Science of the Total Environment 407 (2009) 4633–4641

Contents lists available at ScienceDirect

Science of the Total Environment

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

Long-term trends in hydro-climatology of a major Scottish mountain river

N.J. Baggaley [a,*], S.J. Langan [a], M.N. Futter [a], J.M. Potts [b], S.M. Dunn [a]

[a] Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK
[b] Biomathematics and Statistics Scotland, Craigiebuckler, Aberdeen, AB15 8QH, UK

ARTICLE INFO

Article history:
Received 23 July 2008
Received in revised form 11 March 2009
Accepted 14 April 2009
Available online 26 May 2009

Keywords:
Climate change
River flow
Mountain rivers
Flood
Drought
Sampling frequency
River Dee

ABSTRACT

The River Dee, in North East Scotland, is a mountainous river strongly influenced by patterns of snow accumulation and melt from the Cairngorm Mountains. Analysis of this river's flow record from 1929–2004, the longest in Scotland, supports anecdotal evidence that river extreme flows are increasing. There was no detectable change in the overall annual flow patterns. However, an analysis of seasonal data suggested a shift towards increased flows in spring (March–May) and decreased flows in summer (June–August) over the 75 years of the record. Flows in spring exceeded 29 $m^3 s^{-1}$ for 50% of the time over the earliest part of the record (1930 to 1954), whereas in the last 25 years of the record (1979 to 2004) 50% of the flows exceeded 35 $m^3 s^{-1}$. Precipitation is increasing in the spring and decreasing in July and August. If these trends continue they have important implications for water management in the Dee, with a potential increase in flood risk in spring and the increased possibility of drought in summer. Combined with this increase in flows the river appears to be more responsive to precipitation events in the catchment. In large heterogeneous catchments with a marginal alpine/high latitude climate it is difficult to assess the amount of precipitation falling as snow and its relative accumulation and ablation dynamics on daily to seasonal time scales. Changes in the temporal pattern of coherence between flow and precipitation are thought to be linked to changing snow patterns in the upland part of the catchment. A decreased amount of precipitation occurring as snow has led to higher coherence. We also show that in responsive systems it is important to record river flows at an hourly rather than daily time step in order to characterise peak flow events.

1. Introduction

In the UK trends in climate are towards more intense precipitation events in the winter, with similar patterns seen in autumn and spring and reverse trends over the summer months (Osborn et al., 2000). In North East Scotland increasing precipitation has been reported between 1961 and 1995 (Barnett et al., 2006). Climate change predictions suggest that these trends will continue; leading to increased winter precipitation, increasing temperatures and an increase in extreme events (Hulme and Jenkins, 2002). Climate predictions for the upland areas also suggest a decline in snow fall (Harrison et al., 2000). This will have impacts on the annual flow regime of rivers with their head waters in the mountains. In Europe climate cycles are driven by the North Atlantic Oscillation (NAO), with high positive values of the NAO index associated with warm wet winters in Northern Europe and low and negative values colder drier winters, this in turn has been shown to be correlated with river flows (Shorthouse and Arnell, 1999).

Projected changes in climate have fuelled research into the effects on river flow. This has taken two forms. Existing flow records have been analysed to examine the nature of trends that may already be evident. Arnell (1992) and Arnell and Reynard (1996) have shown that trends are more apparent in seasonal and monthly data than in annual mean flows. Trends towards increasing high flows, particularly in spring and autumn, are evident in the available records (Werritty, 2002). In the UK decreases in summer flows are rarely significant. However in the USA and Canada patterns towards decreasing flows, particularly in summer, have been shown to be already evident and have been linked to combinations of changing climate and increased urbanisation in some rivers (Zhang et al., 2001, Zhu and Day, 2005).

The timing of peak precipitation events and catchment Soil Moisture Deficit (SMD) has also been shown to have an effect on the seasonality of flood events in Northern Britain (Black and Werritty, 1997). Both soil moisture and snow dynamics in upland dominated catchments are likely to show a shift as a result of climate change and consequently have an important effect on the seasonality of extreme events, in terms of both flooding and drought.

The second form of research has been the use of modelled climate change scenarios coupled with hydrological models to predict future stream flows. The work by Wilby (2006) on northern upland areas of the UK suggests that changes in summer flows will be difficult to detect up to the 2020s, while, for rivers in England and Wales, monthly average flows may have to change in excess of 70% at certain times

* Corresponding author. Tel.: +44 1224 498200; fax: +44 1224 311556.
E-mail address: n.baggaley@macaulay.ac.uk (N.J. Baggaley).

0048-9697/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2009.04.015

of the year for changes to be detected. Arnell (2003) suggests that decreasing trends in summer flows will only become visible when the record length extends to the 2050s. This is due to the low signal to noise ratio in stream flow predictions, climate cycles and uncertainty in climate change scenarios. Other work, such as Ziegler et al. (2005), has suggested that climate induced changes may already be occurring, but are unable to be detected at a statistically significant level. In the Mississippi, Ziegler et al. (2005) suggest that time series of between 50 and 350 years may be required to detect plausible changes in annual time series.

Projected climate change-related trends in river flows are not necessarily consistent throughout the year suggesting a change in seasonality. In Lithuanian rivers it is suggested that decreasing snow accumulation in headwater catchments will lead to a change in the timing of high flows from April to March and possibly into February (Kilkus et al., 2006).

Changing patterns of river flow have potentially significant impacts for water quality, water abstraction, flooding and habitat availability for a range of aquatic and riparian species (Langan et al., 1997, Moir et al., 2002, Whitehead et al., 2009). It is suggested that water resource planning may need to account for these changes before many of them become statistically significant (Wilby, 2006, Arnell, 2003, Ziegler et al., 2005).

The flow regime of many rivers with their head waters in mountainous areas is often strongly influenced by snow accumulation in winter and subsequent snow melt in spring. Snow melt events lead to increased flows that can contribute to major flood events in a catchment due to the quick release of water with rising temperatures (Ferguson and Morris, 1987). These characteristics influence catchment management and are of concern to regulatory authorities (e.g. SEPA, 2000).

A number of major river systems, including the Dee, of national importance for their contribution to the economic well being of the country through hydropower generation and/or significance in supporting aquatic species have their headwaters in the Cairngorm massif in North East Scotland. The authors have been consulted and told on a number of occasions by people who live and work along the Dee that flows in the river have changed considerably in the last 30 or so years. The Dee supplies 50% of the regions water and is an important salmon fishing river, with game fishing contributing between £5 and £6 million to the local economy in 1995.

This paper sets out to present an analysis of available precipitation, temperature and flow records. The aim is to determine if the available data of the longest continuous flow record in Scotland (1929–2005) supports the hypothesis that flows in the river are changing in a manner consistent with observed patterns climate change.

2. Methods

2.1. Data

A long historic record of daily meteorological data is available from Balmoral (Fig. 1). Precipitation and temperature records date back to 1918. The mean annual temperature is 7 °C with winter minima averaging −14 °C and summer maxima 26 °C. The mean annual precipitation is 850 mm. There is however a significant precipitation gradient across the catchment with annual rainfall in the Cairngorm Mountains in the west of between 1500 and 2000 mm.

Flow data is available from four primary gauging stations on the River Dee: Mar Lodge, Polhollick, Woodend and Park (Fig. 1). These sites are maintained by the Scottish Environment Protection Agency (SEPA) as part of their national flow recording network. There are 15 min flow records available for Park (1973–1980), Polhollick (1975–1980) and Woodend (1972–1980) and all stations from 1990–2005. A continuous record of mean daily flow is available from 1929–2005 at Woodend. Mean daily flow data represents the average flow between

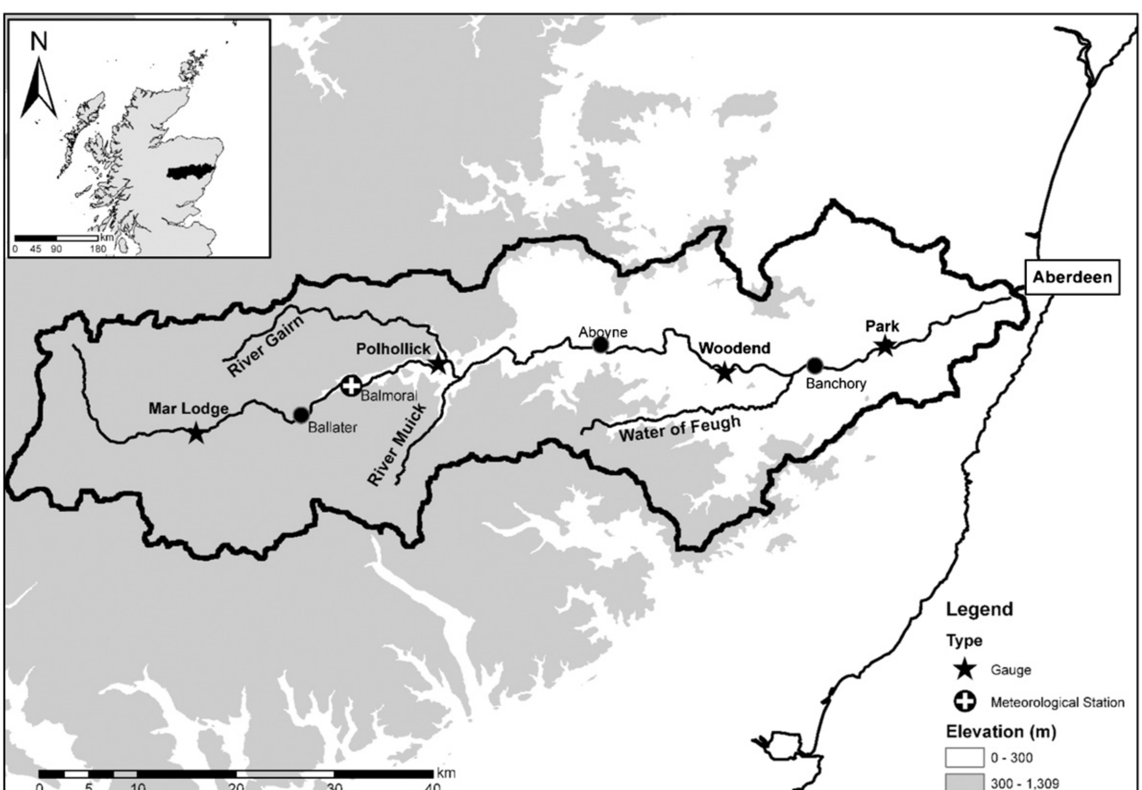

Fig. 1. The Dee Catchment. Showing upland (>300 m) and lowland (<300 m) areas of the catchment. Also shown are the gauging stations and meteorological station at Balmoral. The insert map shows the location of the Dee Catchment in Scotland. Based on OS data (© Crown copyright Ordnance Survey All rights reserved MLURI GD27237X 2009).