurrell et al. 2003), including Britain (Werritty & Foster 1998). Therefore the climate over the UK is typically wetter in a positive NAO state in comparison to a negative NAO state, when it is southern Europe that experiences a wetter than average winter (Trigo et al. 2004).

Another mode of climate variability affecting the UK is the Atlantic Multidecadal Oscillation (AMO), which is an oscillation of sea surface temperatures in the North Atlantic Ocean. A positive phase of the AMO is associated with a decrease in mean sea level pressure over the North Atlantic and higher than average precipitation over the UK, particularly during the summer and autumn months. An opposite climatic signal to that of north-western Europe is observed in North America during a positive phase of the AMO (Knight et al. 2006), and Enfield et al. (2001) showed that
the climatic impacts of the AMO influence the variability of reservoir inflows in the United States.

An understanding of climate variability is thus essential to water infrastructure planning (Mason 2010), as it determines the favourable type of water supply system (river intake scheme or reservoir) and the size of the latter. If the average inflow is sufficient to meet the demand and the variability is low, the amount of storage required will be small. However, for the same average inflow but with a large variability, more storage will be needed to meet the same demand. The assessment of climatic risks to water supply systems is typically based on information gathered from historical records, with the assumption that the climate is stationary (Milly et al. 2008), an approach which is unlikely to be justified under climate change. Fowler et al. (2003) suggest that the potential increase in climate variability under climate change is of greater concern to water resources than changes in mean climate. Thus, quantifying the impacts of climate variability on water supply systems, as well as determining the measure of variability most affecting their reliability, can provide useful information to water resource managers.

Even though Scotland is dependent on surface water supplies to meet demand, little attention has been given to date on the effect of rainfall variability on water resource systems in the country. Hence, this paper aims to improve our understanding of the role of climate variability on the reliability of water supply systems in Scotland. The objectives are: (1) to examine the temporal and spatial distribution in reservoir reliability across Scotland; (2) to investigate the relationships between the reliability of water supply systems, including reservoirs and river-intake schemes, and the variability and periodicity of rainfall; and (3) to assess the contribution of variations in climatic variables other than precipitation on the reliability of water resources.

In the following section, the sources of data and the analytical methods used in this study are explained. The results section is divided into five components. First the results of the calibration and validation of the rainfall-runoff model are described. Second, temporal and spatial patterns in reservoir reliability across Scotland are depicted. Third, the results of the correlation analysis between different measures of rainfall variability and the reliability of the river-intake schemes and the storage reservoirs is presented with the aim of determining which variables are most closely connected with the performance of these two types of surface water supply schemes. Fourth, the influence of the periodicity of rainfall on the reliability of storage reservoirs is presented. The last part of the results section presents the contribution of evapotranspiration, and the climatic variables used to calculate it, on water storage reliability.

**METHODS**

**Sources of data**

Climatic data (i.e. rainfall, maximum and minimum temperatures, sunshine duration, and wind speed) were used as input variables to a Rainfall-Runoff (R-R) model. Daily precipitation and maximum and minimum temperature data for 40 weather stations across Scotland were obtained from the Met Office Integrated Data Archive System (MIDAS) through the British Atmospheric Data Centre (BADC) (UK Meteorological Office 2006). Figure 1 depicts the location of the 40 weather stations, with further information about those weather stations provided in Table 1.
Also shown are the three climatological regions of Scotland as defined by Barnett et al. (2006), i.e. North, West, and East Scotland. As noted in previous research (e.g. Sweeney & O'Hare (1992)), the network of precipitation gauges is highest in southern and central Scotland where the majority of the population resides, and sparse in North Scotland. Daily wind speed data were also obtained from MIDAS, but from only five of the above weather stations (Figure 2). Daily sunshine duration data interpolated on a 5 × 5 km grid were obtained from the baseline (1961–1990) dataset of the UK Climate Impacts Programme for the 21 grid cells corresponding to the location of the weather stations analysed in Afzal et al. (2015), which is a subset of the stations shown in Figure 1.

Figure 2 depicts the location of the river catchments, the river-intake schemes, and the case study reservoirs with their storage volumes. The selection of the eight catchments whose data were used to calibrate the R-R model was based on the availability of river flow data for a minimum continuous period of 10 years, and the quality of the climatic data at a weather station located in close proximity to a gauged catchment. Small catchments were preferred for the model calibration, given the dependence of Scotland on water supplies from small rivers (Smith 1977). This is because the majority of reservoirs in the UK are in upland areas, and are therefore fed by rivers with small catchments (Orr et al. 2008). It was also aimed to have a reasonable spread of catchments across Scotland. The Scottish Environmental Protection Agency (SEPA) and the Centre for Ecology and Hydrology (CEH) provided the daily river flow data for the eight catchments (Table 2).

### Table 1 | The 40 weather stations with mean total annual precipitation

<table>
<thead>
<tr>
<th>Weather station</th>
<th>Ref. no.</th>
<th>WMO station number</th>
<th>Total annual precipitation(a) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North of Scotland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greenland</td>
<td>1</td>
<td>14,368</td>
<td>999.8</td>
</tr>
<tr>
<td>Loch Calder</td>
<td>2</td>
<td>14,364</td>
<td>983.7</td>
</tr>
<tr>
<td>Fairburn</td>
<td>3</td>
<td>14,560</td>
<td>1034.9</td>
</tr>
<tr>
<td>Craggie</td>
<td>4</td>
<td>14,705</td>
<td>682.7</td>
</tr>
<tr>
<td>Cluny Castle</td>
<td>5</td>
<td>14,768</td>
<td>1146.0</td>
</tr>
<tr>
<td>Mull: Gruline</td>
<td>6</td>
<td>14,152</td>
<td>2120.1</td>
</tr>
<tr>
<td>Aros</td>
<td>7</td>
<td>900</td>
<td>1090.9</td>
</tr>
<tr>
<td>Regional average</td>
<td></td>
<td></td>
<td><strong>953.8</strong></td>
</tr>
<tr>
<td>East of Scotland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Braemar</td>
<td>8</td>
<td>147</td>
<td>921.3</td>
</tr>
<tr>
<td>Balnord</td>
<td>9</td>
<td>148</td>
<td>844.2</td>
</tr>
<tr>
<td>Mannofield</td>
<td>10</td>
<td>163</td>
<td>771.2</td>
</tr>
<tr>
<td>Invercannie</td>
<td>11</td>
<td>14,964</td>
<td>849.3</td>
</tr>
<tr>
<td>Cameron</td>
<td>12</td>
<td>15,393</td>
<td>823.4</td>
</tr>
<tr>
<td>Belliston</td>
<td>13</td>
<td>237</td>
<td>762.5</td>
</tr>
<tr>
<td>Tulliian</td>
<td>14</td>
<td>15,450</td>
<td>854.3</td>
</tr>
<tr>
<td>Tillicoultry</td>
<td>15</td>
<td>15,601</td>
<td>1030.7</td>
</tr>
<tr>
<td>Kirkcaldy</td>
<td>16</td>
<td>15,439</td>
<td>820.0</td>
</tr>
<tr>
<td>Edinburgh</td>
<td>17</td>
<td>251</td>
<td>715.1</td>
</tr>
<tr>
<td>Samuelston</td>
<td>18</td>
<td>15,844</td>
<td>619.1</td>
</tr>
<tr>
<td>Dunglass</td>
<td>19</td>
<td>15,876</td>
<td>674.9</td>
</tr>
<tr>
<td>Blyth Bridge</td>
<td>20</td>
<td>274</td>
<td>905.5</td>
</tr>
<tr>
<td>Rosebery</td>
<td>21</td>
<td>15,782</td>
<td>894.1</td>
</tr>
<tr>
<td>Bowhill</td>
<td>22</td>
<td>279</td>
<td>909.2</td>
</tr>
<tr>
<td>Rawburn</td>
<td>23</td>
<td>16,057</td>
<td>907.0</td>
</tr>
<tr>
<td>Lochton</td>
<td>24</td>
<td>16,021</td>
<td>638.4</td>
</tr>
<tr>
<td>Regional average</td>
<td></td>
<td></td>
<td><strong>743.8</strong></td>
</tr>
<tr>
<td>West of Scotland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dumfries</td>
<td>25</td>
<td>1,017</td>
<td>1086.4</td>
</tr>
<tr>
<td>Blackwood</td>
<td>26</td>
<td>13,224</td>
<td>1752.5</td>
</tr>
<tr>
<td>Forest Lodge</td>
<td>27</td>
<td>13,290</td>
<td>2042.1</td>
</tr>
<tr>
<td>Drumjohn</td>
<td>28</td>
<td>13,281</td>
<td>1807.0</td>
</tr>
<tr>
<td>Gailes</td>
<td>29</td>
<td>13,419</td>
<td>1016.7</td>
</tr>
<tr>
<td>Garpel Burn</td>
<td>30</td>
<td>13,378</td>
<td>1749.7</td>
</tr>
<tr>
<td>Leadhills</td>
<td>31</td>
<td>983</td>
<td>1742.3</td>
</tr>
<tr>
<td>Glassford</td>
<td>32</td>
<td>13,588</td>
<td>1278.1</td>
</tr>
<tr>
<td>Dunsdie</td>
<td>33</td>
<td>13,569</td>
<td>1454.8</td>
</tr>
<tr>
<td>Paisley</td>
<td>34</td>
<td>968</td>
<td>1234.9</td>
</tr>
</tbody>
</table>

\(a\)Calculated over the period 1976–1990.
Scottish Water provided daily water abstraction data for two river-intake schemes for the period 2009–2012 as well as data on the mean annual inflow, the mean annual demand, and the storage capacity of six case study reservoirs. The selection of the reservoirs was based on their storage volume in comparison to mean annual inflow, i.e., the storage ratio, and the average daily demand in relation to mean annual inflow, i.e., the demand ratio. The selection process aimed at choosing a number of reservoirs that would cover a wide range of storage and demand ratios, as shown in Figure 3, as well as different parts of Scotland.

The selected reservoirs were provided from a list of reservoirs referred to as drought reservoirs (Scottish Water, personal communication, July 2011). Hence, these reservoirs are not representative of all reservoirs across Scotland, but represent reservoirs at greater risk of failure because they are relatively small and/or independent. Small and independent reservoirs are more sensitive to changes in climate variability than large reservoirs (Marsh & Turton 1996). Had only large reservoirs been selected, such as Loch Lomond, the number of failures would have been limited, making it difficult to examine the relationships
between reservoir reliability with different measures of rainfall variability.

**The conceptual R-R model**

A conceptual R-R model was used to generate catchment runoff, which then served as input into a reservoir model. Model generated runoff was used so that the effect of various patterns of rainfall could be investigated and because long records of reservoir inflow are scarce in Scotland and even unavailable for many reservoirs (Jowitt & Hay-Smith 2002). In order to investigate the effect of reservoir characteristics on reliability, the concept of notional reservoirs was used. A notional reservoir was considered to be a hypothetical reservoir that is not connected to other sources and which has arbitrary storage and demand characteristics.

The R-R model was based on the probability distribution model described in Moore (1985, 2007), which is widely used in the UK (Christierson et al. 2012). It determines the change in soil moisture storage using a simple water balance approach, i.e. the storage volume increases due to precipitation and decreases due to evapotranspiration. Potential evapotranspiration was estimated using the modified Penman–Monteith equation outlined in Allen et al. (1998).

The R-R model has five parameters that require having values assigned by calibration with respect to observed flow data. The calibration and validation was carried out using a minimum period of 5 years each. A number of statistical indices exist to compare simulated and observed data. This study used the Nash–Sutcliffe efficiency (NSE) coefficient, as it is one of the most widely used techniques to assess the performance of hydrological models (Singh et al. 1998).

Krause et al. (2005) indicated that extreme values in a time series can result in a poor NSE coefficient because hydrological models tend to underestimate river flow during peak flows. For this reason, they suggested calculating the NSE coefficient with logarithmic values:

\[
\ln \text{NSE} = 1 - \frac{\sum_{i=1}^{n} (\ln O_i - \ln S_i)^2}{\sum_{i=1}^{n} (\ln O_i - \ln \bar{O})^2}
\]

where \(O_i\) and \(S_i\) refer to the observed and simulated river flow data, respectively, and \(\bar{O}\) is the mean of the observed data. By applying the logarithmic values, the peak flows tend to be flattened while low values remain unchanged;

**Table 2 | Analysis of the efficiency of the R-R model**

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Surface area (km²)</th>
<th>Calibration time-period</th>
<th>In NSE</th>
<th>Validation time-period</th>
<th>In NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strathy at Strathy Bridge</td>
<td>111.8</td>
<td>1991–1997</td>
<td>0.66</td>
<td>1998–2004</td>
<td>0.53</td>
</tr>
<tr>
<td>Strathmore at Allnablad</td>
<td>105.0</td>
<td>1988–1995</td>
<td>0.55</td>
<td>1996–2003</td>
<td>0.57</td>
</tr>
<tr>
<td>Brothock Water at Arbroath</td>
<td>50.0</td>
<td>1989–1995</td>
<td>0.55</td>
<td>1996–2002</td>
<td>0.51</td>
</tr>
<tr>
<td>Craigmill Burn at Craigmill</td>
<td>29.0</td>
<td>1987–1993</td>
<td>0.72</td>
<td>1994–2000</td>
<td>0.64</td>
</tr>
<tr>
<td>Eden at Strathmiglo</td>
<td>26.0</td>
<td>1991–1995</td>
<td>0.64</td>
<td>1996–2000</td>
<td>0.58</td>
</tr>
<tr>
<td>Black Cart Water at Milliken Park</td>
<td>103.1</td>
<td>1968–1987</td>
<td>0.80</td>
<td>1988–2006</td>
<td>0.71</td>
</tr>
<tr>
<td>Carradale at Dippen</td>
<td>58.5</td>
<td>1996–2001</td>
<td>0.75</td>
<td>2002–2007</td>
<td>0.70</td>
</tr>
<tr>
<td>Water of Fleet at Rusko</td>
<td>77.0</td>
<td>1988–1992</td>
<td>0.77</td>
<td>1993–1998</td>
<td>0.66</td>
</tr>
</tbody>
</table>

*The NSE coefficient was calculated using daily data.*

**Figure 3 | The reliability of the six case study reservoirs based on their storage and demand ratio.**


consequently, the influence of low flow values increases and that of very high flow values decreases (Krause et al. 2005).

The river flow time series were divided into two with the first half used to calibrate the model and the second half to validate it. The calibration procedure consisted of adjusting manually the five tuneable parameters to achieve the best model fit, with the latter assessed using the logarithmic value of the NSE coefficient as described above.

Reservoir model and reliability analysis

The operation of the reservoirs was modelled using a simple tank model with the storage volume of a reservoir, $S$, at time step $t + 1$ calculated using the following equation:

$$S_{t+1} = S_t + Q_t - D_t \text{ (if } S_t < S_{\text{max}})$$

$$S_{t+1} = S_{\text{max}} \text{ otherwise}$$

where $Q_t$ and $D_t$ are the inflow and outflow into and out of the reservoir, respectively. For simplicity, it is assumed that the net precipitation (precipitation–evaporation) on the reservoir surface as well as seepage into groundwater is negligible.

Reliability was used to determine the performance of the river intake schemes and storage reservoirs. It is defined as the probability that a given water supply will meet the demand in any given year (McMahon & Adeloye 2005). In this study, the time-based definition of reliability was used. For every year, the reliability, $R$, of the reservoirs was calculated as:

$$R = \left(1 - \frac{N_f}{365}\right) \times 100$$

where $N_f$ is the number of failure days. A ‘failure’ was arbitrarily defined to have occurred when the reservoir volume fell below 30% capacity, as supply restrictions are often initiated when this threshold volume is reached (Kiern & Franks 2005). For the two river-intake schemes a ‘failure’ was recorded when the river flow after abstraction was less than the Q95 (i.e. the flow exceeded 95% of the time and in this case calculated over 4 years), with abstraction assumed to be constant between years and calculated using data for the period 2009–2012. The Q95 is widely used to guide abstraction and consent policies in the UK (Scottish Environment Protection Agency 1997), and is a good proxy measure of ‘drought’ runoff, as used in the UK Climate Change Risk Assessment (Arnell et al. 2014).

Three important characteristics of a reservoir are its storage volume, annual inflow, and annual demand. The storage volume and annual demand can be expressed as non-dimensional ratios by dividing them by the mean annual inflow. Hence, the storage factor was defined by:

$$S_f = \frac{S}{Q_{\text{av}} \times 365}$$

where $S$ is the storage volume of the reservoir and $Q_{\text{av}}$ is the average daily inflow (m$^3$/day). This storage ratio is a good indicator of the resilience of a water supply system to climate variability, with systems having a large volume of storage in comparison to their inflow more likely to be able to withstand a prolonged drought (Smith & Bennett 1994). The demand ratio was defined by:

$$D_f = \frac{Q_d}{Q_{\text{av}}}$$

where $Q_d$ is the average daily demand. The storage and demand ratios of all case study reservoirs remained between 0 and 1 (Figure 3).

To examine the temporal variability in the reliability of the notional reservoirs, the precipitation time series at each of the 40 weather stations was divided into three time periods of 15 years each, i.e. 1961–1975, 1976–1990, and 1991–2005. Then, the reliability of 29 notional reservoirs consisting of different combinations of storage and demand ratios (i.e. one for each combination of storage and demand ratio varying from 0 to 1.0 with an interval of 0.2) was calculated using the above rainfall datasets. As mentioned above, the R-R model was calibrated over eight gauged catchments, resulting in eight parameter sets. To simulate the inflow into the notional reservoirs, the mean of those eight values was used for each of the five model parameters. The constant catchment parameter set was used so that attention would be focused on the effect of the storage characteristics of the reservoirs. At each weather station the
mean reliability value was computed for each of the three time periods.

The mean reliability for each combination of storage and demand ratio is shown as a contour plot in Figure 3, together with the reliability of the six actual reservoirs. The Knockquhassen, Loch Calder, and Dhu Loch reservoirs have, on average, over 80% reliability, whereas the Glendevon reservoir, located in a drier part of Scotland, has the lowest reliability of the six actual reservoirs due to its low storage ratio and high demand ratio. This study assumed a constant storage and demand ratio with time. However, these could vary between years, since both the storage and demand ratios are functions of reservoir inflow and the demand ratio is also calculated using the average daily demand.

Measures of variability

The following nine measures of rainfall variability were computed.

Variability within a year: intra-annual variance, intra-annual cumulative summation (CUSUM) range, w/s ratio, and ratios of winter and summer precipitation to total annual precipitation.

Variability from year to year: coefficient of variation, CUSUM of annual precipitation, annual number of dry days, and average length of a dry spell per year. A dry day was defined as when precipitation was less than 0.2 mm (Afzal et al. 2015) or when the effective rainfall was equal to zero.

The intra-annual variance of precipitation was calculated using monthly precipitation totals, as daily data include days without any precipitation, which would result in a distorted variance value. The CUSUM refers to the cumulative sum of differences between the values of a time series and its average. For example, let $X_1, X_2, \ldots, X_{365}$ represent the daily values of an annual precipitation time series and $\bar{X}$ the mean of that time series. From this, the cumulative sums, $S$, are calculated using the following equation:

$$ S_i = S_{i-1} + (X_i - \bar{X}) $$

for $i = 1, 2, \ldots, 365$. The cumulative sum begins with $S_0 = 0$ and because the average is subtracted from each value, the cumulative sum also ends at zero ($S_{365} = 0$). For each year, the annual CUSUM range was calculated by subtracting the maximum CUSUM value from the minimum CUSUM value. Thus, the intra-annual CUSUM range is a measure of the temporal distribution of rainfall within a year, with a small value meaning that rainfall is more uniformly distributed throughout the year (Afzal et al. 2015). Both the intra-annual variance and the intra-annual CUSUM range were normalised by dividing by the square of the mean and the mean, respectively.

Seasonal changes in precipitation were calculated using the w/s ratio of precipitation, which in this study is defined as the ratio of average precipitation from December through February to average precipitation during the June–August season.

The CUSUM of annual precipitation was also computed using Equation (6), but with $X_i$ and $\bar{X}$ representing individual values in a total annual precipitation time series and average annual precipitation over a 20-year period, respectively. Hence the CUSUM of annual precipitation shows how individual values compare to the 20-year average. During periods when total annual precipitation is below average, the CUSUM will decrease, while it will increase when annual precipitation values are above the 20-year average.

Periodicity of rainfall

The above measures of rainfall variability represent semi-random variations within a year and from year to year, and have limited use in describing periodic variations. Where there is a periodic variation in rainfall the amount of storage required is a function of both the amplitude and the period of variation. The reliability of reservoirs can therefore be expected to be proportional to both the period and amplitude of such variations. This is represented in Figure 4, which illustrates the decrease in reliability for a simple cosine input of different periods for different storage ratios.

The presence of regular periodic variations in the precipitation time series was therefore investigated using autocorrelation and Fourier analysis at 21 of the 40 weather stations for the period 1961–2000. The latter represents the amplitude of variations in terms of the spectral energy and periods by the predominant frequency peaks. The precipitation data were expressed as standardised residuals from a linear trend line calculated using the least squares
approach. The removal of a linear trend prior to plotting the autocorrelation function and the periodogram was necessary in order to meet the stationarity requirements of the two techniques, while the use of anomalies ensured that the annual cycle did not dominate the spectral signal. In the periodogram, the peak periodicity in each of the three ranges of frequency depicted in Figure 5 was identified.

Relationship between reliability of water supply systems and the variability and periodicity of rainfall

To investigate the relationship between rainfall variability and reservoir reliability, the rainfall time series of each of the 40 weather stations were divided into time periods of 20–30 years (depending on the length of data records available), creating a total of 87 rainfall datasets. The reliability of a notional reservoir having the mean storage and demand ratio of the six case study reservoirs was calculated for each rainfall dataset (and as above using the mean catchment characteristics of the eight calibrated R-R models to simulate reservoir inflow). The reliability datasets were then correlated with nine measures of variability, which were constructed using the rainfall datasets, for the same time periods.

A visual inspection was performed to determine whether there is any association between reservoir reliability and the peak periodicities calculated over the same time period in terms of both the amplitude and period of the variation. In addition, the reliability of the two river-intake schemes was calculated at the annual timescale during the periods 1976–2005 and 1963–2005 for the Strontian and Killicrankie rivers, respectively, and was then compared with the variability of rainfall at the nearest weather station.

Re-sequencing of the rainfall time series

Re-arranging the rainfall data created a number of semi-artificial rainfall patterns that were used to investigate further the relationship between extreme rainfall patterns and the reliability of both storage reservoirs and river-intake schemes. This was done to examine the influence of droughts over periods longer than seen during the study period on reliability. The re-sequencing was performed on effective rainfall data; consequently, other meteorological data such as sunshine duration, and maximum and minimum temperatures, which were used to estimate evapotranspiration, did not have to be re-sequenced separately. The method consisted of increasing the concentration of rainfall into two, three, four, and five rainy periods in each year by breaking the daily non-zero rainfall data over a year into equal continuous periods of rain separated by dry periods of the same length. As an example, Figure 6 illustrates the re-sequenced effective rainfall time series at Balmoral.

The effect of evapotranspiration on the reliability of water supply systems

Evapotranspiration was estimated from maximum and minimum temperature and sunshine duration data obtained from
21 weather stations across Scotland, in addition to wind speed, which was assumed to be constant at 2.5 ms\(^{-1}\). This subset of the 40 weather stations was selected because the climatic variables used to calculate evapotranspiration were only available at those weather stations. The analysis was performed over the period 1961–1990, given the availability of the sunshine duration data during that period only.

In the first instance, a sensitivity analysis was performed to assess the influence of each climatic variable on the estimate of evapotranspiration. Then, to determine the effect of changes in evapotranspiration on reservoir reliability, evapotranspiration was arbitrarily increased by 5% and the resulting change in reliability was calculated. Kay et al. (2013) estimated that evaporation has increased in Scotland by approximately 0.6 mm/year during the period 1961–2012. This corresponds to about 0.13%/year, meaning that a 5% increase in evaporation would be expected to be reached in three to four decades if the trend were to continue at the same rate. Nonetheless, other factors affect changes in evapotranspiration such as land use, vegetation type, and urbanisation.

**RESULTS AND DISCUSSION**

**Calibration and validation of the R-R model and sensitivity to the tuneable parameters**

A summary of the results of the calibration and validation of the R-R model is shown in Table 2. It can be seen that the calibration of the R-R model resulted in natural log values of the NSE coefficients greater than 0.5 for all eight catchments. On the one hand, Figure 7(a) shows that the simulated flow of the River Black Cart compares relatively well with the observed flow. This year was selected as its NSE value is similar to the average NSE value of the entire validation period. It can be seen that some of the peak flows were underestimated, as is often the case with R-R models, and that one high flow event was not represented by the model. On the other hand, Figure 7(b) shows the relationship for the 8-year validation period. The model performance was considered satisfactory given that it is modelling the effect of a variety of catchment characteristics such as topography and the conductivity,
porosity, and storage capacity of the soil, the vegetation, and land use (Mansell 2003), all of which affect the partitioning between evapotranspiration, infiltration, and soil moisture storage (Brown & Ward 2013).

The sensitivity of the model to the changes in the values of the five calibrated parameters showed that the model is most sensitive to changes in the value of the translation diffusion coefficient, $\lambda$, with a 5% increase in the value of that variable resulting in a change in runoff greater than 2%. The percentage change in runoff resulting from a 5% change in the value of each of the four other tuneable parameters resulted in an increase/decrease in runoff of 0.5% or less (Figure 8).

Spatial and temporal patterns in the reliability of notional reservoirs

A clear East-West pattern is seen in the average reliability of the notional reservoirs during the period 1976–1990, with higher reliability values observed in the East than in the West (Figure 1). This spatial pattern in reservoir reliability reflects the spatial distribution of rainfall variability across the country, with reliability being lower in the West where rainfall is on average more variable than in the East (Afzal et al. 2013). In addition, reservoir reliability has decreased slightly over time from an average of 79% during the
period 1961–1975 for Scotland as a whole to 77% during the period 1976–1990, and further decreased to 76% during the period 1991–2005 (Figure 9). The highest decrease was observed in the West, although 1976–1990 and 1991–2005 have almost identical means. An examination of the temporal changes at three locations with longer data records showed that reservoir reliability has decreased overall during the period 1931–2005, showing that the decrease in reliability seen in recent decades is a continuation of a trend that started a few decades earlier (Figure 10).

**Relationship between reliability of water supply systems and rainfall variability**

In view of the range of variables measuring different aspects of rainfall variability, it is useful to investigate which variables are most closely connected with reservoir performance.

Eight out of the nine measures of rainfall variability showed a statistically significant correlation with the average reliability of the six case study reservoirs. The strongest correlation is seen for the w/s ratio of precipitation (Figure 11(a)). It was found that both an increase in summer rainfall as a proportion of total annual precipitation, and a decrease in winter precipitation as a proportion of total annual precipitation, increase reservoir reliability (Figure 11(b)), which reflects the fact that water supply systems are more likely to fail during the summers months in the UK when precipitation is lower and demand higher. The combined effect on reservoir reliability of precipitation during all seasons as observed using the normalised CUSUM of daily precipitation was slightly weaker, although still statistically significant (Figure 11(c)). A relationship of similar magnitude was seen between the normalised intra-annual variance of monthly precipitation and reservoir reliability (Figure 11(d)).

A statistically significant correlation was also observed between reservoir reliability and measures representing the variability of rainfall between years. A strong relationship was noted with the normalised CUSUM of total annual precipitation (Figure 11(e)), although it is weaker than for the w/s ratio, while the coefficient of variation showed a weak correlation with reservoir reliability (Figure 11(f)). The annual number of dry days was unexpectedly found to be positively correlated with reservoir reliability (Figure 11(g)), although the relationship is weak. This could be due to the sequences of dry days within a year, which can be made up of many short dry periods that have little impact on reservoir reliability. There is also a possibility that this could be the impact of more precipitation, but coming from fewer wet
days. Figure 11(h), which includes re-sequenced rainfall data, shows that there is no significant relationship between reservoir reliability and the average length of a dry spell in a year.

The above analysis demonstrated that the measures related to the distribution of rainfall within the year were seen to be the best indicators of rainfall variability with regards to the reliability of storage reservoirs in Scotland.
These included the w/s ratio of precipitation and the proportion of summer rainfall to total annual precipitation. Some measures related to the variability of rainfall from year to year were also found to significantly influence reservoir reliability, in particular, the CUSUM of total annual precipitation, suggesting the potential influence of rainfall periodicities on reservoir reliability.

The w/s precipitation ratio was not seen to significantly influence the reliability of the river-intake schemes (Figure 12(a)), nor did the ratios of winter or summer precipitation.
precipitation to total annual precipitation (Figure 12(b) and 12(c)). The normalised annual CUSUM of daily precipitation and the intra-annual variance of monthly precipitation showed the strongest correlation with the reliability of both river-intake schemes (Figure 12(d) and 12(e)). This indicates that the distribution of rainfall during the year and its variability between months are the most important variables influencing the reliability of the river-intake schemes in Scotland. No statistically significant correlation was seen with either the number of dry days per year or the average dry spell length.

**Relationship between reliability of water supply systems and the periodicity of rainfall**

Figure 13 shows that many weather stations exhibit statistically significant autocorrelation coefficients at different lags in the monthly precipitation anomaly time series. Repeating patterns in rainfall anomalies appear to be particularly dominant in West Scotland, and many weather stations experience positive autocorrelation at lags between 8 and 14 months and between 18 and 20 months (see Figure 1 for the depiction of the three regions of Scotland). A similar spatial pattern is seen in the spectral analyses, which show that weather stations with greater spectral energy prevail in West Scotland (Figure 14), where reservoir reliability is, on average, lower than in the East (Figure 1).

The peak energy level of the longer-term periodicities (Figure 14), which is also shown by the limited number of weather stations having significant autocorrelation at lags of less than 8 months (without considering lag-one). Figure 14 also shows that the East–West asymmetry in the amplitude of the periodicities, as represented by the energy spectrum, is similar for the three categories of periods of variations, i.e. less than 6 months, between 6 and 12 months, and longer than 12 months.

One would expect reservoir reliability to decrease as a result of an increase in the amplitude of the inflow variation and/or an increase in the period of variation. This analysis has demonstrated that the lower reservoir reliability seen in the West is associated with the presence of significant periodicities in rainfall anomalies as shown by autocorrelation and spectral analyses. In the East the autocorrelation coefficients were not as statistically significant and the amplitude of the periodicities, as represented by the peak energy spectrum, was found to be much weaker than in the West.

**Relationship between reliability of water supply systems and evapotranspiration**

The sensitivity analysis of the components of evapotranspiration revealed that sunshine duration is the climatic variable that has the greatest influence on evapotranspiration, but temperature is also significant (Table 3), which is consistent with the work of Gao et al. (2006) in China. Due to the limited availability of wind speed data at many
weather stations, a constant wind speed value was used; although wind speed was found to influence the estimate of evapotranspiration, it was less significant than the other climatic variables.

It was also shown that a 5% increase in evapotranspiration in the R-R model (keeping rainfall unchanged) decreased reservoir reliability by less than 1% with the exception of one time-period at one reservoir (Figure 15). This is because this 5% change in evapotranspiration resulted in a decrease in runoff of only 1.4%, whereas the same percentage change in rainfall increased runoff by 6.6%. This suggests that the influence of evapotranspiration is weak in comparison to that of rainfall, although such a modest percentage change is about the same magnitude as the changes in the reliability of storage reservoirs experienced in Scotland during the period 1961–2005.

### Table 3

<table>
<thead>
<tr>
<th>Climate variable</th>
<th>Change in evapotranspiration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>9.5</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>10.6</td>
</tr>
<tr>
<td>Wind speed</td>
<td>5.3</td>
</tr>
</tbody>
</table>

![Figure 15](image-url) | Change in reliability as a result of 5% increase in evapotranspiration.

**CONCLUSIONS**

The motivation of this study was that a warmer climate under global warming will intensify the water cycle, leading to an increase in the occurrence of extreme events as well as
a general increase in precipitation, thereby potentially leading to changes in water resource availability. Trends in global precipitation and evapotranspiration suggest that an acceleration of the hydrological cycle is already occurring, with higher evapotranspiration rates in the summer months leading to the drying of soils and vegetation (Huntington 2006).

An increase in rainfall variability, including the presence of periodicities, is of particular concern to Scotland whose water supply originates mostly from surface sources. Hence this paper provided an insight into the relative importance of climate variability on the reliability of water resource systems in Scotland. It was found that the temporal distribution of rainfall within a year, and in particular the w/s ratio, significantly influences reservoir reliability. In addition, reservoir reliability was found to be influenced by variations in precipitation from year to year as measured by the CUSUM of annual precipitation. However, the w/s ratio was found not to significantly influence the reliability of river-intake schemes, which was rather related to variations in the intra-annual CUSUM range and the intra-annual variance of precipitation. In addition, the presence of periodic patterns in rainfall anomalies was found to be more prevalent in the West, and accordingly reservoir reliability is, on average, lower in the West than in other parts of Scotland.

The results of this study do not foresee an alarming trend in water supply reliability across Scotland, as the decrease in reliability seen over the last few decades has as yet been modest in comparison to the percentage of water lost through leakage, for example, the latter accounting for 34% of the water abstracted nationally (Scottish Water, personal communication, July 2013). Nevertheless climate models predict enhanced seasonality under climate change (i.e. wetter winters and drier summers) and bearing in mind the significance of the w/s ratio observed in this study, a decrease in the yield to demand ratio might become a concern in some localised areas, particularly if climate change also leads to an increase in the demand for water (Arnell 1998). An increase in variability at shorter timescale, as represented by the variance of precipitation between months, under climate change, would also negatively impact on the supply of water from river-intake schemes, which is the main source of water in many parts of the country.

This study has some limitation, however. It should be noted that the correlation analysis between the different measures of rainfall variability and the reliability of storage reservoirs was not calculated at individual reservoirs, but on a notional reservoir having the mean characteristics of the case study reservoirs. As six reservoirs and two river-intake schemes were used, the current analysis does not include a comprehensive analysis of water supply systems across the country, but does provide a synopsis of the role of the variability and periodicity of rainfall as well as evapotranspiration on the reliability of surface water supplies in Scotland, a topic that has to date not been given sufficient attention. Further research will assess how climate variability is projected to change under climate change and its potential impacts on the reliability of water supply systems in Scotland.

ACKNOWLEDGEMENTS

The authors wish to thank the British Atmospheric Data Centre (BADC) for the climatic data, and CEH and SEPA for providing the river flow data. We are also thankful to Dr Owen Bramwell, Mary Lynch, and Derek Ball from Scottish Water for providing the required reservoir and river-intake scheme data. A. S. Gagnon acknowledges financial support from the Scottish Alliance for Geoscience, Environment and Society (SAGES). We also acknowledge the constructive comments of three anonymous reviewers.

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First received 3 December 2014; accepted in revised form 23 September 2015. Available online 30 October 2015