How low can you go? Using drought indices to protect environmental flows in Scottish rivers.

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Abstract
Prolonged dry spells in a maritime climate such as Scotland are rare. The corollary of this is that when they do occur, riverine ecosystems are poorly adapted and are vulnerable to the impacts of reduced flows. A set of drought and low flow indices have been developed for use by the Scottish Environmental Protection Agency (SEPA) to quantify the severity and duration of dry spells. These indices provide a robust and consistent method of assessing imminent drought conditions using both rainfall and flow time series to quantify the range of drought types which can occur in Scotland. This paper demonstrates the efficacy of these indices using case studies from the years 1976, 1984, 2003 and 2010. The indices are tested for their ability to accurately represent the regional patterns, timing of initiation and severity of droughts using quantitative and anecdotal information from water resource managers. SEPA’s operational use of these indices is discussed in relation to how water resource can be managed during dry spells to optimise the balance between socio-economic demands and the needs of the aquatic environment.

Introduction
At the time of writing (April 2012) a potentially severe drought is developing in parts of southern and eastern England where over a year of lower than average rainfall has led to depressed groundwater, river and reservoir levels and large soil moisture deficits (Environment Agency, 2012). In Scotland the current situation is much less severe and it is tempting to believe that this is further evidence that drought impacts are rare in the wetter, maritime Scottish climate. The evidence, however, points to a rather different conclusion. An analysis of historical drought impacts in Scotland (Zaidman et al., 2012) shows that it is departure from normal rather than a measure of absolute water supply that determines whether water scarcity impacts occur. This is not surprising since economic considerations lead to the design of water resource management systems that make use of the plentiful supply of water in Scotland and balance the cost of building resilience against low water supply episodes against the risk of occurrence. The same conclusion, i.e. that it is relative rather than absolute deficits that cause water resource related stress, may be made for many aquatic species in rivers and lochs where, in these cases, the processes of natural selection and competition have resulted in biological communities that are adapted to a range of flow or water level conditions typical to the habitat (Maitland, 1964). Under drought conditions, those species which are more specialised to the typical environmental conditions may suffer large drops in productivity. The degree of impact upon aquatic flora and fauna and the subsequent recovery times vary depending upon the timing and severity of the drought but are also be impacted by the degree of anthropogenic modification of the habitat. Alterations to sediment supply, channel modifications and obstructions to species migration have been shown to exacerbate the impacts of low flow episodes (Wood and Petts, 1999, Dunbar et al., 2010).

Development of the drought indices
There are many published drought indices in use worldwide and indeed many comparisons of indices (e.g. Heim, 2002, Hayes, 2007 and Niemeyer, 2008) reflecting the complexity of drought-forming mechanisms and the wide range of effects that can fit within the umbrella definition of drought impacts. The process of selecting and testing drought indices for use within Scotland followed four phases, namely:

- The development of a drought catalogue for Scotland, including a categorisation of historic events in terms of severity;
- A literature review of existing drought indices in commonplace use worldwide;
- The selection of candidate drought indices using evaluation criteria;
- The validation of drought indices and their severity threshold values using case studies chosen from the drought catalogue.
A catalogue of historic droughts in Scotland

A drought catalogue for Scotland has been assembled, consisting of two key components:
1. A timeline of historic droughts and impacts chiefly based on anecdotal information, although drawing on other peer reviewed literature where available and contemporary scientific reports and datasets. The drought catalogue is shown in Table 1.
2. Case studies: Following on from point 1, a more detailed review of the droughts of 1975/76, 1984, 2003/04 and 2010 has been undertaken. This has considered extent, duration and underlying hydro-meteorological drivers as well as the degree to which each event impacted on water resource availability (e.g. reservoir for public supply, river abstraction for irrigation, hydropower).

Existing drought indices and the evaluation criteria

For the purposes of the review, drought indices were divided into three broad categories: meteorological, soil moisture/agricultural, hydrological. A review of the more widely-used indices falling within these categories is available in Zaidman et al. (2012). Within these categories, a number of indices or index types with similar characteristics were identified and it was these that were considered for evaluation. Although soil moisture/agricultural indices were evaluated, they were rejected as operational indices as they generally required data that SEPA could not guarantee to have access to in real time. The review also avoided those indices specifically aimed at defining droughts on a regional basis, such as those described by Hannaford et al. (2010). The indices and index types evaluated were:

**Meteorological indices**
- Percent of normal, discrete and cumulative precipitation anomalies. These indices are widely used because they are versatile, straightforward to calculate and readily understood, e.g. percentage of long term average rainfall. However, they typically do not account for the skewed distribution of rainfall data and can be misleading when used to compare regions.
- Standardised rainfall anomalies. These consider the scale of departures from long term averages relative to the standard deviation but usually also account for the fact that rainfall data are not normally distributed, e.g. in the well-known Standardized Precipitation Index (SPI) (McKee et al., 1993) where the rainfall data are transformed to a normal distribution.

<table>
<thead>
<tr>
<th>Year</th>
<th>Period</th>
<th>Description of drought</th>
<th>Location of impacts</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1666</td>
<td>May to mid-July</td>
<td>&quot;phenomenal dryness&quot;</td>
<td>England Wales and Scotland</td>
<td>Chronicle of the Frasers cited in CBHE*</td>
</tr>
<tr>
<td>1826</td>
<td>July - August</td>
<td>Extraordinarily dry and hot</td>
<td>Widespread. From Isle of Bute, to Tayside and Aberdeenshire</td>
<td>CBHE</td>
</tr>
<tr>
<td>1871</td>
<td>Not known</td>
<td>High rainfall deficiency index</td>
<td>Scotland</td>
<td>Marsh and Lees 1985</td>
</tr>
<tr>
<td>1887</td>
<td>Not known</td>
<td>&quot;The capacity of those schemes which were in operation during 1887 was more severely taxed than in those of forty subsequent years&quot;.</td>
<td>NW England and Scotland</td>
<td>Brooks and Glasspoole (1928)</td>
</tr>
<tr>
<td>1902</td>
<td>Winter/Spring</td>
<td>&quot;The lack of rain in the winter months began to be felt, the ground being very dry and the springs low.&quot;</td>
<td>Aberdeenshire</td>
<td>CBHE</td>
</tr>
<tr>
<td>1913</td>
<td>July to October</td>
<td>&quot;Glasgow has only 77 days’ water supply, the river Tay has reached the lowest level on record&quot;**.</td>
<td>Glasgow, Rivers Tay and Garry</td>
<td>Colonist, Volume LV, Issue 13808, 23 August 1913, Page 5</td>
</tr>
<tr>
<td>1933/4</td>
<td>Annual</td>
<td>Low rainfall totals across much of the UK</td>
<td>England Wales and Scotland</td>
<td>CBHE</td>
</tr>
<tr>
<td>1941</td>
<td>Spring/Summer</td>
<td>The January to June rainfall totals for Scotland in 1941 remained the lowest on record until 2010</td>
<td>Scotland</td>
<td>Source unknown</td>
</tr>
<tr>
<td>1955</td>
<td>Summer</td>
<td>Very sunny and hot during July and August</td>
<td>Scotland</td>
<td>Marsh and Lees 1985</td>
</tr>
<tr>
<td>1959</td>
<td>Summer</td>
<td>Gladhouse Reservoir was almost dry and standpipes were in use widely across Clackmannanshire.</td>
<td>Forth river basin</td>
<td>Pathe News 1959</td>
</tr>
<tr>
<td>1975/6</td>
<td>Peaking in summer 1976</td>
<td>Hot dry summer following 18 months of below average rainfall</td>
<td>South East Scotland</td>
<td>Rodda and Marsh 2011</td>
</tr>
<tr>
<td>1984</td>
<td>April to September</td>
<td>Considered an extremely severe drought with rainfall averages typically less than 70% of the LTA</td>
<td>Dumfries and Galloway, the eastern Cheviots, the Clyde Valley and Tayside</td>
<td>Marsh and Lees 1985</td>
</tr>
<tr>
<td>1995</td>
<td>April to August</td>
<td>Rainfall 68% of LTA</td>
<td>Highland and also Lothian Rivers</td>
<td>Marsh 1996</td>
</tr>
<tr>
<td>2003/4</td>
<td>Summer 2003 but extending to 2004 in E Scotland</td>
<td>Long-term rainfall deficiencies over this period were amongst the lowest on record for many of catchments in North West Scotland.</td>
<td>Scotland and in particular Angus, Tayside and Dundee</td>
<td>Scottish Water 2005</td>
</tr>
<tr>
<td>2008</td>
<td>May and June</td>
<td>Very low rainfall and river flows</td>
<td>NW Highlands, Skye and the Western Isles</td>
<td>Scottish Water 2008</td>
</tr>
<tr>
<td>2010</td>
<td>May and June</td>
<td>Low rainfall during preceeding winter followed</td>
<td>Southern and Central Scotland</td>
<td>Scottish Water 2010</td>
</tr>
</tbody>
</table>

*http://www.dundee.ac.uk/geography/cbhe/
distribution by assuming the data fit a Gamma distribution

- Decile based system. This uses the long term data to express the current rainfall in terms of percentiles.

**Hydrological Indices**

- Percent of normal, discrete and cumulative flow anomalies.
- Standardised flow anomalies.
- Percentile based system. As with rainfall but with using flow data these require the production of percentiles from the long term data and then use a threshold percentile to define the onset of drought.
- The Palmer Hydrological Drought Index (PHDI) and the Surface Water Supply Index (SWSI). Two indices grouped together as they are data demanding and computationally intensive.

Several studies have described desirable drought index characteristics and have gone on to use these criteria to evaluate different indices (e.g. Keyantash and Dracup, 2002; Nalbantis and Tsakiris, 2009). Using these studies alongside the particular requirements for operational use by SEPA, a set of general criteria has been developed and used to evaluate the meteorological and hydrological drought indices. The results of this evaluation are presented in Tables 2 and 3.

The scoring system used to evaluate the indices assisted in the identification of four drought indices warranting further investigation, namely the standardised anomalies (meteorological and hydrological), the SPI (meteorological) and the percentile approach (hydrological). As pointed out earlier, the SPI is a particular version of standardised anomaly where the data are transformed assuming either a 2- or 3-parameter form of the Gamma distribution. A simpler approach is to assume the data fits a Log-normal distribution where the anomaly or Z score becomes:

\[
Z\text{-score} = \frac{\ln(X) - \text{Average of logged values}}{\text{Standard deviation of logged sample}}
\]

This approach has been previously applied by Zaidman et al. (2002) and Shukla and Wood (2008) amongst others. Except for the different underlying distribution, this approach is analogous to the SPI, but is more straightforward to apply in practice. A suggested term for this index is the ‘normalized precipitation index’ (NPI) or, where applied to flow data, the ‘normalized flow index’ (NFI).

Each of the indices can be applied to any suitable duration such as 1, 3, 6 or 12 months. The duration determines the period over which the anomaly or percentile is calculated, e.g. a 3-month NPI determines the standardised anomaly of logged rainfall values over the previous 3 months. Clearly, longer durations are suitable for picking up seasonal or multi-year droughts whereas short duration indices will be more sensitive in identifying acute drought impacts.

Using daily data from 10 SEPA flow gauging stations and 7 UK Met. Office rainfall stations distributed across much of the Scottish mainland, the four indices (NPI, SPI, NFI and percentiles) were assessed to determine how successful they were in picking out the droughts since the early 1970s, as identified in the drought catalogue.

**Results**

Figure 1 compares the results of applying the four indices to data from the Clyde region, based on a 3-month duration. The period of record in each case is 1960–2011. A 3-month duration is used as this is generally indicative of the length of droughts affecting Scotland, which tend to be short and focused on the spring and summer months (see Table 1). The NFI and NPI produce positive values for dry episodes whereas the SPI produces negative values.
The first point to note from the analysis of indices in Figure 1 is that all four indices were successful in picking out the key drought years in Scotland. The drought-rich period in the early 1970s, the 1976 drought, the 1984 drought, the 1995/96 drought and the 2003 drought can clearly be seen in each set of results. Similar relationships between the indices shown in Figure 1 were to be found in the other regions of Scotland and lead to the following main conclusions:

- The SPI and NPI tend to identify the same events and assign those similar values (albeit of opposite signs). From a practical viewpoint there are two reasons to favour the NPI over the SPI; it is easier to calculate and gives a positive value for drought events (the data are therefore easier to manipulate or show graphically).
- The percentiles method does not distinguish dry periods as strongly as the other drought indices.
- The drought response captured in the rainfall record may be quite different to the drought response captured in the flow record for a nearby gauging station. This may reflect catchment factors or may suggest that a log-normal distribution is not characteristic of some flow records in Scotland.
- There are strong regional patterns in drought across Scotland. These patterns initially seem to be aligned with anecdotal evidence.

The standardised anomaly NPI was shown to consistently replicate the more complex SPI across all regions and, along with the NFI, was able to identify the severity of past drought events. The NFI and NPI were also sensitive indices, due to their representation of the non-normal distribution of the data, and were therefore suitable for the application of thresholds to assess drought severity. Finally, the NFI and NPI could be shown to be both site-specific but also easily adaptable to regional characterisation of drought and as a consequence, these indices have been chosen by SEPA as the preferred tools for operational drought monitoring.
Identification of drought thresholds

Using the drought catalogue it was possible to determine the most appropriate index durations and severity thresholds to best capture past drought events. It was shown that applying the rainfall index, NPI, at a duration of three months was most suitable for capturing the drought events since the early 1970s whereas a one-month duration was optimal for the NFI. The historical analysis also indicated that drought severity thresholds do need to be different, depending upon the duration of the index. Table 4 illustrates the suggested trigger levels for the different indices and durations.

Using the drought indices to protect the water environment

The key to managing the environmental impacts of a drought, particularly where the water environment is already vulnerable from existing impacts, is in advanced planning and by producing a clear set of actions both at the broad national and regional levels and, where the environmental risk is high, at a site-specific level. SEPA regulates water resource impacts in Scotland through the Water Environment (Controlled Activities) (Scotland) Regulations 2011 (CAR). The standard determination time for a CAR licence can be up to four months and in emergency situations like a drought, such a delay would be unacceptable. As a result, further provisions were introduced in CAR 2011 to ensure sufficient flexibility to respond to emergencies provided a number of conditions are met, including the demonstration that the circumstances, such as the dry episode, are exceptional. One use of the drought indices will be in providing evidence of whether or not conditions are exceptional and will therefore limit the allowance of a temporary deterioration of ecological status to only those events where such actions are necessary.

Actions that can be taken during a drought

A consultation on the national water shortage plan for Scotland is being led by SEPA in 2012. The consultation will determine the types of actions to be taken during a drought. Consultees are being asked to comment on a progressive, staged approach to managing impacts as drought risk and severity increases. Actions that can be taken include:

- Early warning and providing advice about water saving measures. Under CAR, those operators carrying out controlled activities such as water abstractions have a duty to "...take all reasonable steps to secure efficient and sustainable water use" (Regulation 6 CAR). Although this requirement is valid at all times, providing advice and early warning of drought risk should assist operators in choosing options such as publicising water saving information, making changes in storage management and the operation of alternative sources. Timely adoption of water saving measures and supply management has the aim of mitigating the impact of shortages in natural water supply and therefore reducing the potential risk to the water environment.

- Implementing scheduling of water abstractions. In some catchments experiencing low flow conditions, the impact of multiple abstractions upon aquatic ecology can be reduced by scheduling abstractions so that they are spread out over time rather than occurring simultaneously. Such agreements can be planned and written into management agreements long before a drought occurs and triggered by evidence of drought risk including that provided by the drought indices. Here it is likely that a local Normalised Flow Index would be of greatest use.

- Reducing the quantities that operators can abstract. A staged approach to drought management can include a progressive reduction in allowable take as drought risk increases. Once again, such actions could be informed by the local NFI.

- Temporary amendments to environmental flow requirements. Where the socio-economic benefit of an abstraction is high, such as in the provision of drinking water, it may be necessary to make temporary amendments to mitigation such as compensation flows or freshets. Such actions should be planned well in advance at a site specific level and should take account of the sensitivity of the aquatic habitat. As pointed out above, drought indices will help in the assessment of drought severity and will be used in conjunction with the assessment of risk to water supply.

- Stop notices. When drought risk is high it may be necessary to suspend the licence to abstract in order to protect the aquatic environment.

As has been suggested, the choice of when to implement each stage in the progression of measures can be informed by the drought indices. It is likely that the early stages of a drought will be assessed using the NPI at a three month or longer duration. However, as the drought develops and measures become more closely related to localised impacts, such as risk of rivers running dry, the shorter term indices such as the one month NFI will become more relevant. It should be pointed out that sole reliance on drought indices as risk increases may not be the best option. The indices add to the weight of evidence of the increased risk of drought impacts occurring. At the early stages as a drought begins to develop, the indices may provide the only indication of risk and as such it may be appropriate to use them to drive action. However, as drought severity increases and actions become more intrusive, additional information may be required, such as evidence of ecological or water quality impacts and these may need to be balanced against the evidence of risk to water supply. Once again, the a priori development of national, regional and local plans or, indeed, water resource sector-specific plans, should help make clear the processes of how to assess such evidence so that, as a drought develops, appropriate mitigation can be applied in a timely manner.

Summary and Conclusions

By examining the ability of a range of drought indices to assess the timing and severity of known water shortage impacts in Scotland over the last 50 years, it has been possible...
to select two indices which can be used operationally by SEPA to assess drought risk. SEPA propose to develop a tool which will produce and display near real-time drought risk for the whole of Scotland and in so doing, will provide evidence to support a range of actions aimed at protecting the water environment during exceptionally dry spells.

References


