Assessing the impact of projected climate change on drought vulnerability in Scotland

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ABSTRACT

Although Scotland is relatively water resource rich in a UK and European context, water resource scarcity can occur during exceptional dry periods such as those experienced in North West Scotland during July 2012. Precipitation and flow anomaly indices have been recently developed and introduced operationally by the Scottish Environment Protection Agency, in order to assess the severity of dry episodes and use this information within the decision-making process when managing the ecological implications of measures required to ensure continuity of water supply. The latest projections of future climate in the UK (UKCP09) point to warmer, drier summers across much of Scotland and, as such, imply an increased frequency of periods of water shortage. This study makes use of the results from a collaborative project in which projected values of climate variables have been used to derive projected river flows at a number of catchments across the UK. These datasets have been used to evaluate the change in frequency of significant precipitation and flow deficits in Scotland. The findings suggest a marked increase in frequency of summer water resource scarcity across much of Scotland which has implications for water resource management, particularly where current storage is relatively low.

Key words | climate change, drought, rainfall-runoff modelling, Scotland

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INTRODUCTION

Scotland has a maritime climate, strongly influenced by a relatively warm and moist North Atlantic air stream, the result being that, in the UK context, Scotland receives high average annual precipitation totals and, due to relatively low rates of evapotranspiration, high runoff (Table 1).

This broad picture of ample water resource masks significant regional differences in both the supply and demand of water in Scotland. The Scottish Environmental Protection Agency (SEPA) monitors river discharge across Scotland and using these data for the period 1981–2011, mean annual runoff depths can be seen to vary from 3,084 mm at Eas Daimh in the West Highlands to as little as 205 mm at Luffness in East Lothian in South East Scotland. Supply of and demand for water resources are also spatially variable with catchment abstractions licensed under the Water Environment (Controlled Activities) (Scotland) Regulations 2005 ranging from less than $10\ \mathrm{m^3\ km^{-2}\ yr^{-1}}$ in sparsely populated Sutherland to over $5{,}000\ \mathrm{m^3\ km^{-2}\ yr^{-1}}$ in the Leven catchment which supplies the city of Glasgow.

Excluding non-consumptive use for hydropower generation, typically the demand for water resources is highest in the populous central Scotland and across the prime agricultural land of the south and east where runoff is lowest. However, it does not necessarily follow that such regions are most vulnerable to existing or, indeed, future droughts. An analysis of historical drought impacts in Scotland (Zaidman *et al.* 2012) has shown that it is the degree of departure from normal climatic conditions rather than a measure of absolute water supply that determines whether water scarcity impacts occur. Water resource management systems aim to make best use of the expected supply of water, and how this is achieved involves a balancing of the cost of building resilience to low water supply episodes against

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Table 1 | Long-term average rainfall and runoff in the UK

	England and Wales	Scotland	Great Britain	Northern Ireland	United Kingdom
Rainfall km^3 yr^{-1}	135.3	113.2	248.5	14.9	263.4
Runoff km^3 yr^{-1}	65.7	82.7	148.4	9.2	157.6
Runoff as a percentage of rainfall	49	73	60	62	60

Data supplied by the Centre for Ecology and Hydrology for the e-Digest of Environmental Statistics (DEFRA 2004).

the probability of their occurrence. As a result, water supply systems in some parts of Scotland have relatively low levels of storage, relying on small lochs or abstractions directly from rivers with little groundwater contribution. The success of these schemes is dependent upon the regular supply from precipitation and, as such, can be vulnerable during exceptionally dry episodes. An example of such an episode occurred during the early summer of 2012 in the north west of Scotland and the Western Isles where less than 60% of the long-term average precipitation was received during July. This resulted in the lowest runoff for that month over the 42 year record of the River Ewe (Centre for Ecology & Hydrology (CEH) 2012). Although the dry period lasted less than 2 months, water supply problems were reported resulting in the public water supply company, Scottish Water, requiring additional abstractions and, in some cases, temporary relaxations in environmental flow provisions.

Attempts at producing a common definition of drought are fraught with difficulties due to the entanglement between cause (lack of precipitation) and effect (the socio-economic or environmental impacts). Redmond (2002), for example, defines drought as occurring when there is ‘insufficient water to meet needs’ whereas the European Commission (2007) makes the distinction between drought – a natural phenomenon resulting in a temporary decrease of the average water availability, and water scarcity – a situation where insufficient water resources are available to satisfy long-term average requirements, in which supply and demand are both relevant. In many of the definitions of drought within the literature (e.g. Dracup *et al.* 1980) use is made of a classification into distinct drought types such as:

- meteorological – deficit in precipitation in comparison with long-term average;
- agricultural – inadequate soil moisture to meet the needs of a particular crop at a particular time;
- hydrological – where surface or groundwater flows and levels are significantly below levels expected for the time of year.

In terms of managing the environmental impacts of drought, the identification of hydrological drought may best reflect the impacts upon the water environment. However, early warning of such impacts may be informed by the measurement of meteorological drought since precipitation, or rather lack of it, is the key driver of drought.

The responsibility for licensing those measures required to supplement water supply during dry episodes lies with SEPA. It is their role to ensure that any reduction in environmental flows (those flows maintained through licensing to ensure ecological health in the water environment) is justified on account of the severity and, by implication, rarity of the weather event. SEPA has a responsibility to quantify the severity of a dry period in order to make a balanced judgement on the allowance of additional water abstraction so as to ensure that this occurs as a result of exceptional natural conditions rather than through a failure in operation of the water supply system.

To help with this role, SEPA has developed a suite of water shortage indicators which are used to assess the severity of the precipitation and river flow anomalies over a range of time periods.

An analysis of available drought indices led to the choice of standardised anomaly type indices for both precipitation and flow, similar to the widely used Standardised Precipitation Index (SPI) described by McKee *et al.* (1993).

The indices chosen assume the precipitation and flow data fit a log-normal distribution where the anomaly or Z score is given by:

$$Z - \text{score} = (\text{Average of logarithms of values} - \ln(X))/\text{Standard deviation of logarithms of values} \quad (1)$$

This approach has previously been applied by Zaidman *et al.* (2002) and Shukla & Wood (2008) amongst others. A suggested term for this index is the ‘normalised precipitation index' (NPI) or, where applied to flow data, the 'normalised flow index' (NFI). Details of the methodology including the evaluation criteria used to choose these indices are given in Gosling *et al.* (2012).

The NFI and NPI can be applied over any suitable time scale such as 1, 3 or 6 months where the duration determines the period over which the anomaly is calculated. For example, a 3-month NFI reported on the first day of July would be calculated by first evaluating the anomaly between the logged mean flow from the recent period from April to June and the logged mean flow of all the periods from April to June averaged over the long-term record. This anomaly is then normalised by the standard deviation of the logged mean April to June mean flows over the long-term record.

In regions where storage is low, vulnerability or risk of water supply failure may best be indicated by a 1-month duration, whereas those systems with significant storage are likely to be more vulnerable to longer duration anomalies. The indices express precipitation and flow deficits in terms of positive values which reflect the anomaly in terms of standard deviations from the long-term mean of the (logged) data. The NPI and NFI provide a method of determining the severity of a dry period which can be translated into a probability of occurrence or return period. Assuming the reference time period is representative of the long-term climate, then an index of 1.96 for a particular time period, e.g. July, would have a probability of occurrence of 0.025 in any one year, which can be expressed as a 1 in 40-year return period. The relevance of the 40-year time period is that, under the Water Industry (Scotland) Act 2002, there is a requirement for Scottish Water to ensure that supply zones are protected against conditions that have a probability of a 1 in 40-year return period. The indices can be used to assess the meteorological conditions which are likely to lead to a 1 in 40-year event under current or rather, recent historical conditions and furthermore, given a set of future precipitation and flow scenarios, can be used to express the change in probability of such events occurring.

Since the indices are standardised they provide a measure which can be compared across a region such as Scotland. As part of the development of these indices, a drought catalogue for Scotland was created from a wide literature review. Using case studies from previous years where water shortages have been reported (1975/6, 1984, 2003 and 2010), it was shown that applying the precipitation index, NPI, at a duration of 3 months was most suitable for capturing these main drought events since the early 1970s, whereas a 1-month duration was optimal for the NFI (Zaidman *et al.* 2012). As pointed out above, however, the 1-month precipitation index remains a useful index for those areas with little storage and, operationally, a combination of indices over a range of durations is recommended. A matching exercise between the reported severity of these historical drought episodes and the corresponding drought indices has allowed thresholds to be calibrated in order to express the severity of the precipitation and flow anomalies (Table 2).

Table 2 | Suggested thresholds for SEPA drought indices

Condition	NPI, D = 1	NPI, D = 3	NFI, D = 1
Not significant	<0.5	<0.25	<0.25
Deficit early warning	0.5	0.25	0.25
Deficit alert	1.0	0.5	0.5
Moderate deficit	2.0	1.0	1.0
Significant deficit	2.5	2.0	2.0
Extreme deficit	3.0	2.5	2.5

D = duration in months.

As indicated earlier, the indices give an expression of the severity by virtue of its probability of occurrence. The probability of occurrence is dependent upon the time period over which the long-term (logged) means and standard deviations are evaluated (Equation (1)) and the method implies climatic stationarity. Since climate is known to be non-stationary it is the task of drought index users to choose a reference time period that is relevant for their use.

CLIMATE CHANGE

The latest UK climate projections (UKCP09, Jenkins *et al.* 2009) detail changes in a range of climatological variables and provide these in a probabilistic format by virtue of combining information from perturbed physics and multi-model ensemble results (Murphy *et al.* 2009). Projections from UKCP09 have been made available at a UK and regional

Table 3 | Projected % changes from baseline in mean precipitation for the three regions in Scotland for 2050s medium emissions scenario (Data from UKCP09 2009 © UK Climate Projections 2009)

	Annual			**Summer**			**Winter**		
	10%	**50%**	**90%**	**10%**	**50%**	**90%**	**10%**	**50%**	**90%**
North	−7	−1	5	−24	−11	2	3	13	24
East	−6	0	6	−27	−13	1	1	10	20
West	−7	−1	5	−27	−13	1	5	15	29

10, 50 and 90% refer to the projection probability levels.

level with an example of some of the output shown in Table 3.

These results combine to produce a broad picture of projected climate change in Scotland which can be summarised as wetter winters and drier summers coupled with an increase in temperature. Changes broadly reflecting the pattern of wetter winters have been observed in the recent (1961–2004) climatological history of Scotland (Barnett *et al.* 2006) although, as with the projections themselves, a generalised summary of changes mask some significant regional variation. Changes in summer precipitation in Scotland show no clear trend over the recent record although there is evidence of a significant decrease in East Scotland between 1914 and 2004. Analyses of trends in flows in Scotland show an unclear picture of change over longer time periods. Hannaford & Marsh (2008) have shown significant rises in high flows over the last 50 years in Scotland but demonstrate that much of this change can be explained by changes in the North Atlantic Oscillation Index. In a study of 111 SEPA gauging station flow records between 1977 and 2009 Gosling (2012) has found similar rises in winter monthly mean flows but little evidence of a change in summer flows. The picture over a longer period (1930 to 2009) for the river Dee at Woodend equally shows no clear trend in either winter or summer mean flows. The lack of observable trend in historical records may not contradict the projected changes in precipitation given by UKCP09 (Jenkins *et al.* 2009). Several studies have recently shown that, given the rate at which climate is expected to change and given the high natural variability of the maritime climate of the UK, it may not be possible to detect climate change in river flows for some time to come. For example, a study into the detectability of projected changes in extreme rainfall suggests that changes are unlikely to be detectable before 2030 (Fowler *et al.* 2010). Similarly Radziejewski & Kundzewicz (2004) have demonstrated that tests on hydrological time series with high natural variability that are not able to detect weak changes or changes which have not lasted long cannot be interpreted as a demonstration of absence of a change.

Whilst the projections of change in both temperature and precipitation within Scotland indicate that water resources may become more scarce during summer, more information on the implications for water resource may be acquired by using the projected climate variables to drive the modelling of catchment hydrological processes. Prudhomme *et al.* (2012a, 2012b) have used the outputs from 11 members of the HadRM3-PPE regional climate model (RCM) to produce sets of bias-corrected daily gridded climate data for the period 1951–2098. These data have, in turn, been used by Haxton *et al.* (2012) to drive a set of PDM (Moore 2007), CERF (Griffiths *et al.* 2008) and CLASSIC (Crooks & Naden 2007) rainfall-runoff models to produce synthetic flow time series for over 200 catchments in England, Scotland and Wales. These time series represent an ensemble of transient projections of daily mean flows. Although probabilistic outputs were available as products from the latest United Kingdom climate projections (UKCP09, Jenkins *et al.* 2009), at the time of undertaking the project, these were not available as spatially coherent projections and could not be used to provide catchment scale inputs. As a result, the 11 spatially coherent RCM members were used to produce climate projections for the UK under a medium emissions scenario. The outputs consist of 11 equally likely projections that can be used to help understand the range of projected impacts in flows and groundwater levels due to climate change over the course of the 21st century.

Although precipitation deficit is the key indicator of drought severity, impacts will be exacerbated or mitigated by the other catchment processes, in particular, evapotranspiration and its impact on soil moisture deficit. Prudhomme *et al.* (2012b) have produced a spatially downscaled and bias-corrected 5 km daily temperature time series from the HADRM3-PPE temperature dataset and used this to derive a monthly 1 km gridded potential evapotranspiration (PE) dataset based upon the FAO-56 Penman–Monteith method (Allen *et al.* 1998). These data were used within the catchment runoff models such that resultant flows incorporate the combined effects of projected changes in precipitation and temperature.

An evaluation of the effectiveness of the rainfall-runoff models to recreate observed flow time series in Scottish catchments from observed climate for the control period 1962–1991 indicates that the models perform well, with average biases at mean flow and Q75 of −1.5 and 0.59% respectively and a mean Nash-Sutcliffe efficiency value of 0.67 (Prudhomme *et al.* 2012c). However, the mean biases can mask individual models that perform less well and consequently the data for each catchment are accompanied by a catchment factsheet indicating the model performance for the catchment across a range of flows. Model performance was banded into three categories (1 = highest, 2 = medium, 3 = lowest) for a range of flow statistics, details of which are given in Crooks *et al.* (2012).

METHODOLOGY

The projected precipitation and flow data from 22 catchments across Scotland have been used to evaluate NPI and NFI at 1- and 3-month durations for the time periods 1961–1990 and 2041–2070, hereafter referred to as the baseline and 2050s, respectively. Catchments were chosen to represent a wide geographic coverage of Scotland, with the limitation that only models evaluated as performance band 1 for the low flow statistic Q90 were included (since the focus of this analysis was low flow periods).

The aim of this study was to assess the projected change in probability of a dry period both in terms of precipitation and river flow. This has been achieved by calibrating the indices using the baseline reference period and evaluating the frequency of occurrence within the future time period of the index value corresponding to the baseline 1 in 40-year return period event. As mentioned earlier, from the way the indices are evaluated, it is expected that the 1 in 40-year event corresponds to an index value of 1.96, so the analysis can be summarised as analysing the frequency of occurrence of an index value greater than 1.96 in each of the 11 future precipitation and flow time series. The probability of exceeding the index value of 1.96 (calibrated using the baseline time series) was evaluated for each of the 11 members for both the baseline and future scenarios. These probabilities were tested to the 90th percentile confidence level for the null hypothesis that there was no difference in exceedance probabilities between the baseline and future time series using a paired *t* test.

Since the 11 RCM members are considered to be equally likely, there are insufficient projected time series to allow the changes in drought indices to be expressed in terms of a probabilistic output. However, the results can be presented to illustrate the number of RCM members that show an increased frequency of the 1 in 40-year event and the confidence level associated with this change. The median projected return periods for the set of 11 future scenarios have also been determined and each of these statistics has been evaluated over annual and seasonal subsets of the time series.

The 1-month normalised precipitation indices were calculated for each of the 22 sites evaluating anomalies from the 1961 to 1990 baseline period. If there were no changes in the probability of a drought under future climate scenarios then the probability of exceedance within the 11 RCM members for the 2050s would not differ significantly from the probabilities in the 11 baseline time series, i.e. the current 1 in 40-year event would not become more likely in future. This was tested to the 90th per cent confidence level. At those sites where a significant change was evident, the number of scenarios where the probability had increased gave an indication of the likelihood of the change. Results from a site where all 11 members showed an increase in occurrence of drought indicated a strong signal of change. Equally where few members indicated an increase, i.e. many demonstrated a decrease, this also signalled a strong signal of reducing drought frequency.

RESULTS

Normalised precipitation index

Figure 1 shows the distribution of stations and the number of scenarios in which an increase in annual frequency of the 1-month NPI value corresponding to the baseline 1 in 40-year event was determined. The annual frequency of the drought indices makes no distinction between the frequency of events in different calendar months. An increase in frequency could be as a result of changes in drought frequency at any time of the year, as each of the 12 1-month drought index values relate to the likelihood of the precipitation anomaly in that particular month. As such, an increased frequency of drought in one season could be offset by a reduced frequency in another.

Figure 1 | The number of 2050s medium emissions scenarios showing an increase in annual frequency of the 1-month NPI value corresponding to the baseline 1 in 40-year event.

It can be seen that the majority ($n = 15$) of sites showed no significant change in drought frequency. These results indicate that, where no distinction is made in terms of the seasonality of the precipitation anomaly, drought frequency is largely unchanged in most areas under climate change scenarios for the 2050s. This result can be explained by the fact that, broadly speaking, little overall change in mean annual precipitation for Scotland is projected for the 2050s (Table 2). A reduction in annual drought frequency is observable in a minority of sites ($n = 7$), largely in the south and west of Scotland. In these areas, the net effect of changes in precipitation over the year is a reduction in drought frequency. This is particularly relevant to sites where storage of water resource is sufficient to allow any projected enhanced precipitation in one season to offset reductions in another.

Figure 2 illustrates that, where a distinction is made between seasons, significant changes in the frequency of precipitation deficit are observed at many sites. An increase in frequency of spring and summer droughts is evident at many sites across Scotland, whereas marked decreases in 1-month precipitation deficit frequency occur in autumn and winter. The pattern of higher summer and lower winter drought frequencies mirrors the general picture of wetter winters and drier summers projected for much of Scotland by UKCP09 (Table 2). Seasonality is a key consideration when considering drought impacts, particularly where storage of water resource is low. Rodgers *et al.* (2012) have shown that some water resource reservoirs in Scotland have relatively low storage in comparison to the mean annual inflow and, as such, have critical drawdown periods (the length of time a reservoir takes to go from full to empty during a 1 in 40-year drought) of less than 4 months. Furthermore, there are some regions where water supply is sourced directly from river abstraction in areas with a small groundwater component to river flow. These sites are particularly vulnerable to changes in seasonal drought frequency.

Normalised flow index

Figure 3 illustrates the combined effect of projected changes in precipitation and temperature on 1-month NFI. The impacts on the frequency of drought in spring and winter largely reflect those changes seen in the 1-month

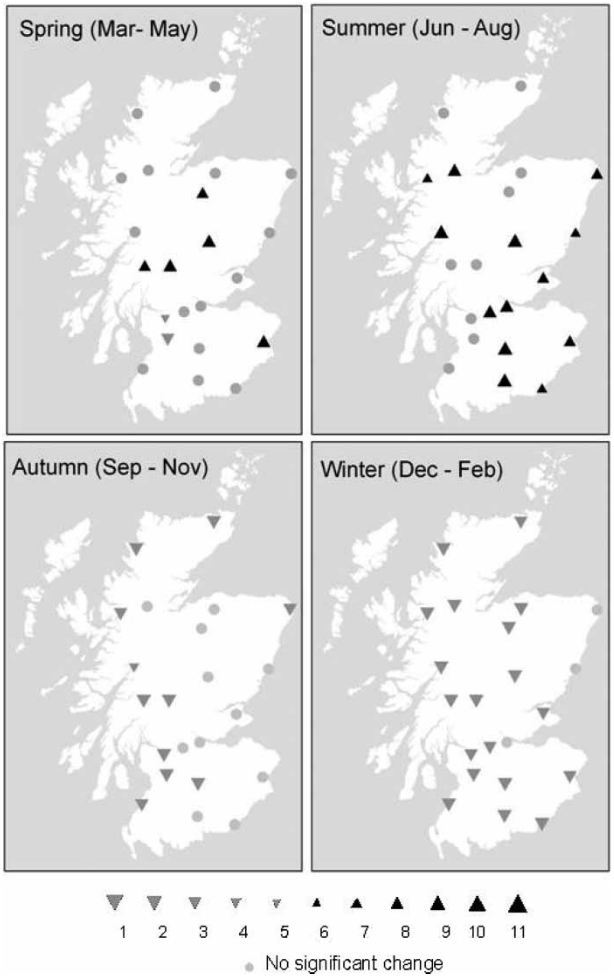

Figure 2 | The number of 2050s medium emissions scenarios showing an increase in seasonal frequency of the 1-month NPI value corresponding to the baseline 1 in 40-year event.

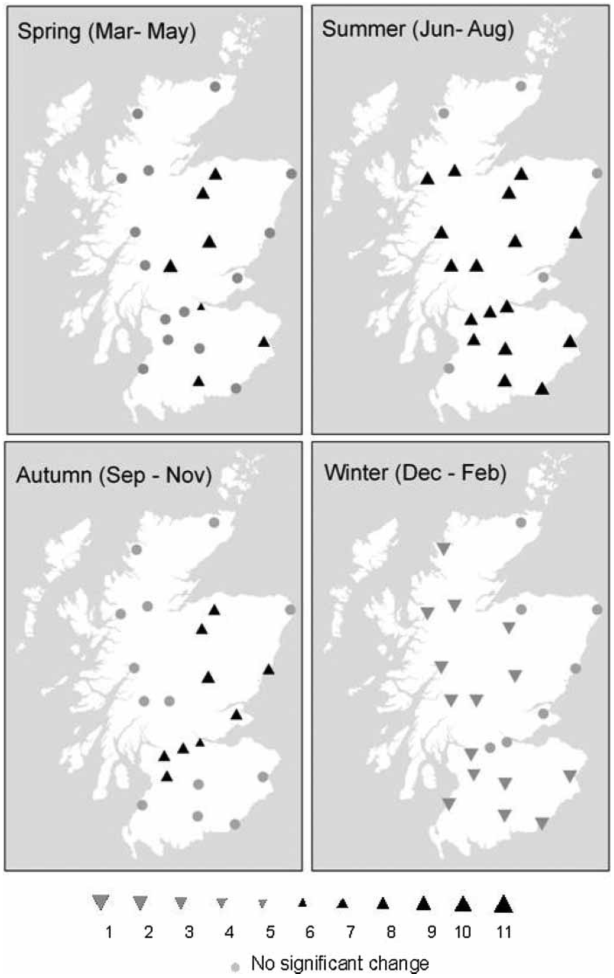

Figure 3 | The number of 2050s medium emissions scenarios showing an increase in seasonal frequency of the 1-month NFI value corresponding to the baseline1 in 40-year event.

precipitation indices (Figure 2). In summer the number of sites with significant increases in drought frequency has increased compared with the changes in NPI, potentially suggesting that the effect of higher summer temperatures within the projections is higher rates of evapotranspiration and an increase in the occurrence of summer low flow periods. In autumn, whereas the projected changes in 1-month NPI show reductions in meteorological drought frequency, a number of sites in central and eastern Scotland indicate increases in hydrological drought frequency. The discrepancy between the precipitation and flow indices suggest that a role is being played within the modelled catchment processes as a consequence of either higher autumn temperatures and PE rates and/or a lag in soil moisture deficit or groundwater contribution to flows immediately following the drier summers.

Figure 4 shows the change in frequency of 3-month NFI for winter, spring, summer and autumn. These changes largely reflect those of the 1-month index although the increases in autumn drought frequency seen in the 1-month index are not evident in the 3-month index.

Changes in return period of the 1 in 40-year drought

In the analysis of 1-month and 3-month NPI and NFI, changes in the frequency of occurrence of the 1 in 40-year baseline index value have been assessed. The return period of the drought index values can be evaluated as the

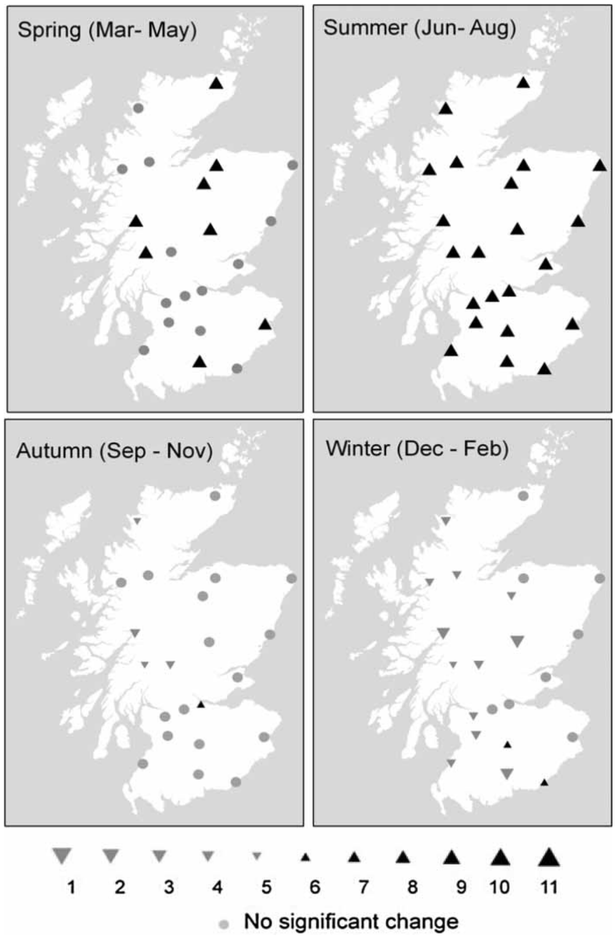

Figure 4 | The number of 2050s medium emissions scenarios showing an increase in seasonal frequency of the 3-month NFI value corresponding to the baseline 1 in 40-year event.

number of years in the record divided by the number of occurrences of the event. The increased or reduced frequency of occurrence of the drought indices examined in this analysis can be expressed in terms of a reduction or increase in return period. As has been shown, the greatest increase in frequency of precipitation and flow deficits can be seen to occur in summer. Table 4 presents the changes in 1 in 40-year return period summer drought index value for NPI and NFI for the 2050s expressed as the maximum, minimum and median of the 11 RCM members. Although a probabilistic interpretation of the 11 RCM members is not valid, the maximum, minimum and median values indicate the range of return periods from the model runs. All but one of the median values for each of the indices fall between 9 and 29-year return periods, mirroring the previous analysis, showing the increased frequency of precipitation and river flow deficits.

DISCUSSION

Within the projected climate and flow time series derived from the HadRM3-PPE RCM, clear patterns in the changes of seasonal drought frequency have been observed. These patterns can largely be summarised as increases and decreases in the frequency of precipitation and hydrological drought in summer and winter, respectively. These findings fit the general picture of wetter winters and drier summers projected for much of Scotland by most RCM members. However, whereas autumn precipitation is generally projected to increase by the 2050s, for the sites used in this study, the Haxton *et al.* (2012) projected flow time series indicate some increases in autumn 1-month hydrological drought and it is suggested that this is as a result of drier catchments in some areas due to lower summer precipitation and increases in autumn evapotranspiration. An analysis of the PE data for the 22 catchments demonstrates that, for all sites, the median daily PE from September to November is modelled to increase by between 10 and 20% compared with baseline values. This increase in PE may contribute to lower autumn flows during dry periods, particularly where the models estimate low post-summer soil and groundwater storage. The fact that little evidence of change in autumnal drought is evident over a 3-month duration may indicate that this effect is short-lived and, averaged over the whole season, a drier catchment at the start of autumn may be offset by higher precipitation as the season progresses.

Both the PDM and CERF models used to produce the flow time series from the projected climate scenarios incorporate sub-models that are aimed at representing the soil and groundwater components of catchment hydrology. Under a changed climate where summer precipitation totals are lower and evapotranspiration rates are higher, the sensitivity of low flows to climate change may be expected to vary depending upon the contributions to river flow from the quick and slow components of the catchment response.

Table 4 | Projected return periods of the 1 in 40-year summer droughts in the 2050s

	1-month NPI			**1-month NFI**			**3-month NFI**		
Station number	**Min**	**Median**	**Max**	**Min**	**Median**	**Max**	**Min**	**Median**	**Max**
4005	15	29	29	8	12	44	10	15	22
7006	12	17	100	8	11	29	8	11	29
8009	10	22	100	6	10	17	6	10	17
10002	15	17	29	15	44	87	12	29	87
13001	15	22	44	9	22	44	7	22	44
14001	12	17	100	17	29	100	17	29	100
15014	11	22	100	6	11	29	5	12	22
15024	10	22	44	7	9	29	7	9	22
17005	15	22	29	11	17	29	11	15	29
21021	12	22	87	7	15	17	7	15	22
77002	15	17	44	10	17	22	10	17	44
79002	15	22	44	9	15	29	9	17	22
82001	12	17	100	12	22	100	12	22	100
83010	15	22	44	11	22	44	11	22	87
84012	11	17	29	11	22	44	9	22	44
84016	12	15	44	11	15	44	8	17	87
84022	12	17	44	11	17	29	12	22	29
89003	11	22	44	9	12	22	8	12	22
90003	15	17	29	8	12	22	8	11	17
93001	12	17	44	12	17	29	12	17	29
95001	15	29	100	22	29	87	17	29	87
97002	12	22	100	17	22	87	15	29	87

Note: Marsh & Hannaford (2008) give details of gauging station records referred to by the station numbers.

Examining the relationships between a range of catchment characteristics and the change in frequency of 1-month summer NFI (expressed as the number of RCM members indicating increased drought frequency) it can be shown that base flow index (BFI) and altitude demonstrate the highest degrees of correlation with change in drought frequency (Table 5). Although it may be expected that there would be some cross-correlation between BFI and altitude, stepwise linear regression indicates that, within this dataset, this does not apply and these catchment characteristics, along with the lake attenuation index, FARL, stand as independent variables which explain 45% of the variation in the change in summer hydrological drought frequency ($p < 0.05$).

In the absence of an examination of the changes in parameters within the model components during the future flow scenario runs, the results from Table 5 indicate that higher altitude catchments with little lake and reservoir storage and low base flow indices are most sensitive to the changes in climate with respect to short-term summer drought. This conclusion may have particular bearing upon the possible ecological response to climate change in that the ecological assemblages in these river typologies have been identified as being most sensitive to changes in flow. In a study of ecological sensitivity to flow pressures as part of the development of the UK water resource environmental standards for the implementation of the Water Framework Directive, Acreman *et al.* (2008) presented a typological framework which suggested that the riverine ecology of catchment headwaters with low base flow indices may be most sensitive to reductions in flow.

Table 5 | Catchment characteristics correlated with change in frequency of summer 1-month NFI

Catchment characteristic	Correlation coefficient	Significant independent variable ($p < 0.05$)
BFI	**– 0.59**	**True**
SAAR (61–90)	0.29	False
Loss %	–0.33	False
Log CA	–0.11	False
FARL	**0.32**	**True**
PROPWET	0.41	False
DPSBAR	0.39	False
Altitude	**0.59**	**True**

BFI = Base flow index calculated from the gauging station record.
SAAR = Standard period average annual rainfall.
Loss% = 100*(SAAR – mean annual runoff)/SAAR.
Log CA = the log of catchment area.
FARL = Flood Attenuation by Rivers and Lakes Index (A value close to 1 indicates the absence of flood attenuation by lakes).
PROPWET = PROPortion of time soils are Wet index.
DPSBAR = mean drainage path slope.
Data from Marsh & Hannaford (2008).

CONCLUSION

This study has demonstrated a method of combining indices of drought with projections of future climate and hydrology to produce an indication of the potential change in drought vulnerability in Scotland. The results indicate a greater prevalence of summer drought, particularly when assessed as hydrological drought using an index based upon flow anomalies. Summer drought at both 1-month and 3-month durations are seen to become more frequent where, in broad terms, the current 1 in 40-year drought translates to approximately a 1 in 20-year event by the 2050s. Such a finding may have implications for the adaptation required in water resource management where existing resilience can be shown to be vulnerable to such an increase in drought frequency. This evidence suggests that those water resource supply zones which are most sensitive to changes in summer precipitation and flow conditions may be most vulnerable to the projected changes in climate. Further work is required to tie the projected changes in precipitation and flow in with the existing resilience of water resource systems to understand current vulnerability. However, the combination of projected future climate and river flows and tools for objectively assessing drought severity, benchmarked against historical events, may provide a useful framework for undertaking this analysis.

The findings also point to the fact that catchment sensitivity to the projected changes in climate is variable across Scotland, a result which mirrors those of similar studies undertaken on catchment vulnerability to flooding (Reynard *et al.* 2009). The implications are particularly relevant if it is shown that those catchments where low flows are most sensitive to the projected changes may also include ecological communities sensitive to flow impacts. Further work is being undertaken by the UK environment agencies to develop biological indices sensitive to flow impacts, e.g. Extence *et al.* (1999), in order to understand better the linkages between pressure and response in riverine habitats.

The degree of uncertainty in climate change projections has been addressed within UKCP09 (Jenkins *et al.* 2009) by the utilisation of techniques to produce probabilistic outputs and, while in this study the requirement for spatially coherent projections has precluded a probabilistic output, the range of the 11 RCM members gives a useful indication of the likely direction and range of projected change. These findings highlight a requirement for the consideration of climate change impacts upon drought and low flows in Scotland and demonstrate the added value of using climate variables to drive hydrological models in order to assess the implications for flow-dependent water resource and ecological systems.

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