Journal of Hydrology 550 (2017) 368–385

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

# National-scale analysis of simulated hydrological droughts (1891–2015)

Alison C. Rudd *, Victoria A. Bell, Alison L. Kay

*Centre for Ecology & Hydrology, Wallingford, Oxfordshire OX10 8BB, UK*

ARTICLE INFO

*Article history:*
Received 1 November 2016
Received in revised form 5 May 2017
Accepted 10 May 2017
Available online 11 May 2017
This manuscript was handled by T. McVicar, Editor-in-Chief, with the assistance of M. Vicente-Serrano, Associate Editor

*Keywords:*
Drought severity
River flow modelling
Low flow
Soil moisture
Drought characteristics
Great Britain

ABSTRACT

Droughts are phenomena that affect people and ecosystems in a variety of ways. One way to help with resilience to future droughts is to understand the characteristics of historic droughts and how these have changed over the recent past. Although, on average, Great Britain experiences a relatively wet climate it is also prone to periods of low rainfall which can lead to droughts. Until recently research into droughts of Great Britain has been neglected compared to other natural hazards such as storms and floods. This study is the first to use a national-scale gridded hydrological model to characterise droughts across Great Britain over the last century. Firstly, the model performance at low flows is assessed and it is found that the model can simulate low flows well in many catchments across Great Britain. Next, the threshold level method is applied to time series of monthly mean river flow and soil moisture to identify historic droughts (1891–2015). It is shown that the national-scale gridded output can be used to identify historic drought periods. A quantitative assessment of drought characteristics shows that groundwater-dependent areas typically experience more severe droughts, which have longer durations rather than higher intensities. There is substantial spatial and temporal variability in the drought characteristics, but there are no consistent changes through time.



## 1. Introduction

Drought is a recurrent natural hazard that impacts many sectors, for example agriculture (rain fed and irrigated), ecosystems (terrestrial and aquatic), energy and industry (hydropower and cooling water), navigation, drinking water and recreation (Van Loon, 2015). Droughts are different to other weather hazards in that they tend to develop slowly, over a large area, with the exact beginning and end often difficult to identify (NHP, 2013). Studying historic droughts is essential to inform water management practises and improve efficiencies in order to build resilience.

The terms droughts, aridity and water scarcity are often confused. Van Loon et al. (2016) define drought as "simply an exceptional lack of water compared to normal conditions" whereas aridity is a climatic feature of a region (low rainfall area) and water scarcity occurs when there is not enough water to meet the demand. Most droughts of the world today have both natural and human drivers (Van Dijk et al., 2013; Van Loon et al., 2016). Artificial influences such as surface and subsurface abstractions, urbanisation and deforestation can all affect the impact of a drought. There are different types of droughts (Wilhite and Glantz, 1985; Alley, 1985; Van Loon, 2015) for example, meteorological (period of below normal rainfall), hydrological (below normal river flow or water level in lakes, reservoirs, groundwater), agricultural (below normal soil moisture levels), and socio-economic (associated with the impacts of the environmental drought types). It is however difficult to define and quantify a drought in absolute terms due to regional and local variations in the extent, duration and intensity of an event.

An array of indices exist to define a drought, broadly separated into two classes (Zargar et al., 2011; Van Loon, 2015;): (i) standardised drought indices; and (ii) thresholds. Commonly used standardised meteorological drought indices are the Standardised Precipitation Index (SPI; Mckee et al., 1993), the Standardised Precipitation and Evaporation Index (SPEI; Vicente-Serrano et al., 2010) and the Standardised Palmer Drought Index (SPDI; Ma et al., 2014). Examples of standardised hydrological indices are the Standardised Streamflow Index (SSI: Vicente-Serrano et al., 2012) and the Standardised Runoff Index (SRI: Shukla and Wood, 2008). An advantage of standardised indices is that regional comparisons can be made because they represent anomalies from a normal situation in a standard way. A disadvantage is that they generally require an appropriate statistical distribution to be identified (unless no extrapolation is required, Vidal et al., 2010). There are similar indices based on spatially continuous remotely sensed data, for example vegetation indices (Aghakouchak et al., 2015; McVicar and Jupp, 1998).

* Corresponding author.
*E-mail address:* alirud@ceh.ac.uk (A.C. Rudd).

http://dx.doi.org/10.1016/j.jhydrol.2017.05.018
0022-1694/

The threshold level method can be used to derive drought characteristics from time series of observed or simulated hydrometeorological variables. With this method, a period of deficit or drought occurs when the variable of interest (e.g. flow, soil moisture, ground water storage) is below a predefined threshold level (fixed, or variable though the year e.g. seasonal, monthly or daily). A drought event starts when the variable falls below the threshold and continues until the threshold is exceeded again. Characteristics such as drought severity, intensity and duration can then be calculated (Yevjevich, 1967; Hisdal et al., 2004). Advantages of the threshold level method are that there is no need to fit a distribution to the data and that it is easy to calculate the drought characteristics. A disadvantage is that there is no standard definition for the threshold level(s).

One of the main applications of drought indices is drought monitoring and early warning (M&EW). Little can be done to prevent a meteorological drought, however steps can be taken to prevent or alleviate the impact of a hydrological or agricultural drought. Systems such as the U.S. Drought Monitor (droughtmonitor.unl.edu) and the European Drought Observatory (edo.jrc.ec.europa.eu) provide M&EW of droughts. Drought indices can also be used retrospectively to analyse past droughts. In France Vidal et al. (2010) have identified droughts using standardised indices (1958–2008) and in Norway Tallaksen and Hisdal (1997) analyse regional characteristics of drought duration and deficit volume using streamflow data (1931–1990) and the threshold level method.Corzo Perez et al. (2011) provide a global perspective on the spatio-temporal nature of hydrological droughts (1963–2001) using the threshold level method and the WaterGAP Global Hydrology Model. Thanks to flow reconstructions, drought analysis can be carried out even further back in time; Caillouet et al. (2016b), in France, and Meko et al. (2012), in the Colorado basin, make use of reconstructions from Twentieth Century Reanalysis (1871–2012) and dendrochronology (A.D. 762–2005) respectively. See Table 1 in Wada et al. (2013) for more examples of hydrological drought studies using streamflow data.

In this study a national-scale hydrological model, Grid-to-Grid (G2G), is used to examine British droughts from 1891 to 2015 using the threshold level method. The study objectives are to:

(i) Assess the model performance of the G2G hydrological model at simulating low flows;
(ii) Identify droughts at a national-scale (1891–2015); and
(iii) Analyse drought characteristics in space and time.

These objectives provide the structural sub-headings used in the following Methods, Results and Discussions sections.

## 2. Study area and materials

Despite Britain's reputation as a rainy country, parts of south-east England in particular are relatively water stressed (Environment Agency, 2008), and it is important to be prepared for drought in order to limit impacts and sustain water supplies (Environment Agency, 2015). Marsh (2007) commented that England and Wales are now considerably more resilient to drought stress than in the nineteenth century when droughts posed a real threat to lives and livelihoods. However, with climate change affecting the water cycle (Watts et al., 2015) and increases in water demand from population growth, it is necessary to continue to build on this resilience. There is no coherent drought-focussed M&EW in the UK (Barker et al., 2016), although the National Hydrological Monitoring Programme assesses the on-going hydrological situation (nrfa.ceh.ac.uk/nhmp) and the UK Hydrological Outlook provides predictions of river flow and groundwater for the next 1 and 3 months (www.hydoutuk.net).

The UK can experience both summer and multi-year droughts. Summer droughts are usually associated with a heat-wave (Yin et al., 2014), and they can be severe but the impacts can be short lived if autumn rainfall levels are healthy (e.g. 2003; Marsh, 2004). Multi-year droughts are often associated with dry winters and springs where aquifer and reservoir stocks are not replenished. These droughts can have long-lasting impacts (e.g. 1988–1992; Marsh et al., 1994). In general, for the wetter parts of northern and western Britain, household and industrial water supply is from surface reservoirs in upland regions (e.g. the Pennines and Wales), and droughts that cause supply difficulties tend to be of shorter duration and due to a dry spring and summer (Jones and Lister, 1998). In the south and east of England, where groundwater is the principle water supply, problems only tend to occur when flows have been low for at least 15 months (Jones and Lister, 1998) and where groundwater recharge has been minimal.

Direct drought impacts of relevance to the UK include: reduction/loss of agricultural production, reduction of water supply, reduction of energy supply, and environmental impacts such as algal blooms, wildfires, loss of habitats, and river and lake pollution (NHP, 2013). Indirect drought impacts (i.e. those associated with droughts happening elsewhere) include droughts in food producing regions driving higher food prices. The actual impact depends on preparedness and vulnerability to drought and risk reduction during a drought. The impacts of droughts are typically poorly documented, although initiatives such as the European Drought Impact Report Inventory (www.geo.uio.no/edc/droughtdb) and the Chronology of British Hydrological Events (CBHE; cbhe.hydrology.org.uk) provide searchable databases of text records of historical events.

Compared to flood research, drought research in the UK has been relatively neglected, although recent studies have looked at standardised drought indicators (Barker et al., 2016), drought termination (Parry et al., 2016), multi-annual droughts in the English Lowlands (Folland et al., 2015) and implications of historic droughts on water supply yield calculations (Lennard et al., 2016).

### 2.1. Hydrological model

The Grid-to-Grid (G2G) is a national-scale runoff-production and routing model that provides estimates of river flows, runoff and soil moisture on a 1 $km^2$ grid across Great Britain (Bell et al., 2009). The model has a time step of 15 mins and is used within the Flood Forecasting Centre (England and Wales) and the Scottish Flood Forecasting Service for countrywide operational forecasting (Price et al., 2012; Maxey et al., 2012). The G2G has also been used to assess the impact of climate change on flooding (Bell et al., 2012, 2016). An advantage of G2G is that it has one spatially consistent configuration for the whole model domain, and is able to represent a wide range of hydrological regimes due to use of present day spatial datasets of soil, digital terrain and land cover in the model construction. The river flow estimates produced by the model are natural flows and do not take into account surface or groundwater abstractions. Work on enhancing the model to account for abstractions is underway, but not reported here.

The G2G requires as input gridded time series of precipitation and potential evaporation (PE). For the analyses undertaken here, two model simulations have been produced, one for low flow model performance assessment (1971–2000) and one for historic drought identification and characterisation (1891–2015) (Fig. 1). Both model runs use 1 $km^2$ daily precipitation from CEH Gridded Estimates of Areal Rainfall (CEH-GEAR; Tanguy et al., 2015; Keller et al., 2015), which is based on measurements from a national network of rain gauges (see Figs. 2 and 3 of Keller et al.