Do catchment characteristics explain differences in coherence and trends in hydroclimatic behaviour in an upland region?

Scott J. McGrane, Doerthe Tetzlaff, Richard Essery and Chris Soulsby

ABSTRACT

To explore the link between catchment characteristics and sensitivity to environmental change, longer-term data from 21 contrasting mesoscale (67–690 km^2) catchments in northern Scotland were analysed to examine the influence of hydroclimatic drivers on hydrological response. Cluster analysis was used to classify the catchments into four distinct groups, with topography and annual precipitation being the two most significant differentiating factors. Using 12 years of data from the 21 sites, inter-catchment coherence of intra- and inter-annual variation of precipitation, air temperatures and stream discharge were assessed both within and between clusters. Whilst catchments in clusters characterised by lower elevations exhibited coherence in hydroclimatic drivers and streamflow response, the higher altitude catchments did not. Annual trends were evident for widespread increases in temperature and also increasing values of precipitation in the higher elevation catchments. Seasonal trends indicate a lack of consistent change during winter, but most other seasons exhibit an increase in temperatures, with isolated increases in measures of precipitation and discharge particularly during the transitional seasons of spring and autumn. These trends ultimately could not be related with catchment typology where increasing upland area results in a breakdown of hydroclimatic coherence between sites.

Key words | classification, climate, clusters, hydrology, trends

Scott J. McGrane (corresponding author)
Doerthe Tetzlaff
Chris Soulsby
Northern Rivers Institute,
School of Geography,
University of Aberdeen,
Aberdeen AB24 3UF,
UK
E-mail: *s.mcgrane@surrey.ac.uk*

Richard Essery
Grant Institute,
School of Geosciences,
University of Edinburgh,
Edinburgh EH9 3JW,
UK

INTRODUCTION

It is often argued that a consistent multivariate approach to catchment classification has the potential to provide a coherent scientific framework for understanding the links between catchment form and function and consequent sensitivities to environmental change (e.g. Wagener *et al.* 2007). However, progress towards such a unified organising principle has been frustratingly slow and it has been argued that complexities of the 'uniqueness of place' and difficulties in scaling place severe constraints that may ultimately preclude the development of such tools (Beven 2000). However being able to improve understanding of the relationships between catchment form and function through inter-comparison remains a useful objective for extrapolating process understanding from one catchment to another, particularly for prediction at ungauged sites (McDonnell & Woods 2004; Tetzlaff *et al.* 2010). This can allow the inter-relationships between physical catchment characteristics and hydroclimatic drivers to be assessed and can help underpin more regional classification schemes which group sites and allow extrapolation and hypothesis testing (Tetzlaff *et al.* 2008; Carey *et al.* 2010).

Catchment inter-comparison is widely used in hydrological research (e.g. Jones 2005; Buttle & Eimers 2009; Carey *et al.* 2010) and is often employed to ascertain how the impact of one or more drivers of environmental change (such as deforestation, urbanisation and climate change) affects catchment behaviour at a regional (Hall 2006; Hrachowitz *et al.* 2009; Srinivasin & McDowell

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2009; Zhao *et al.* 2010) or national scale (Olden & Poff 2003; Engle & Lemos 2009; Fu *et al.* 2010). As with classification, a standardised method for catchment comparison has not been developed on account of highly variable (spatial and temporal) catchment conditions and processes (Carey *et al.* 2010). A central problem focuses on establishing a parsimonious set of indices which can be used to classify catchments as contrasting geographical regions are affected by different physical and climatological factors in different ways (Wagener *et al.* 2007). With the increased availability of digital datasets from Digital Terrain Models (DTMs) and other sources, it is often difficult to identify diverse catchment indices which can be applied at regional, national and global scales to facilitate accurate discrimination of specific catchment typologies where different hydrological regions are affected by contrasting physical and hydroclimatic dynamics. Although this absence of a framework for catchment classification appears to have no immediate solution, it remains an important aspiration within the field of hydrology even if only for specific geographical regions where differentiation on the basis of common indices may be most justifiable (Ali *et al.* 2012).

A key requirement for catchment classification is to understand how climatic forcing relates to hydrological response (Sawicz *et al.* 2011). Increasing awareness of the limitation of the assumption of climatic stationarity means there is an importance to identifying how climate conditions and hydrological regimes have varied in the recent past by identifying trends within the data (Lettenmaier & Burges 1978; Xu *et al.* 2010). The detection of trends in precipitation, temperature and discharge time series can provide indicators of change and can also provide insights into the degree to which climatic variability or change might affect the hydroclimatic variables in the region (Qin *et al.* 2010). Understanding the potential impacts of climate change on water resources is a major frontier of interdisciplinary research (Arnell 2011). In Scotland, water supplies are abundant in most areas but these many resources are often utilised for industrial, domestic and agricultural abstractions which in some cases may be seasonally stressed (Scottish Environmental Protection Agency 2005). In addition, many of Scotland's water bodies are also of high ecological significance, with protected flora and fauna existing in and around these habitats (Gilvear *et al.* 2002; Tetzlaff *et al.* 2008; Soulsby *et al.* 2009; Hrachowitz *et al.* 2010a, b). Finally, many human settlements have historically been developed on the banks of rivers and lochs and are at significant risk from flooding (Werritty 2002). As such, it is important that potential effects of climate change are understood to allow adaptive management to protect such resources and also assess how any changes are likely to impact on flood risk.

Previous studies have examined the emergence of trends in both precipitation and streamflow records across Scotland at both the national and regional scales. In general, the west of Scotland has been getting much wetter (by *c.* 23% between 1961 and 2004) than the east (by 18% for the same period) (SNIFFER 2006). Also, temperatures have consistently increased up to 0.8 °C in the past three decades (UKCIP09, www.ukcip.org.uk). However, although such studies have looked at regional and seasonal changes, none has examined the way in which changing hydroclimatic drivers might be mediated by catchment characteristics. Thus there is a need to address whether there is similarity in catchment responses to changing environmental drivers and discern the extent to which different catchment types might be more susceptible to such changes influencing their hydrological regimes (Werritty 2002; Gosling 2009).

The Cairngorm region of Scotland has the largest area of land above 800 m in the UK. The headwaters of rivers in this region are located within a region with a transitional subarctic climate where flow regimes can be susceptible to small variations in climatic drivers (e.g. Rouse *et al.* 1997; Carey *et al.* 2010). Small changes in the temperatures will affect the spatial and temporal distribution of the 0 °C isotherm which will impact on the phase of precipitation and snowpack melt dynamics, affecting the magnitude and timing of runoff generation. Here, a comparison of 21 catchments (67–690 km^2) draining from and around the Cairngorm region is undertaken to identify variability and changes in their hydroclimatic regimes over a 12-year period. The specific objectives are: (i) to identify distinct catchment typologies based on physical and hydroclimatic characteristics; (ii) to identify trends in the hydroclimatic data at both annual and seasonal scales; and (iii) to determine whether specific hydroclimatic trends correspond to identified catchment types.

STUDY AREA

All of the 21 study catchments are located in the NE of Scotland (Figure 1 and Table 1), with the majority having their headwaters in the Cairngorm Mountains or acting as tributaries to rivers which drain this region; lowland catchments (mean elevation < 250 m.a.s.l) 1, 20 and 21 are exceptions to this. The study sites cover an area of around 8,400 km^2, extending from the rivers Lossie (57.4 °N, –3.2 °W) and Tilt (56.7 °N, –3.9 °W) in the north and west, to Dighty Water (56.4 °N, –2.9 °W) and Lunan Water (56.6 °N, –2.5 °W) in the south and east, respectively.

The region is characterised by marked climatic gradients. The western parts of the Cairngorms (e.g. catchments 2, 5, 6, 12, 13 and 15) can receive more than double the precipitation in the east (e.g. catchments 4, 7, 11, 18, 20 and 21) which lies in a rain shadow created by the orographic effect generated by the rising altitude of the west coast (Table 2). The same topographic influence also leads to lower temperatures in the higher western slopes, with an increase (by up to 3–4 °C) in mean annual temperatures in the east.

The region has been heavily altered by glacial dissection (Gordon & Wignall 2006). As deglaciation occurred, large U-shaped valleys became drainage lines for much of the melt leading to the development of drift covered catchments (Brazier *et al.* 1996). The underlying bedrock comprises mostly sedimentary Dalradian rocks, punctuated by granitic intrusions which form most of the upland peaks (Thomas *et al.* 2004). Catchment soil cover reflects topography, geology and drift and has an important influence on hydrological function (Soulsby & Tetzlaff 2008). The lowland landscape is dominated by more freely draining podzolic and alluvial soils. The uplands are characterised by the presence of low permeability glacial drift deposits in valley bottoms, which are overlain by peaty gleyed soils and blanket peats (*Histosols*). As altitude increases, the soil cover becomes thinner and is dominated by peaty podzols and shallow ranker soils (*Umbric Leptosols*) (Tetzlaff *et al.* 2007).

Land cover has been heavily influenced by human activity; much of the upland native Scots pine (*Pinus sylvestris*) forest has been felled for timber supply and large lowland areas are managed for agricultural practices (Scottish Natural Heritage 2010). However, vegetation

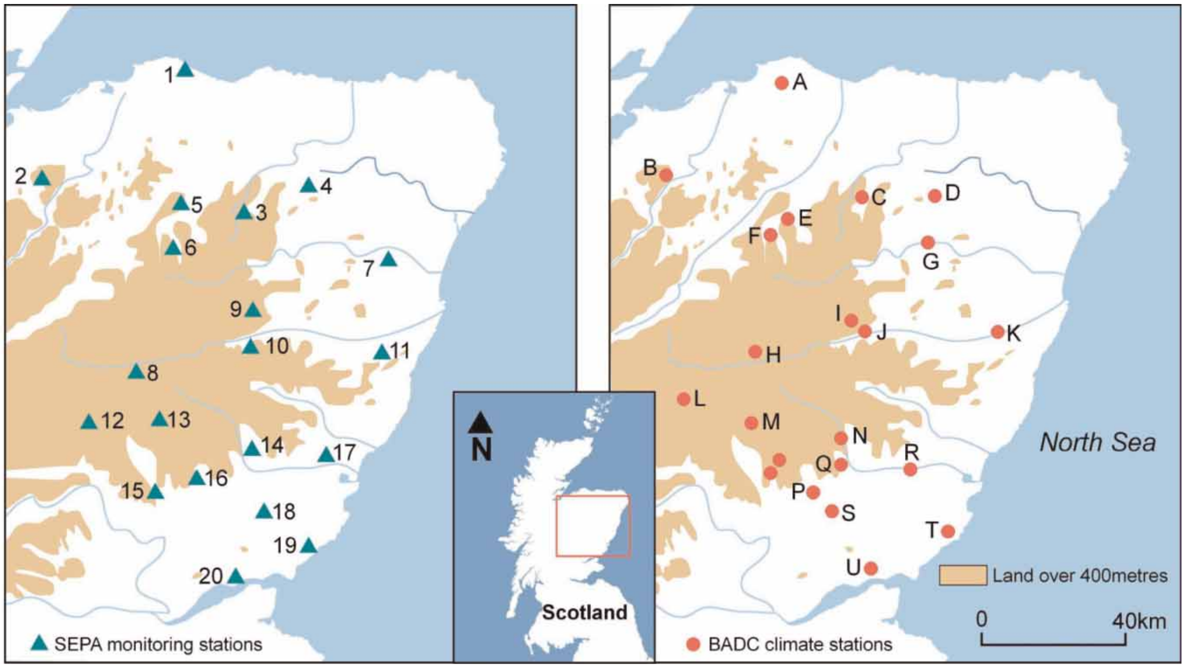


Figure 1 | Location of the SEPA monitoring stations (1–21) and BADC Climate Stations (A–T) for the 21 sites investigated in this study. Reference IDs are in Table 1 (SEPA) and Table 2 (BADC).

Table 1 | Physical characteristics of the 21 catchments investigated; all catchments are sorted from north to south and west to east

			Elevation		**Slope**			
Catchment	**ID**	**Area (km^2)^a**	**Mean (m)^a**	**Max (m)^a**	**Mean (°)^a**	**Max (°)^a**	**Dominant geology^b**	**Dominant land use (%)^b**
Lossie	1	216	248	521	4.4	33.6	Psammite	Woodland (41)
Findhorn	2	416	556	933	7.7	44.7	Schists	Montane (76)
Allt Deveron	3	67	456	720	6.9	29.3	Granite/Schist	Montane (68)
Bogie	4	179	292	707	7.4	32.1	Schists	Grassland (35)
Livet	5	104	430	824	9.1	37.1	Granite/Schist	Montane (56)
Avon	6	185	682	1,292	11.5	63.3	Granite/Schist	Montane (71)
Don	7	499	255	874	6.2	37.5	Schists	Montane (49)
Dee (Mar Lodge)	8	289	683	1,309	13.1	57.0	Psammite/Schists	Montane (93)
Dee (Polhollick)	9	690	621	1,309	12.3	57.0	Granite/Diorite	Montane (85)
Muick	10	110	585	1,145	10.5	61.0	Granites/Schists	Montane (81)
Feugh	11	229	329	775	8.3	38.3	Granite/Diorite	Montane (70)
Tilt	12	165	675	1,120	13.6	49.5	Schists	Montane (90)
Ardle	13	108	502	1,103	10.2	41.5	Psammite/Schists	Montane (65)
South Esk (Gella Bridge)	14	130	556	1,029	14.2	75.9	Granites/Schists	Montane (71)
Ericht	15	432	451	1,103	9.7	45.8	Psammite/Schists	Montane (51)
Isla	16	367	302	744	8.0	63.2	Granites/Schists	Montane (36)
Prosen Water	17	104	430	944	12.5	66.0	Schists	Montane (64)
South Esk (Brechin)	18	488	344	1,029	9.7	75.8	Granites/Schists	Montane (43)
Dean Water	19	230	139	453	3.8	40.7	Old Red Sandstone	Arable (53)
Lunan	20	131	97	250	2.4	25.3	Old Red Sandstone	Arable (69)
Dighty Water	21	127	145	453	3.9	55.6	Old Red Sandstone	Arable (46)

Elevation and slope data derived from 50 m DTM in GIS software. Geological information sourced from EDINA.

[a] denotes use in the clustering and principal component analyses.

Both geology and land use ([b]) are only represented in the table by dominant values but full percentage breakdowns for geology and land use type were used in the clustering and PCA.

reflects altitude and climate, with widespread (*c*. 69%) montane heath found at altitudes above 800 m in the Cairngorm region (Table 1). Heather (*Calluna vulgaris*) moorland is more dominant at moderate altitudes. Coniferous woodland makes up 12% of the landscape, with grassland types (12%), arable landscape (5%) and built up land (2%) also evident in low-lying areas (Fuller *et al*. 2002).

Such marked variability across this relatively small region makes the area particularly interesting for characterisation, with significant differences in topography, land use, hydrology and climate. Such diversity is normally associated with much larger spatial scales (Carey *et al*. 2010) but the highly varied nature of the Scottish upland landscape creates many different catchment typologies, which present an opportunity to develop a catchment classification system which may still demonstrate utility when transferred to larger scales.

DATA AND METHODS

Hydroclimatic data

Time series of daily precipitation, discharge and temperature were compiled for the 21 sites. Catchments were selected to capture the variability of hydroclimatic regimes across the region. All are unregulated by dams though several are utilised for small abstractions for public water

Table 2 | Hydroclimatic variables for the 21 catchments investigated

				Temperature		**Precipitation**		**Discharge**				**Potential ET**	
Catchment	**SEPA ID**	**MIDAS Station**	**BADC ID**	**Mean (°C)^a**	**CvT^a**	**Total annual (mm)^a**	**Days 0 mm^a**	**Total Annual (mm)^a**	**cvQ^a**	**Q10 (mm)^a**	**Q95 (mm)^a**	**Estimated total annual (mm)^a**	**Q/P Ratio^a**
Lossie	1	Elgin	A	8.79	0.64	754	163	412	0.21	2.06	0.29	569	0.55
Findhorn	2	Tomatin: Freeburn	B	6.14	0.83	1,440	123	1,116	0.18	6.56	0.42	537	0.78
Allt Dev	3	Cabrach	C	6.49	0.77	1,274	141	565	0.19	3.95	0.57	539	0.44
Bogie	4	Fyvie Castle	D	8.00	0.62	1,017	124	628	0.13	2.87	0.44	558	0.62
Livet	5	Glenlivet	E	6.82	0.75	983	115	781	0.07	3.39	0.64	542	0.79
Avon	6	Tomintoul 2	F	6.03	0.84	1,695	145	1,294	0.11	6.35	0.96	541	0.76
Don	7	Craibstone	G	7.90	0.62	910	139	645	0.20	3.20	0.54	556	0.71
Dee (ML)	8	Inverey	H	5.21	0.98	1,590	129	1,327	0.12	7.66	0.64	517	0.83
Dee (Pol)	9	Polhollick	I	6.06	0.85	1,085	140	726	0.12	6.00	0.58	543	0.67
Muick	10	Birkhall	J	5.65	0.93	1,077	141	728	0.12	5.86	0.48	553	0.66
Feugh	11	Invery House	K	8.38	0.56	1,015	167	780	0.22	4.41	0.33	561	0.77
Tilt	12	Faskally	L	7.43	0.68	1,347	137	968	0.16	8.00	0.71	546	0.72
Ardle	13	Kindrogan	M	6.39	0.77	1,252	138	990	0.12	6.24	0.37	546	0.79
S Esk (Gella Br.)	14	Cortachy	N	6.54	0.75	1,467	146	1,269	0.14	7.53	0.61	557	0.87
Ericht	15	Blairgowrie	O	8.00	0.62	1,124	139	915	0.08	5.66	0.39	560	0.81
Isla	16	Alyth	P	8.16	0.60	858	178	660	0.17	3.88	0.37	566	0.77
Prosen Water	17	Cortachy	Q	7.13	0.69	1,086	125	909	0.09	5.37	0.56	557	0.84
S Esk (Brechin)	18	Brechin Wks	R	8.01	0.60	978	171	803	0.16	4.55	0.39	557	0.82
Dean Water	19	Glamis Castle	S	8.35	0.59	786	167	473	0.22	2.80	0.27	566	0.60
Lunan	20	Crombie Park	T	8.36	0.55	802	155	418	0.31	2.55	0.23	554	0.52
Dighty W	21	Mylnefield	U	8.92	0.54	787	107	400	0.23	2.32	0.56	574	0.51

All climate data sourced from BADC Monitoring Network (1980–2010). *Q*95, *Q*10 and mean annual streamflow from SEPA (1980–2010). Calculated coefficients of variation (cv) for overall observed period, using mean cv values for each year.

^{a}denotes use in clustering and PCA analyses.

supply and agricultural irrigation. Crucially, the length of data records was also significant with all catchments having at least 12-year contemporaneous data records from 1998 to 2009 to facilitate comparisons.

Daily discharge (Q) was measured at 21 Scottish Environmental Protection Agency (SEPA) gauging stations. Daily precipitation (P) data were available from the British Atmospheric Data Centre (BADC; http://www.badc.rl.ac.uk). Data were either directly available or interpolated from surrounding stations using distance-weighted averaging (Jones & Hulme 1996). Daily average air temperature (T) data were obtained from the Met Office 5 × 5 km gridded observations dataset (Met Office 2001), which used stations from across the region. Monthly estimates of potential evapotranspiration (PET) were calculated by the Thornthwaite method (Thornthwaite 1948; Chen *et al.* 2005).

Annual actual evapotranspiration (AET) was estimated assuming no change in storage using the basic water balance equation, $\mathrm{AET} = P – Q$. Monthly values of AET were then estimated by multiplying annual values by monthly PET as a fraction of annual PET.

GIS analyses

Physical catchment characteristics were derived using geographic information system (GIS) software (ArcGIS). A

50×50 m DTM and a digital map of the regional geology were used to identify key physical features (Table 1). Extracted values include mean and maximum elevation and slope, as well as the dominant geology of the catchment (University of Edinburgh Joint Information Systems Committee (EDINA; http://edina.ac.uk/digimap), 2010). The software was also used to create a map of the stream network across the region. To identify a suitable stream initiation threshold (Tarboton *et al.* 1991), derived data were compared with the mapped network from an Ordnance Survey map (1:50,000 scale). An iterative approach was used and an optimum threshold of 1.5 ha was identified and applied in the creation of the stream network maps across all sites (Figures 6(a)–6(e)).

Statistical analyses

A *k*-means cluster analysis was conducted to group catchments based on the similarity using both catchment physical and hydroclimatic variables (Tables 1 and 2) using the statistical programme R (R Development Team 2009). Clusters in multivariate space were identified statistically using Euclidian distance as a measure of dissimilarity. The *k*-means algorithm was selected as it is a flexible method to indicatively extract like-groupings of catchments which can then be verified via further statistical analyses and iteratively improved if need be. To verify the clusters, a principal component analysis (PCA) was conducted on the same input variables using PC-ORD (http://www.pcord.com). Catchments were plotted on the bivariate space of the first two principal components and the results of the cluster analysis were used to group catchments graphically, with groupings determined to be significant at the 95% level.

Next, coherence of catchment response was assessed to determine whether similar grouped catchments exhibit similar intra- and inter-annual variability of precipitation, air temperature and stream flow. Further cluster analyses were conducted for both annual and seasonal trends of precipitation, discharge and minimum, mean and maximum variables of temperature to determine catchment groupings with concordant time series. These newly determined clusters (once again, significant at the 95% level) were then compared with the initial clusters identified using the physical catchment and hydroclimatic characteristics, to assess similarity using Jaccard's Index of Similarity (JIS) (Equation (1)) which is a diversity index primarily used in ecology to determine similarity or differences between sample sets (Jaccard 1908; Real & Vargas 1996)

$$\boldsymbol{J}(\boldsymbol{A},\ \boldsymbol{B}) = \frac{\boldsymbol{A} \cap \boldsymbol{B}}{\boldsymbol{A} \cup \boldsymbol{B}} \tag{1}$$

whereby *J* is the Jaccard index derived by dividing the size of the intersection [all common catchments which are present in both clusters (*A* and *B*)] by the union (all catchments which are present in both clusters). For simplicity, similarity is qualitatively broken down into four categories, defined by the strength of the relationship: 'strong' (JIS > 0.7), 'good' (0.5 < JIS < 0.7), 'weak' (0.3 < JIS < 0.5) and 'poor' (JIS < 0.3). These categories, though arbitrary in nature, provide an indication as to how changes in precipitation, discharge and temperature are reflected across the different catchment typologies. Where similarity is deemed to be 'strong' the majority (≥75%) of catchments exhibit similar patterns of change in terms of their hydroclimatic behaviour. Conversely, 'poor' coherence occurs when only one or none of the catchment groupings displays similar changes in behaviour. The remaining 'good' and 'weak' categories are used to differentiate more and less than half of the catchments demonstrating coherence, respectively.

Finally, trends in the annual and seasonal rainfall, air temperature and discharge time series were assessed by a non-parametric Mann–Kendall test (Kendall 1975). The estimation of such trends was indicative to determine whether catchments exhibit similar changes in the behaviour of precipitation, temperature and discharge over time. Representative exemplar catchments (two from each cluster) with long-term (35 years; to comply with 30 year minimum World Meteorological Organisation guidelines for trend estimation) data were assessed to discern any relationship between clustered catchments and their response to climate change. The Mann–Kendall test for trend is a rank-based method which is used to identify trends in variables that are either drivers of, or responses to, environmental change (Gan 1998; Fu *et al.* 2010; Qin *et al.* 2010). The Mann–Kendall test produces a *tau* statistic which was assessed for significance at a 95% confidence level using an associated *p* value. A two-tailed test was used to identify negative cooling/drying trends and positive warming/wetting trends

(Gan 1998). The magnitude of change was estimated via the determination of Sens slope, which was calculated for the long-term trends using the MAKESENS model designed by the Finish Meteorological Institute (Salmi *et al.* 2002). Following Langan *et al.* (2001), the hydrological year was disaggregated into monthly data and compiled into seasons based on the small ranges between monthly temperatures with no overlap into other seasons. Seasons were defined in accordance with the Met Office classifications of winter (December–February), spring (March–May), summer (June–August) and autumn (September–November).

RESULTS

Annual hydroclimatic characteristics

Table 2 summarises key hydroclimatic indices for the 21 sites over the common time period of 12 years, and inter-site variability for selected parameters is shown in Figure 2. Both inter- and intra-site variability in precipitation, temperature and discharge is marked. Values of mean annual precipitation range from 754 mm a^{-1} (ID 1) to 1,695 mm a^{-1} (ID 6) and the inter-annual range of average precipitation also varies substantially between individual sites; for example, the highest ranges were found for the precipitation gauges representing the rivers Findhorn (ID 2) and the South Esk at Gella Bridge (14), with annual ranges up to 590 mm; whilst the gauges for the catchments of the Livet (ID 5) and Bogie (ID 4) were below 200 mm. Mean annual air temperatures (Figure 2(d)) are also variable across the region, largely decreasing with increasing altitude and ranging from 5.21 °C at Mar Lodge (ID 8) to 8.92 °C (ID 21) in the Dighty Water. Estimates of PET (Figure 2(c)) are much more consistent across the catchments, with mean values ranging from 517 mm (ID 8) to 574 mm (ID 21).

Spatial variation in annual runoff largely reflects that of precipitation (Figure 2(b)), with large differences in mean annual discharge, ranging from 1,590 mm in the Dee at Mar Lodge (ID 8) to 430 mm in the Lossie (ID 1). Patterns of runoff variability also are broadly consistent with variations in precipitation, modulated by the influence of evaporation.

The region is humid with an average of 223 rain days per year. The number of rain days ranges from 187 days at the Isla (ID 16) to 258 days at the Ardle (ID 13). High flows (Q10) ranged from 2.06 mm day^{-1} for the Lossie (ID 1) to 8.00 mm day^{-1} for the Tilt (ID 12) with low flows (Q95) ranging from 0.13 mm day^{-1} at Lunan Water (ID 20) to 0.96 mm day^{-1} for the Avon (ID 6). Measured Q/P ratios range from 0.44 for the Allt Deveron (ID 3) to 0.87 for the South Esk at Gella Bridge (ID 14).

Seasonal hydroclimatic characteristics

At most sites, precipitation is highest in the winter and spring months, though summer precipitation is also significant (see examples for selected catchments in Figure 3). Indeed, some sites such as the Lossie (ID 1) (Figure 3(c)) exhibited limited seasonal variation. However, although the catchments of the Dee at Mar Lodge (ID 8) and the South Esk at Gella Bridge (Figure 3(d)) were wetter in winter (*c.* 5–6 mm d^{-1} average inputs), summer inputs (2–3.5 mm d^{-1} average) were still higher than for the Lossie. Seasonality in discharge is also fairly similar to precipitation with elevated flow conditions in the winter/spring and lower flows observed in the summer months (Figures 3 (a), 3(b) and 3(d)). The influence of snowmelt on spring discharge is evident for the upland catchments with both the Dee at Mar Lodge (Figure 3(a)) and the South Esk at Gella Bridge (Figure 3(d)) showing a stepped decrease to low summer conditions as a result of melting of upland snowpacks. Unsurprisingly, seasonality of AET is fairly consistent across all catchments: low values dominate the winter and spring with peak values in the summer when radiation is at its highest, though overall AET losses are low.

Identified catchment clusters

The *k*-means cluster analysis differentiated four distinct catchment types (Figure 4) with minimum distance within the clusters and sufficient distance between clusters to discriminate groupings (Hartigan & Wong 1979). These clusters are shown on a scatter plot of the first two

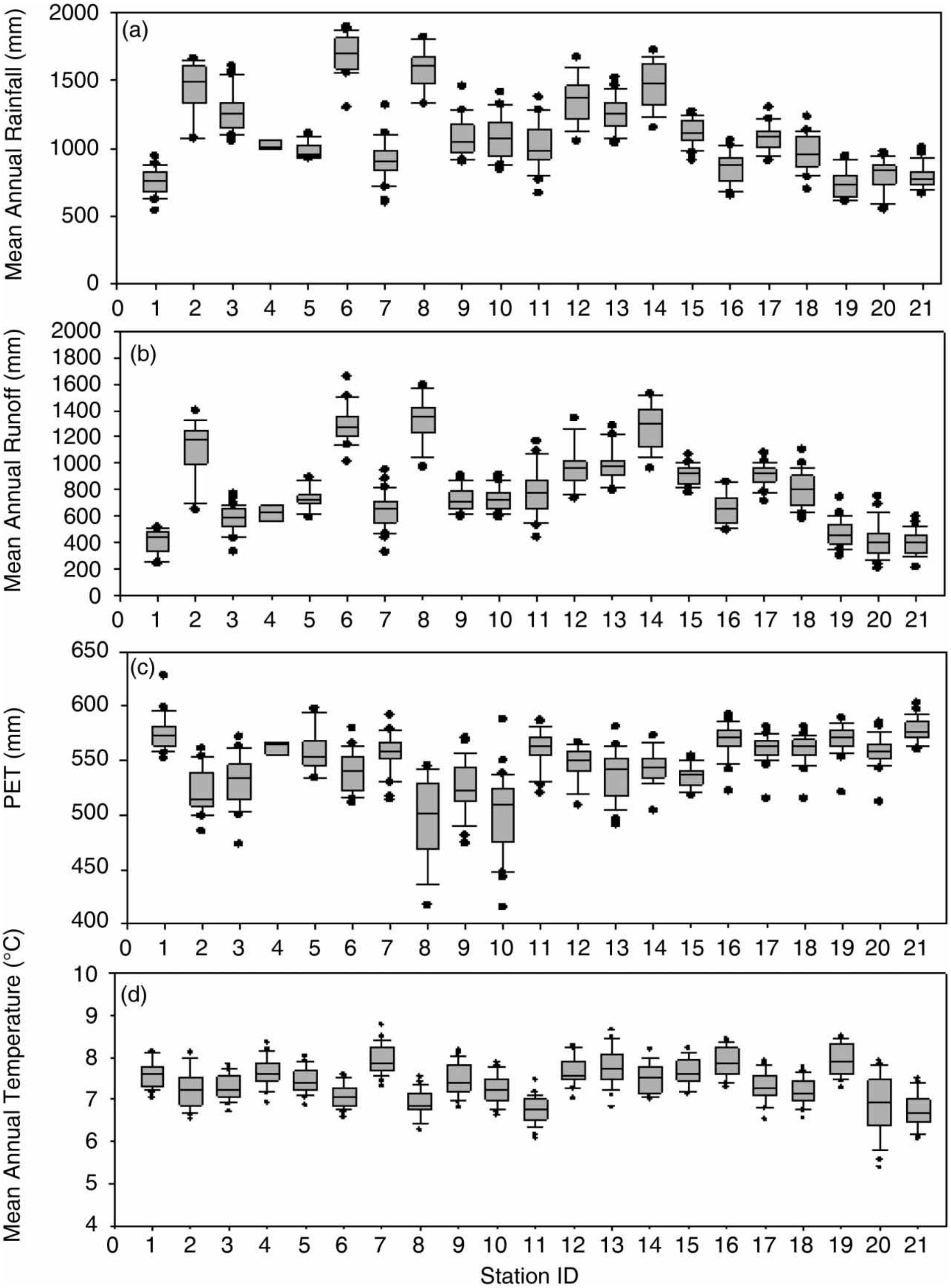


Figure 2 | Summary box-plots of (a) mean annual precipitation, (b) discharge, (c) estimated PET, and (d) mean annual temperature range. Boxes represent (top to bottom) upper quartile, median and lower quartile of data. Whiskers represent (excluding outliers) maximum and minimum values at the top and bottom respectively, with outliers denoted by dots.

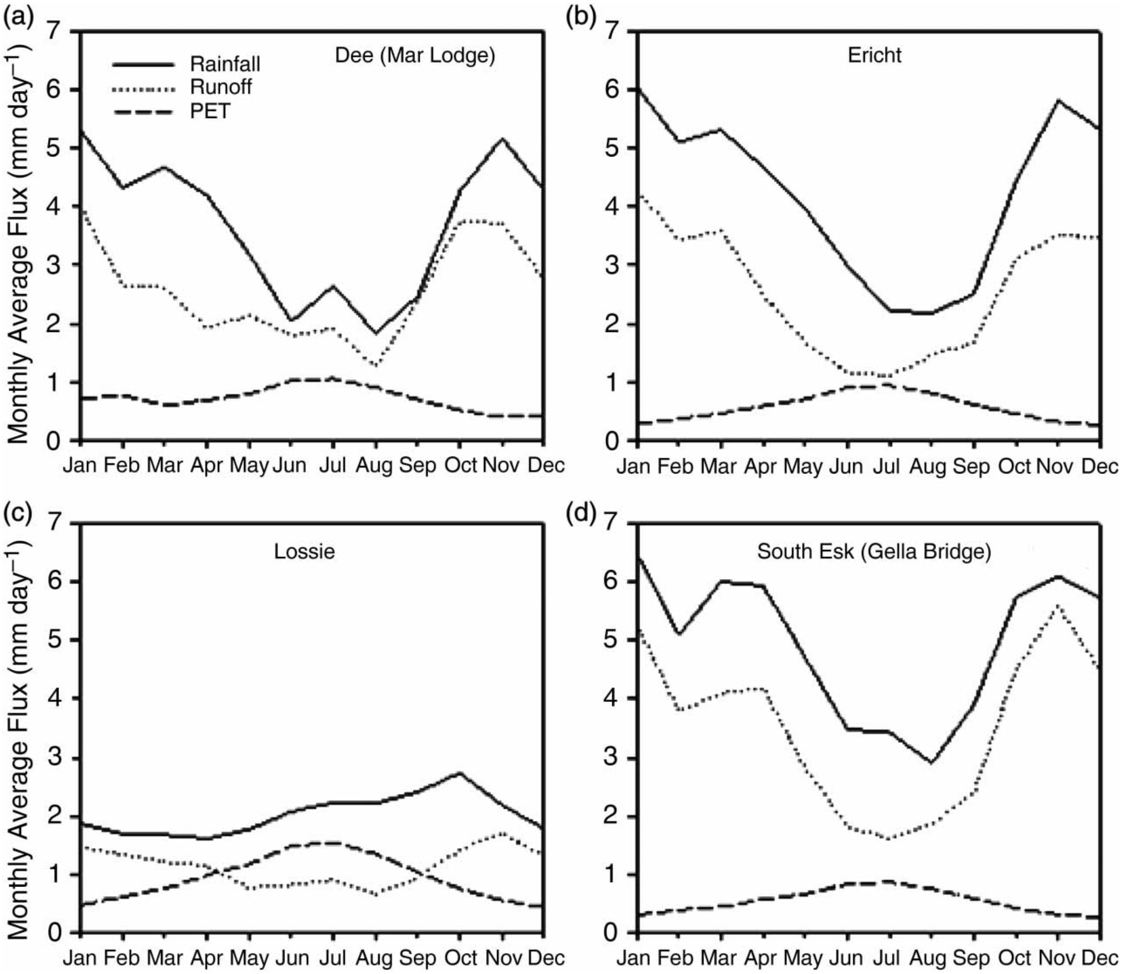


Figure 3 | Monthly flux diagrams of precipitation, discharge and AET for a sample of catchments within the north east region.

principal components (Figure 5), which explain 71% of the overall variance (PC1 explaining 55% and PC2 16%).

The differences in the clusters are primarily explained by PC1 and the physical/hydroclimatic types can be differentiated by the following.

Cluster 1 [IDs – 1 (Lossie), 19 (Dean), 20 (Lunan) and 21 (Dighty)]: 'Small Lowland Catchments'

These small (<250 km^2) catchments are low-lying catchments with gentle slopes (mean elevation < 250 m and slope $< 4.5^{\circ}$) and higher mean annual temperatures. Mean annual precipitation is lower (750–800 mm), as are mean annual values of Q (<475 mm). *cv*Q is highest in cluster 1 (>0.22).

Cluster 2 [ID – 7 (Don), 11 (Feugh), 16 (Isla) and 18 (S.Esk at Brechin)]: 'Larger catchments with strong lowland influence'

These larger (>*c.* 230 km^2) catchments have large low-lying areas but also have upland headwaters, and consequently a higher mean elevation than Cluster 1 (<330 m) and more topographic complexity with a mean slope $<10^{\circ}$. They also have slightly lower temperatures and higher *cv*Q values (>0.16) than Clusters 3 and 4.

Cluster 3 [ID – 2 (Findhorn), 3 (Deveron), 9 (Dee, Polhollick), 4 (Bogie), 5 (Livet), 13 (Ardle), 15 (Ericht), 17 (Prosen) and 10 (Muick)]: 'Upland Catchments'

These encompass both larger (e.g. sites 9 and 15) and smaller (e.g. site 3) sites that are generally located in more upland

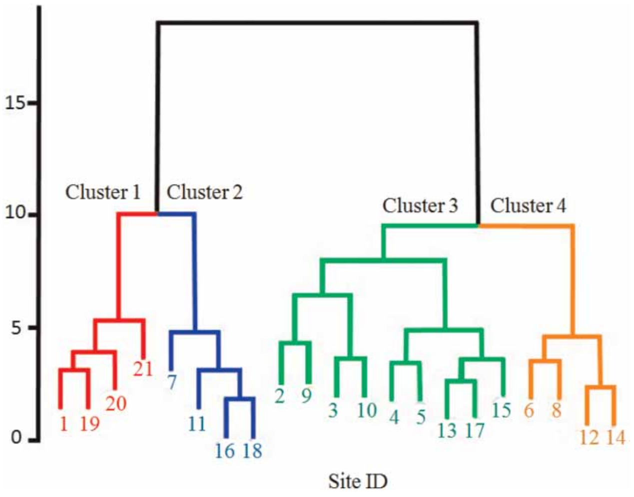


Figure 4 | Hierarchical cluster dendrogram based on Hartigan–Wong index values, showing catchments which display similar behaviours and their identified cluster number.

environments than the previous two clusters (390–682 m and 7–12.2°) with lower mean annual temperatures (<8 °C). These catchments experience a moderate number of rain days (224–250 days) and have similar Q95 runoff, ranging from 0.37 to 0.64 mm day^{-1}.

Cluster 4 [ID – 6 (Avon), 8 (Dee, Mar Lodge), 12 (Tilt) and 14 (S. Esk, Gella Bridge)]: 'Montane catchments'

These sites are the most montane catchments (>550 m mean elevation and >11.5° mean slope). These are dominated by low mean annual temperatures (<7.4 °C) and experience a high number of precipitation days (220 to 236) and some of the highest amounts of mean annual precipitation (>1,350 mm).

Hydroclimatic coherence

Results from the analysis of hydroclimatic coherence within and between the clusters are summarised in Table 3. Cluster 1 ('Small lowland catchments') exhibits the greatest overall coherence, with all sites showing strong or good coherence for all variables, with the exception of minimum summer temperature and spring precipitation, where coherence is moderate. All four catchments within Cluster 2 ('Larger catchments with strong lowland influences') show strong coherence for eight variables with remainder having two or three catchments

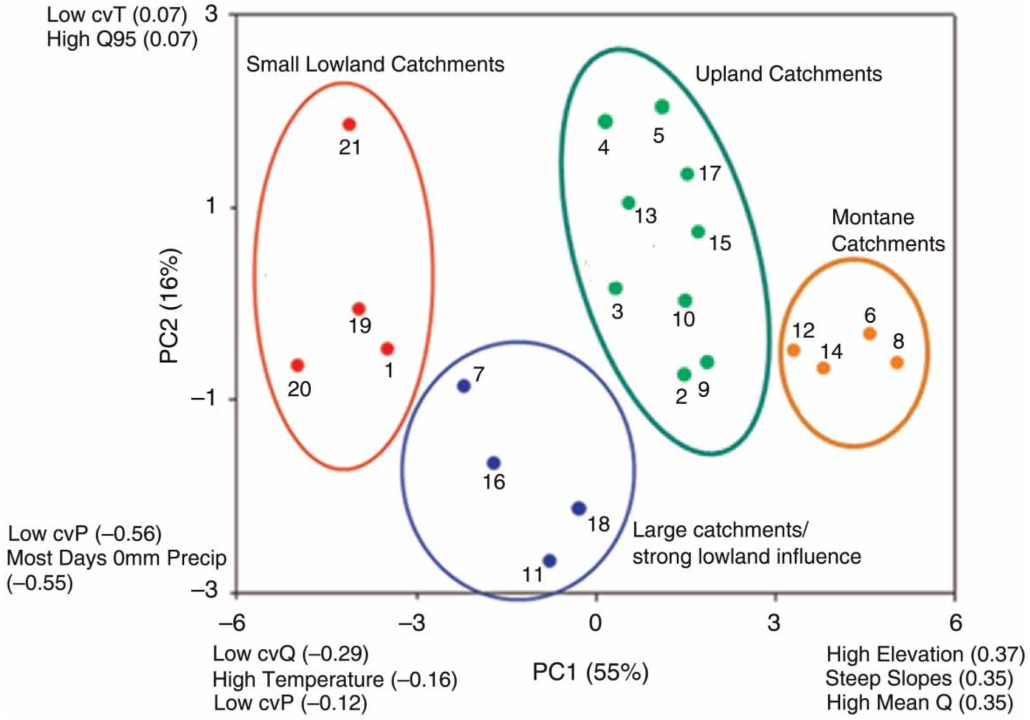


Figure 5 | PCA scatter-plot output (input variables in Tables 1 and 2) of 21 catchments in North East Scotland.

Table 3 | Jaccard's index of similarity results between derived clusters and hydroclimatic behaviour over the 12-year period. The closer to 1 the JIS is, the better the relationship between catchment type and time series response of P, Q or T. Strength of relationship is qualitatively determined as 'strong' (**bold**, > 0.7), 'good' (*italic*, $0.5 < x < 0.7$), 'moderate' (underlined, $0.3 < x < 0.5$) and 'null' (no formatting, < 0.3)

Variable	Small lowland	Larger catchments with strong lowland influence	Upland	Montane
Annual Q	**1**	*0.67*	0.365	1
Annual P	**1**	**0.75**	0.2	0
Ann. Min Temp (°C)	**0.86**	0.4	0.485	0.4
Ann. Mean Temp (°C)	**0.86**	*0.67*	*0.62*	*0.67*
Ann. Max Temp (°C)	**0.86**	**0.86**	0.165	*0.67*
Winter Q	**1**	**0.86**	0.335	0
Winter P	**0.86**	**1**	0.485	0
Win. Min Temp (°C)	**0.86**	**0.86**	**0.785**	0
Win. Mean Temp (°C)	**0.75**	0.4	0.43	0.4
Win. Max Temp (°C)	**1**	0	0.485	0
Spring Q	**1**	*0.67*	0.2	0
Spring P	0.4	**0.75**	0.165	0
Spring Min Temp (°C)	*0.67*	**0.86**	0	0
Spr. Mean Temp (°C)	**0.86**	**0.86**	*0.5*	0
Spr. Max Temp (°C)	**0.75**	0	0	*0.67*
Summer Q	**1**	**1**	0.43	0
Summer P	*0.67*	*0.67*	*0.5*	0
Sum. Min Temp (°C)	0.4	0.4	0	0.4
Sum. Mean Temp (°C)	**0.75**	*0.67*	*0.62*	0
Sum. Max Temp (°C)	**0.86**	0	0	0.4
Autumn Q	**1**	0.4	0.335	0
Autumn P	**0.86**	0	0.285	0.4
Aut. Min Temp (°C)	**0.86**	0.4	0.285	*0.67*
Aut. Mean Temp (°C)	**0.86**	**0.86**	0.43	0
Aut. Max Temp (°C)	**1**	0.4	0.43	0

exhibiting similar behaviours. By contrast, Cluster 3 ('Upland catchments') is most variable. Here, there is one strongly coherent relationship (winter minimum temperature) and only four measures of good coherence, with the remaining variables displaying moderate or null coherence. Cluster 4 ('Montane catchments') also shows a poor correspondence between catchments and hydroclimatic response for all indices except mean annual discharge, which is strong.

In summary, progressing from Cluster 1 to Cluster 4, the degree of coherence in hydroclimatic response generally decreases. Average JIS values decrease from 0.86 to 0.22 between these two clusters. Thus it appears that from lowland to montane catchments, the number of strong or good coherence relationships breaks down and increasingly more moderate or null relationships are identified.

Hydroclimatic trends

Results of the annual and seasonal trends are summarised in Table 4. These are based on a 35-year period for two exemplar sites from each cluster apart from Cluster 4 where the longest available records were 24 (Dee at Mar Lodge) and 19 (South Esk at Gella Bridge) years, respectively. As this falls short of the 30 year criterion recommended by the WMO the results need to be interpreted

Table 4 | 30-year statistically significant ($p < 0.05$) trends for two exemplar catchments per cluster

	Site	**21**	**19**	**18**	**7**	**10**	**13**	**8**	**14**
	Cluster	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
Annual	Q	–	–	–	–	–	–	–	–
	P	–	–	–	–	+(118 mm)	+(273 mm)	+(296 mm)	+(284 mm)
	Min *T*	+(1.02 °C)	+(0.98 °C)	+(0.88 °C)	+(1.00 °C)	+(0.95 °C)	+(1.02 °C)	+(1.12 °C)	+(1.18 °C)
	Mean *T*	+(1.42 °C)	+(1.39 °C)	+(1.24 °C)	+(1.48 °C)	+(0.74 °C)	+(1.30 °C)	+(0.90 °C)	+(1.50 °C)
	Max *T*	+(1.85 °C)	+(1.84 °C)	+(2.28 °C)	+(1.52 °C)	+(1.24 °C)	+(1.84 °C)	+(1.60 °C)	+(1.66 °C)
Winter	Q	–	–	–	–	–	–	–	–
	P	–	–	–	–	–	–	–	–
	Min *T*	–	–	–	+(1.92 °C)	–	–	–	–
	Mean *T*	–	–	–	–	–	–	–	–
	Max *T*	+(1.82 °C)	+(1.87 °C)	+(2.37 °C)	–	–	–	+(3.23 °C)	+(2.74 °C)
Spring	Q	–	–	–	–	–	–	+(78 mm)	+(63 mm)
	P	−(14.8 mm)	–	–	–	–	–	–	–
	Min *T*	+(1.27 °C)	+(1.23 °C)	–	–	–	+(1.24 °C)	–	–
	Mean *T*	+(1.14 °C)	+(1.16 °C)	+(1.15 °C)	+(1.48 °C)	+(0.80 °C)	+(1.09 °C)	–	–
	Max *T*	+(2.18 °C)	+(1.65 °C)	+(2.28 °C)	+(2.27 °C)	+(2.09 °C)	+(1.38 °C)	+(1.88 °C)	+(2.20 °C)
Summer	Q	–	–	–	–	–	–	–	–
	P	–	–	–	–	–	–	–	–
	Min *T*	+(1.62 °C)	+(1.56 °C)	+(1.64 °C)	+(1.45 °C)	+(0.99 °C)	+(1.69 °C)	+(1.09 °C)	+(0.91 °C)
	Mean *T*	+(1.73 °C)	+(2.48 °C)	+(1.77 °C)	+(2.12 °C)	+(2.24 °C)	+(2.17 °C)	+(1.62 °C)	–
	Max *T*	+(2.42 °C)	+(1.76 °C)	+(1.99 °C)	+(2.03 °C)	+(2.57 °C)	+(1.58 °C)	+(3.28 °C)	–
Autumn	Q	–	–	+(34 mm)	–	–	–	–	–
	P	–	–	–	–	–	–	–	–
	Min *T*	–	–	–	–	–	+(1.57 °C)	–	+(1.82 °C)
	Mean *T*	+(1.17 °C)	+(1.37 °C)	+(1.14 °C)	–	+(1.27 °C)	+(1.20 °C)	+(1.70 °C)	+(1.69 °C)
	Max *T*	+(1.13 °C)	+(1.20 °C)	+(1.36 °C)	–	+(1.76 °C)	+(1.14 °C)	+(2.04 °C)	+(2.15 °C)

Positive trends are indicated by a '+', negative trends by a '−' and no trend is signified by a '–', with magnitude of change denoted in brackets.

cautiously and can only be considered indicative, but nonetheless the data were used to discern changes across all clusters.

Annual trends (Figure 6(a))

These exhibit a widespread increase in minimum (0.88 °C–1.18 °C), mean (0.74 °C–1.61 °C) and maximum (1.24 °C–2.28 °C) temperature indicating a very clear warming trend across the region (Table 4). None of the four clusters shows any increase or decrease in catchment discharge, though there is a marked average increase in precipitation in Clusters 3 (+196 mm) and 4 (+290 mm).

Seasonal trends

Changes in hydroclimatic variables are least marked for the 'winter' (Figure 6(b)) season, with no significant change in either precipitation or discharge across the region. Minimum winter air temperature increased significantly at site ID 7 (Don) (+1.92 °C), but no other exemplar in any cluster shows any change. There is no change in mean winter temperature for all clusters, though maximum winter temperatures increased significantly for both exemplars in Clusters 1 (small lowland catchments) and 4 (montane catchments). An increase was also recorded at catchment ID 18 (South Esk at Brechin) in Cluster 3.

An increase in 'spring' (Figure 6(c)) discharge is evident at both catchments in Cluster 4 (Montane), with an average increase of 71 mm. The only change in spring precipitation detected was a small decrease at catchment ID 21 (Dighty Water) (−14.8 mm). Minimum spring air temperature shows an increase in both exemplar sites in Cluster 1 (small lowland catchments) and Cluster 3 (transitional catchments). All sites in Clusters 1–3 exhibited an increase in mean spring air temperatures, though no change was detected at either of the montane sites in Cluster 4. Maximum spring air temperatures have increased across all catchments, ranging from an average increase of 1.74 °C (Cluster 3) to 2.28 °C (Cluster 2). Increases in the maximum spring temperature is likely to impact on the melt dynamics of upland snowpacks, triggering an earlier and more rapid translation into meltwater discharge and replenishment of storages in the upland areas.

Trend analysis for 'summer' (Figure 6(d)) detected no change in either precipitation or discharge though minimum air temperatures exhibited an increase for all clusters. Mean and maximum summer air temperatures also both show increases across all sites in Clusters 1–3 though in Cluster 4 (montane catchments) only site ID 8 (Dee at Mar Lodge) indicated an increase.

Trends in 'autumn' (Figure 6(e)) indicated complex responses with some catchments exhibiting increases in discharge but no consistent change between either of the exemplar sites in any cluster. No trends in autumn precipitation were detected with the exception of the Allt Deveron (ID 3). Changes in autumn air temperatures were varied. Minimum air temperature shows very little change with the exception of the Ardle (ID 13; +1.57 °C) and South Esk at Gella Bridge (ID 14: +1.82 °C). Mean air temperature shows a more consistent increase across Cluster 1 (small lowland catchments – average 1.27 °C), Cluster 3 (transitional catchments – average 1.24 °C) and Cluster 4 (montane – average +1.70 °C). Maximum temperatures also increase across Cluster 1 (+ 1.17 °C), Cluster 3 (+1.45 °C) and Cluster 4 (+2.10 °C).

DISCUSSION

The 21 study sites were classified into four concise catchment typologies with strong emphasis on a transition from lowland to upland catchments. Generic classification schemes that can link catchment form and function from a parsimonious selection of indices with high information content have been identified as a major priority in hydrology (McDonnell & Woods 2004; Wagener *et al.* 2007). However, the specific purpose of any classification tool and geographical variability dictate that approaches used are often idiosyncratic. Thus, previous studies have used indices of various characteristics (e.g. geographical location (Burn & Boorman 1992), elevation (Wolock *et al.* 2004), land-use (Herlihy *et al.* 1998)) for different purposes. Here, the influence of topographic metrics such as elevation and slope, together with concomitant hydroclimatic indices provided the basis for differentiating the catchments on a continuum from the lowlands to montane areas draining the high Cairngorms. Although simplistic, the classification strategy is a

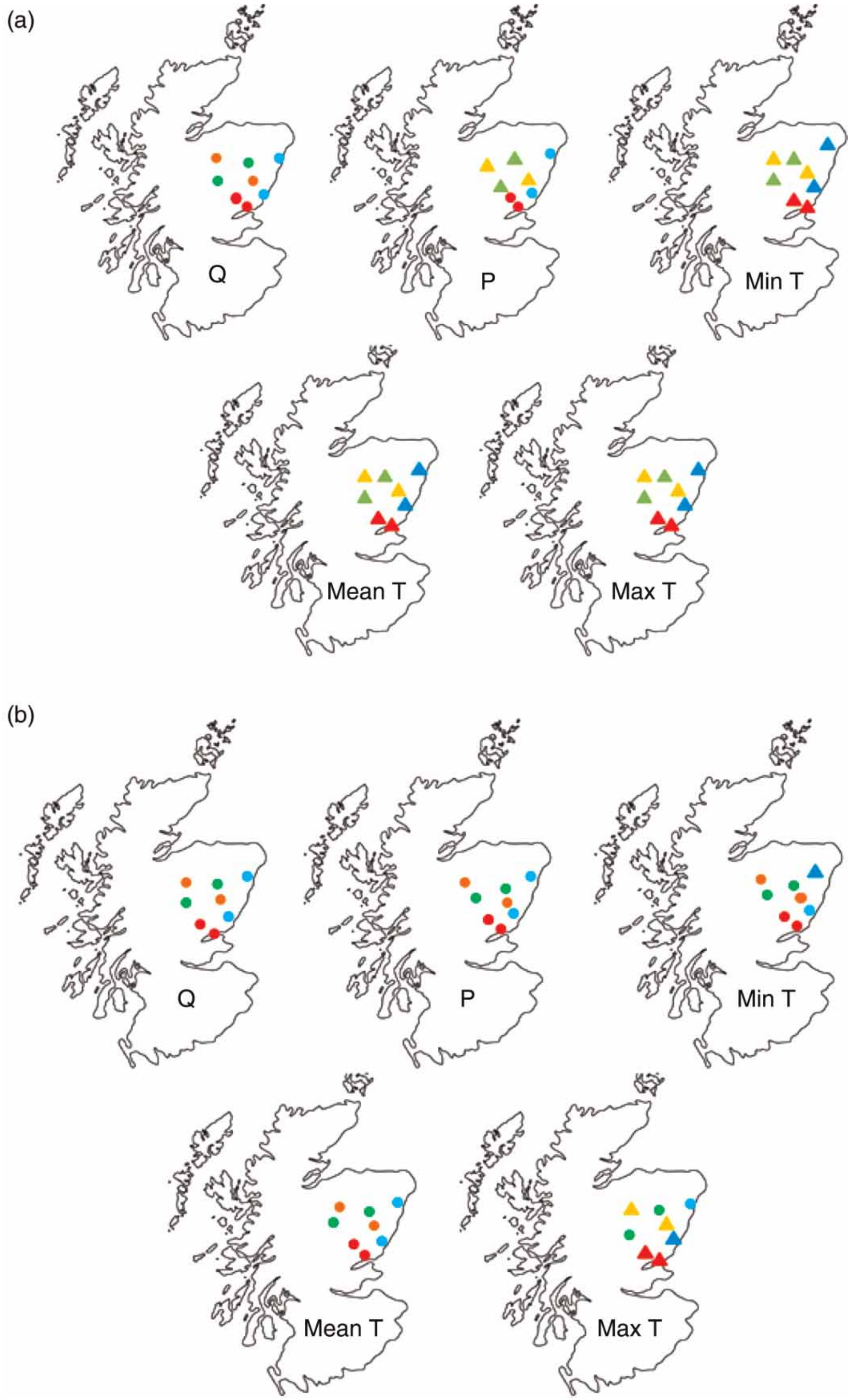
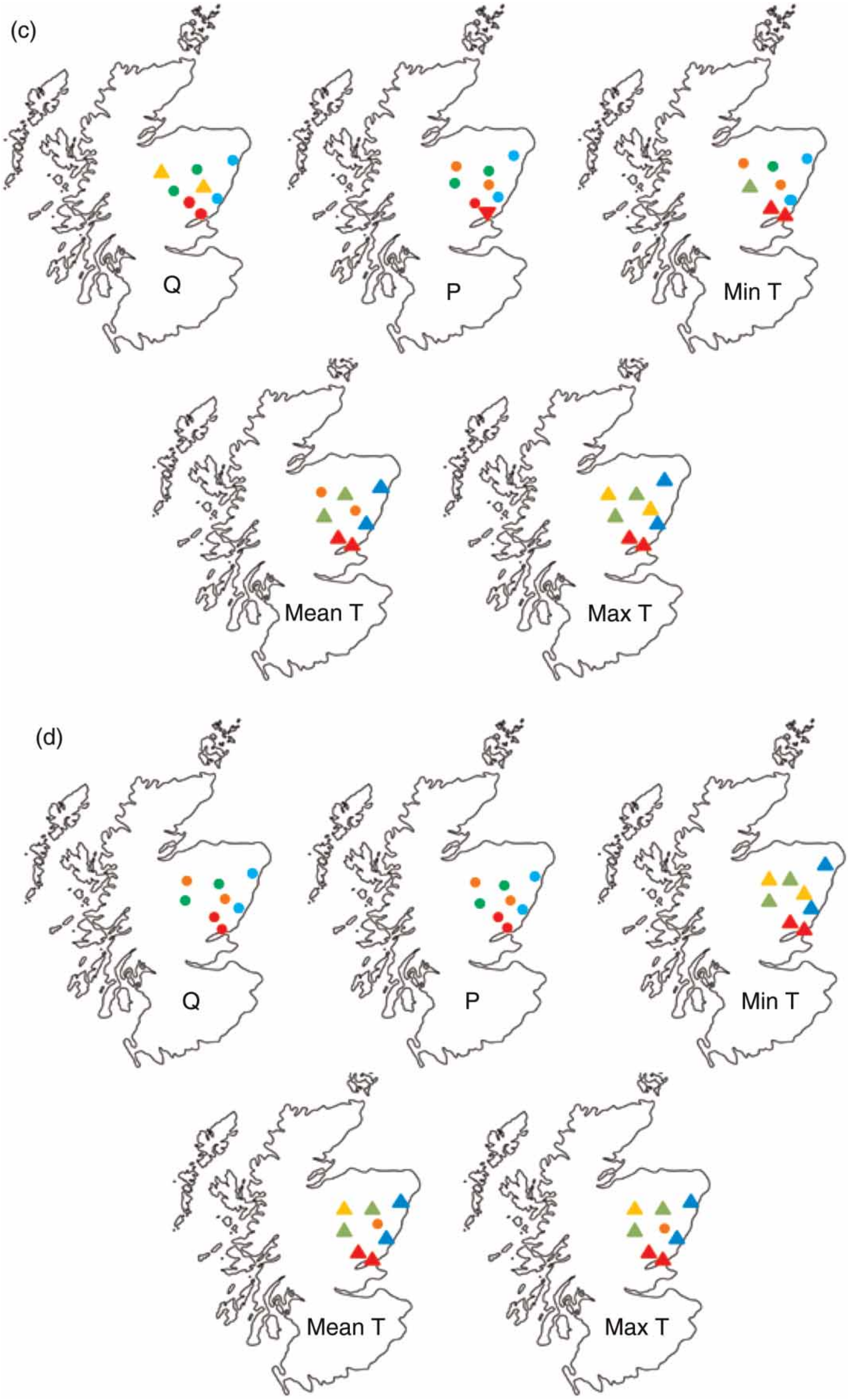


Figure 6 | Statistically significant ($p < 0.05$) trend results for *Q*, *P*, minimum, mean and maximum temperature. Positive trends are denoted by a ▲, negative trends by a ▼ and no trends are signified by a •; colourings relate to cluster groupings; (a) annual, (b) winter, (c) spring, (d) summer, (e) autumn. Please refer to the online version of this paper to see the figure in colour: http://www.iwaponline.com/nh/toc.htm.



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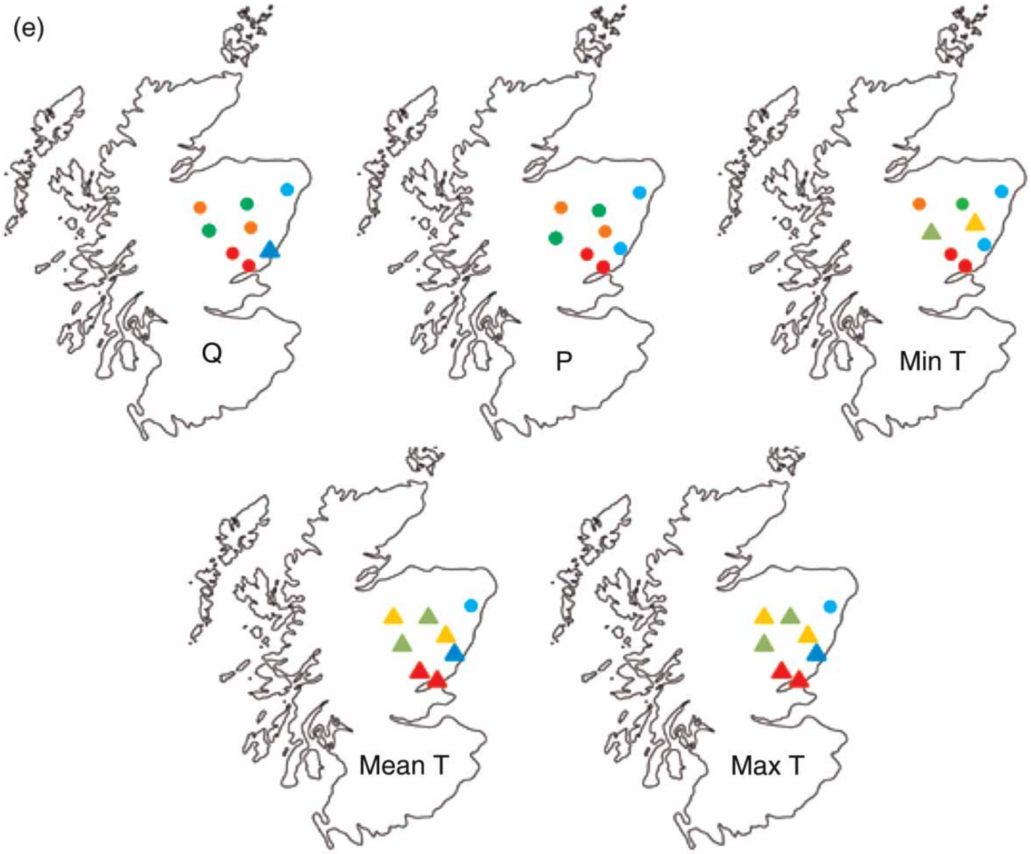

Figure 6 | continued.

useful step. However, it might have been further improved if more integrative, functional indices were available. For example, Ali *et al*. (2012) found tracer-derived estimates of catchment mean transit time (MTT) to be a very useful metric for catchment classification. On the other hand, estimates of MTT have been shown to correlate with topographic indices as a result of the influence of topography on soil cover and as a reflection of geology (Soulsby & Tetzlaff 2008; McGrane *et al.* 2012). As such, it is anticipated that these cluster groupings would be generally maintained by the inclusion of additional metrics. Furthermore, the approach is likely to have utility in application to regions outwith the study area though other metrics may provide the stronger differentiating controls in different hydroclimatic and geomorphic provinces.

The degree of coherence of intra- and inter-annual variation in hydroclimatic drivers and streamflow response varied between the four groupings (Table 3). The similarities were greatest for Cluster 1 (small lowland catchments) which in the cases of sites 19, 20 and 21 is unsurprising as they are in close proximity in the SE of the study area. However, as site 1 is one of the most northerly, this implies greater uniformity over the lowland catchments in the study area. This is also suggested by the high similarities of many indices for Cluster 2 (larger catchments with strong lowland influence). However, this coherence is much less evident in Clusters 3 and 4 where the upland influence is stronger. This may reflect the stronger influence of local factors in determining patterns of weather and climate in complex mountain terrain like the Cairngorms. Moreover, as the rivers in these groups drain from around the circumference of the Cairngorm Mountains they contrast in terms of aspect. This then ranges between sites on the windward (west) and leeward (east) sides of the mountains relative to the prevailing westerly weather systems. It also varies between north facing and south facing catchments with associated implications for patterns of snow accumulation and melt. Indeed it is perhaps telling that the poor coherence in Cluster 4 comes from rivers which encompass much of this variability (Figure 1); the Dee at Mar Lodge flows eastwards, the Avon northwards, and the South Esk and Tilt flow in a south-east and south-west direction, respectively. This is consistent with other findings in the literature whereby physiographical similarity does not necessarily equate to similar hydrologic functioning between catchments (Oudin *et al.* 2010; Ali *et al.* 2012). This is further supported by Merz & Bloschl (2009), who note that runoff generation occurs as a result of a combination of mechanisms and cannot be attributed to such characteristics as slope, elevation and topography individually across catchments in the Austrian and Swiss Alpine region.

The directional trend of hydroclimatic drivers at the site shows fairly consistent increases in annual temperature indices and most spring, summer and autumn indices. For winter, only increases in maximum temperature were observed for some sites. The implications for such warming are greatest at sites of higher elevation where the slight temperature increases can have a profound effect on the form of precipitation (as rain or snow), the extent and longevity of snowpack accumulation and the subsequent rates of melt (Carey *et al.* 2010; Hall *et al.* 2010; Shrestha *et al.* 2011). This is consistent with other findings in the Scottish Highlands. Langan *et al.* (2001) identified increases in daily maximum temperatures in both winter and spring resulting in a concurrent increase in stream water temperatures. Such temperature increases have also been detected in other upland parts of the United Kingdom. Worrall *et al.* (2003) identified that increasing temperatures of 0.7 °C between 1970 and 2000, in the North Pennines has contributed towards a 12% increase in the production rate of dissolved organic carbon. Dettinger & Cayan (1995) also attribute the impact of increasing winter temperatures to the extent of snowpack accumulation in basins across northern and central California, resulting in increased fractions of meltwater occurring earlier in the spring due to warming conditions.

Consistent changes in precipitation under this warming regime are much less evident. Only the exemplar sites in Clusters 3 and 4 show an increase in overall annual precipitation over the period of the study, with this being strongest in the two sites of the montane Cluster 4 (though it should be recalled that these have a shorter period of data record). Resultant increases in annual discharge were also detected in both clusters but were deemed to be statistically insignificant below the 95% certainty level. This may be the result of a portion of this additional rainfall being lost to evapotranspiration as a result of increasing temperatures. Only in the case of one site (Dighty Water, Cluster 1) is there evidence of a seasonal (spring) increase in precipitation (and this is modest at 14.8 mm). Changes in precipitation across Scotland have been shown to be highly variable with no consistent spatial or temporal patterns. Some parts of Western Scotland have demonstrated a marked increase in winter precipitation, but these trends have been harder to determine in the more variable upland environments (Environment Agency 2011). McCabe & Wolock (1997) identified the impact of increasing temperatures on the reducing fraction of precipitation which occurs as snow resulting in an increase in winter rainfall in the higher latitudes. In upland catchments snowfall can occur anytime between September and April, where changes in temperature will impact on the phase of precipitation throughout this period and not be confined to any single arbitrarily defined season.

Despite the increases in annual precipitation in Clusters 3 and 4, there was no increase in annual discharge detected in the two exemplars from each cluster. Only the two sites in Cluster 4 exhibited increases in spring runoff. Recent climate change modelling in the North Esk catchment which drains the Eastern Cairngorms has projected that wetter, warmer winters and drier summers by the mid-21st century are likely (Capell *et al.* 2012) which is the case for a range of emission scenarios. In terms of runoff, the corollary is that winter and spring runoff is projected to increase, as a result of more precipitation falling as rain (in the case of the former) and more rapid rates of melt (in the case of the latter). The data presented here may indicate that increases in spring discharge are already occurring, though the lack of correspondence between precipitation increases and runoff responses means caution is appropriate. The lack of correspondence may be a result of increases in temperatures leading to more precipitation falling as rain during this time rather than snow, bypassing temporary storage as upland snowpacks. Additionally, increases in maximum temperatures may lead to accelerated melt of existing snowpacks, contributing to earlier release of meltwater discharge during spring rather than a graduated release over a more prolonged period. Furthermore, increases in spring temperatures may not only impact on the phase of precipitation and melt dynamics of snowpack but also on the magnitude of evaporative losses through increased temperature. Indeed, Hamlet *et al.* (2007) determined that increases in evaporative losses are related to both increasing temperatures and water availability; the onset of an earlier melt season in the upland areas of the western United States resulted in a shift in the seasonal patterns of evapotranspiration. This seasonal shift of ET coincides with increasing discharge due to the shift in snowmelt discharge. Although a positive trend is detected during spring as a result, increases at an annual scale remain modest.

The availability of long-term data, particularly in the more montane catchments, is limited across the region which resulted in the use of shorter time series, and results from the trend test must be interpreted with caution. Although results appear mostly consistent with other findings from both Scotland and beyond, some of the results go against wider findings, such as the absence of any statistically significant increase in winter precipitation. However, an increase in winter precipitation was identified in the trend analyses but did not meet the required significance threshold, which may have been determined with a longer time series. Additionally, Ali *et al.* (2012) argue the need for greater regional focus and identification of common parameters at more local scales as a basis for establishing comparative catchment databases, perhaps at scales more local than the focus of this research. In addition to changing hydroclimatic trends over time, consideration of the cyclicity of the North Atlantic Oscillation (NAO) may also provide insight into the influence of different air masses on the climate of Scotland and to what extent variations in the NAO can explain variations in the hydroclimatic conditions across these regional catchments. The dynamics of the NAO are outlined in detail by Hurrell (1995). Briefly, the NAO is an atmospheric circulation system which governs the northern hemisphere, determined by the variance in sea-level pressure between the Icelandic Low and Azores High resulting in the generation of changes in wind speeds, latent and sensible heat fluxes and sea-surface temperatures across most of the mid-latitude North Atlantic (Cayan 1992). During positive phases, the NAO is dominated by high pressure systems, resulting in milder and wetter winter conditions whereas negative phases of the NAO, governed by low pressure systems, are associated with cold and dry winter conditions (Gillibrand *et al.* 2004). Such phases tend to cluster together, resulting in prolonged dry and wet periods back to back (Werritty 2002). Although results here from the Mann–Kendall test suggest an increase in key hydroclimatic variables over time, it has been reported that the NAO has been undergoing a phase shift over the past three decades from mostly negative to mostly positive, resulting in wetter and warmer conditions (Visbeck *et al.* 2001). Much remains unknown about the controlling mechanisms of the NAO though it is widely regarded that anthropogenic influence is impacting on the functionality, resulting in changes to the long-term circulation patterns impacting on northern and western Europe, resulting in warming temperatures and changing precipitation patterns (Visbeck *et al.* 2001).

CONCLUSIONS

Despite their differences in physical and hydroclimatological characteristics, catchments from the north east of Scotland were classified by cluster analysis according to various indices of similarity. Topographic variability was the key first-order control. Analysis of variability in hydroclimatic drivers and streamflow response behaviour showed that catchments in the lowland-dominated clusters tended to have greater coherence in intra- and inter-annual function. In upland and montane catchments, this broke down possibly indicating the influence of local factors on upland weather and climatic characteristics. All sites have experienced increases in annual temperature, with warming trends most marked in spring and autumn. Trends in water balance characteristics however are less evident, with only montane catchments indicating increases in annual precipitation, mainly reflecting increased winter rainfall as a result of increasing warming impacting precipitation phase. Streamflow responses are limited to increased spring flows from montane catchments, which is indicative of changing precipitation phase and additionally the earlier onset of snowmelt contributions to runoff. The breakdown of such relationships between catchment typology and hydroclimatic change suggests the role of additional factors which are undetermined here, such as the possible influence of and changes in weather circulation patterns such as the North Atlantic Oscillation.

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