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Inter-catchment comparison to assess the influence of topography and soils on catchment transit times in a geomorphic province; the Cairngorm mountains, Scotland

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Abstract:

A quantitative, process relevant analysis of ten mesoscale (*ca* 10–90 km^2) catchments in the Cairngorm mountains, Scotland was carried out using 10-m digital terrain models (DTMs). This analysis produced a range of topographic indices that described differences in the landscape organisation of the catchments in a way that helped explain contrasts in their hydrology. Mean transit time (MTT)—derived from isotopic tracer data—was used as a metric that characterised differences in the hydrological function of the ten catchments. Some topographic indices exhibited significant correlations with MTT. Most notably, the ratio of the median flow path length to the median flow path gradient was negatively correlated with MTT, whilst the median upslope area was positively correlated. However, the relationships exhibited significant scatter which precluded their use as a predictive tool that could be applied to ungauged basins in this region. In contrast, maps of soil hydrological properties could be used to differentiate hydrologically responsive soils (which are dominated by overland flow and shallow sub-surface storm flow) from free draining soils (that facilitate deeper sub-surface flows). MTT was negatively correlated with the coverage of responsive soils in catchments. This relationship provided a much better basis for predicting MTT in ungauged catchments in this geomorphic province. In the Cairngorms, the extensive cover of various glacial drift deposits appears to be a first order control on soil distributions and strongly influences the porosity and permeability of the sub-surface. These catchment characteristics result in soil cover being a much more discerning indicator of hydrological function than topography alone. The study highlights the potential of quantitative landscape analysis in catchment comparison and the need for caution in extrapolating relationships between landscape controls and metrics of hydrological function beyond specific geomorphic provinces.

KEY WORDS mean transit times; topography; soil distribution; landscape organisation; isotope tracer; ungauged basins

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INTRODUCTION

It is increasingly recognised that contrasting geomorphic evolution of landscapes explains significant differences in catchment topographic structure that, in turn, result in differences in hydrological behaviour (Istanbulluoglu and Bras, 2005; Phillips, 2006). It follows that there is a need for more advanced, process relevant characterisation of catchment topography to understand its influence on hydrological function in a more integrated way (e.g. Bogaart and Troch, 2006)

The topography of catchments is a major hydrological driver, which also influences the distribution of soil types which additionally exerts a major influence on partitioning of water movement between surface and sub-surface flow paths (McGlynn and Seibert, 2003). Indeed the co-evolution of topography and pedogenesis is well recognised in the geomorphologic literature and is implicitly incorporated in many hydrological models such as TOPMODEL (Kirkby, 1997). Recent advances in the resolution and accuracy of digital terrain models (DTMs) have allowed increasingly detailed analyses of catchment topography. Such spatially distributed information can be used to derive simple catchment scale indices that can reveal important insights into the more subtle nature of topographic controls on hydrology (Seibert and McGlynn, 2005). This has been particularly well demonstrated in recent work in relatively young, steep terrain in New Zealand and the Western Cascades, USA where researchers found that catchment mean transit times (MTTs) were strongly correlated with various topographic indices that could be related to hydrological routing and mixing processes (McGlynn *et al.*, 2003; McGuire *et al.*, 2005).

Using MTT as a descriptor of hydrological function has received increased interest over the past decade (McGuire and McDonnell, 2006). MTT–i.e. the average time taken for a water molecule to travel through a catchment from rainfall to runoff–is usually estimated by modelling tracer input–output relationships according to various transit time distributions (TTDs) in order to gain an integrated understanding of the emergent behaviour of complex catchment mixing processes by assessing the timing of water movement through the catchment (Kirchner *et al.*,

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2001). Developing such understanding of the emergence of processes in hydrology is particularly challenging as topographic controls interact with the (usually unknown) porosity and permeability of the sub-surface (McDonnell *et al*., 2007). For example, in ancient glaciated landscapes such as Scotland or Sweden, complex drift distributions and associated, co-evolved soils mean that the influence of topography *per se* is best implied by using soil hydrology as a more useful predictor of MTT (Rodgers *et al*., 2005a,b; Soulsby *et al*., 2006a,b; Laudon *et al*., 2007). Where topographic variation is limited and soils are relatively uniform as in extensive parts of the Canadian Shield, the topology of landscape features adjacent to the river channel network appear to become increasingly important (Devito *et al*., 2005; Buttle, 2006). In most situations, the importance of these controlling factors vary as differences in topography, soil cover and geology interact to govern generic, macroscale characteristics of TTDs in particular catchments (Hrachowitz *et al*., 2009).

Inter-catchment comparisons can be helpful in identifying the contrasting nature of controls on hydrological functioning in different geographical regions (Soulsby *et al*., 2008). This is because problems of scaling and the uniqueness of places are often constraints on developing transferable approaches from individual catchment studies (Beven, 2001). For example, inter-catchment comparisons can help examine the relative influence of topography and soils on functional metrics such as MTT in different hydrogeomorphic and hydroclimatic zones (Tetzlaff *et al*., 2009). Linking such metrics to other indices derived from mapped landscape characteristics (e.g. topographic indices or catchment soil distributions) has considerable potential for application to ungauged basins where many applied issues in hydrology often emerge (Soulsby and Tetzlaff, 2008; Tetzlaff *et al*., 2008). Such map-derived indices would be particularly useful in montane catchments where data collection is difficult and monitoring networks are sparse (Viviroli *et al*., 2003; Soulsby *et al*., 2007).

As a step towards reconciling the ambiguities between topographic and soil-derived controls on MTT, in this paper we examine the integrated nature of landscape influences on MTTs estimated for similar sized mesoscale (*ca* 10–90 km^2) catchments in the geomorphic province of the Cairngorms mountains of Scotland, an ancient, glaciated landscape (Gordon and Wignall, 2006). The catchments have a broadly similar hydroclimatic regime, but contrasting topography and soil characteristics which largely reflect differences in landscape evolution. In these catchments, previous studies have shown that MTT is closely correlated with soil characteristics, in that MTT is lowest where catchments have a high coverage of responsive soils (i.e. those generating overland flow such as peats and gleys, and those generating shallow subsurface storm flow such as regosols) (Soulsby *et al*., 2006a,b). Conversely, MTT is highest when free draining soil (such as podzols and alluvium) cover is high and deeper sub-surface storm flow and groundwater discharge are the dominant runoff processes (Soulsby and Tetzlaff, 2008). Unsurprisingly, there are often also strong correlations with topography. However, these are somewhat counterintuitive and ambiguous. Steeper slopes tend to have more free draining soils, facilitating deeper flow paths, greater tracer mixing and longer MTTs. In contrast, more gently sloping areas are more ambiguous; in valley bottoms or on flatter interfluves, where fine textured glacial drift impedes drainage, responsive peats and gleys are dominant which result in lower MTTs (Tetzlaff *et al*., 2007a). However, where flatter valley bottoms are filled with alluvium or fluvioglacial deposits (e.g. Chen et al., 1997); and higher altitude interfluves are covered by periglacial drift and more ancient weathering surfaces (e.g. Soulsby et al., 1998; 1999), free draining podzolic soils may be present with increasing MTTs.

The aim of this paper therefore seeks to resolve these inconsistencies in topographic and soil controls on MTT in ten intensively studied research catchments. The specific objectives are to (1) characterise contrasts in the landscape organisation of these catchments by deriving a range of process relevant topographic indices from DTMs; (2) examine the extent to which these indices may be predictors of MTTs and (3) assess the degree to which differences in soil hydrology may mediate or override topographic influences on MTTs.

STUDY CATCHMENTS

The three study catchments, with in total ten instrumented sub-catchments, are located in the Cairngorm mountains of Scotland at about 3°2″W (longitude) 57°2″N (latitude) (Figure 1). The Cairngorms form a mostly glaciated area of over 6500 km^2, which at its core includes the most extensive area of high mountain terrain in the UK (Thompson *et al*., 2006). These high altitude areas were formed by a number of intruded granite batholiths; however, subsequent denudation has resulted in a series of ancient erosion surfaces at altitudes of 1100–1300 m, 850–750 m and 700–750 m radiating out from the core mountain areas (Brown and Clapperton, 2002). The landscape below these erosion surfaces has been selectively dissected since the tertiary, most recently by glaciation, and valleys tend to be overwidened and overdeepened in the core area. Precipitation is also high in this area, with annual average totals approaching 1500 mm at the highest altitudes, falling to around 1100 m to the east. Mean annual temperatures are around 10·4 °C (at Met office station Braemar—at 300 m) and increase from average daily minimum of −2·5 °C in January to average daily maximum of 17·6 °C in July. The vegetation cover changes in relation to altitude and climate with montane heath prevalent above 800 m, with heather (*Calluna*) moorland dominating at lower altitudes, apart from steeper slopes which are forest covered. The study catchments were located in basins dissecting the 1200 m plateau (Feshie), as well as the 800 m (Girnock) and the 700 m (Feugh) erosion surfaces.

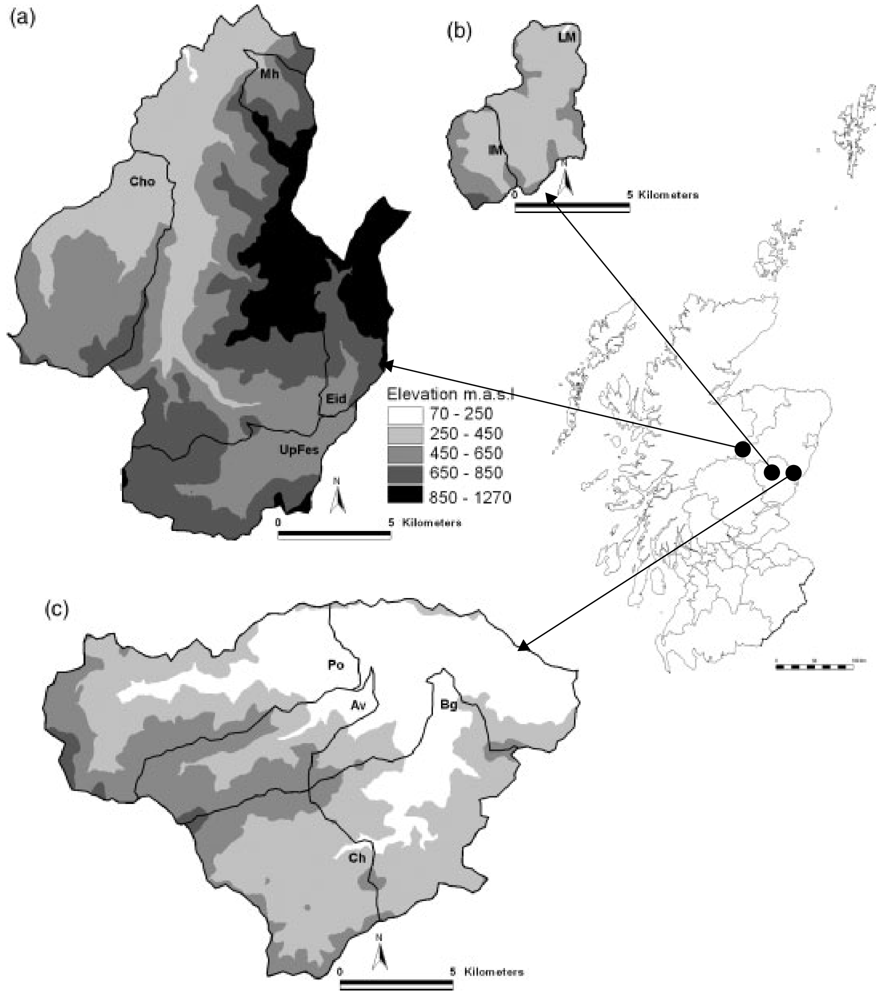

Figure 1. Location and topography of the three study catchments: (a) Feshie, (b) Girnock and (c) Feugh

Feshie

The Feshie is 230 km^2 in area, with an altitude ranging from 230 to 1200 m. Precipitation is *ca* 1280 mm per annum, with snow significant at higher altitudes in winter (Soulsby *et al*., 2004; 2006a). Four major sub-catchments were characterised. The Eidart (Eid) and the Upper Feshie (UpFes) are in the mountain headwaters; the latter has a moderate altitudinal range (Figure 1), and extensive peat soils occupy a wide gently sloping valley bottom dominated by poorly drained drift (Figure 2a). The Eidart is steeper in its upper catchment and dominated by thin regosols; the lower catchment has a lower gradient and peat cover is extensive. In both catchments, work by Rodgers *et al.* (2005b) has shown that groundwater contributions to flow are low (<41% of annual runoff) and MTTs are relatively short in the order of a few months (Table I). The Allt a' Mharcaidh (Mh) and Allt Chomraig (Cho) are tributaries draining the northern part of the catchment. The Mharcaidh is, like the Eidart, relatively high in altitude and steep but is, in contrast, dominated by free draining alpine soils and podzols. The Chomraig is lower in altitude and, like the Upper Feshie, has a wide open valley bottom, although this is dominated by fluvioglacial deposits and free draining alluvial soils. Groundwater contributions to annual runoff in these sub-catchments are higher (>45%) than in the Eidart and Upper Feshie and MTTs are over 1 year (Rodgers *et al*., 2005a).

Girnock

The Girnock is a 31 km^2 tributary of the River Dee in the eastern Cairngorms. Its upper catchment reaches altitudes of 900 m, with some steeper mountains, but is dominated by areas of more moderate relief (Figure 1). Granite dominates the higher mountains, but extensive areas are underlain by schists (Soulsby *et al*., 2007). Mean annual precipitation is around 1100 mm. In general, the upper slopes of the catchment are dominated by podzolic soils and regosols (Figure 2b). In the lower slopes peats (histosols) and peaty gley soils, overlying glacial drift with low permeability, predominate (Soulsby *et al*., 2005). The upper headwaters (9·1 km^2) at Iron Bridge (IB) were analysed as well as the whole catchment at Littlemill (LM). Tetzlaff *et al.* (2007a) showed that the Girnock and IB sub-catchment have relatively short MTTs of *ca* 5–6 months (Table I). Groundwater contributions to annual runoff are also generally low (*ca* 30–40%).

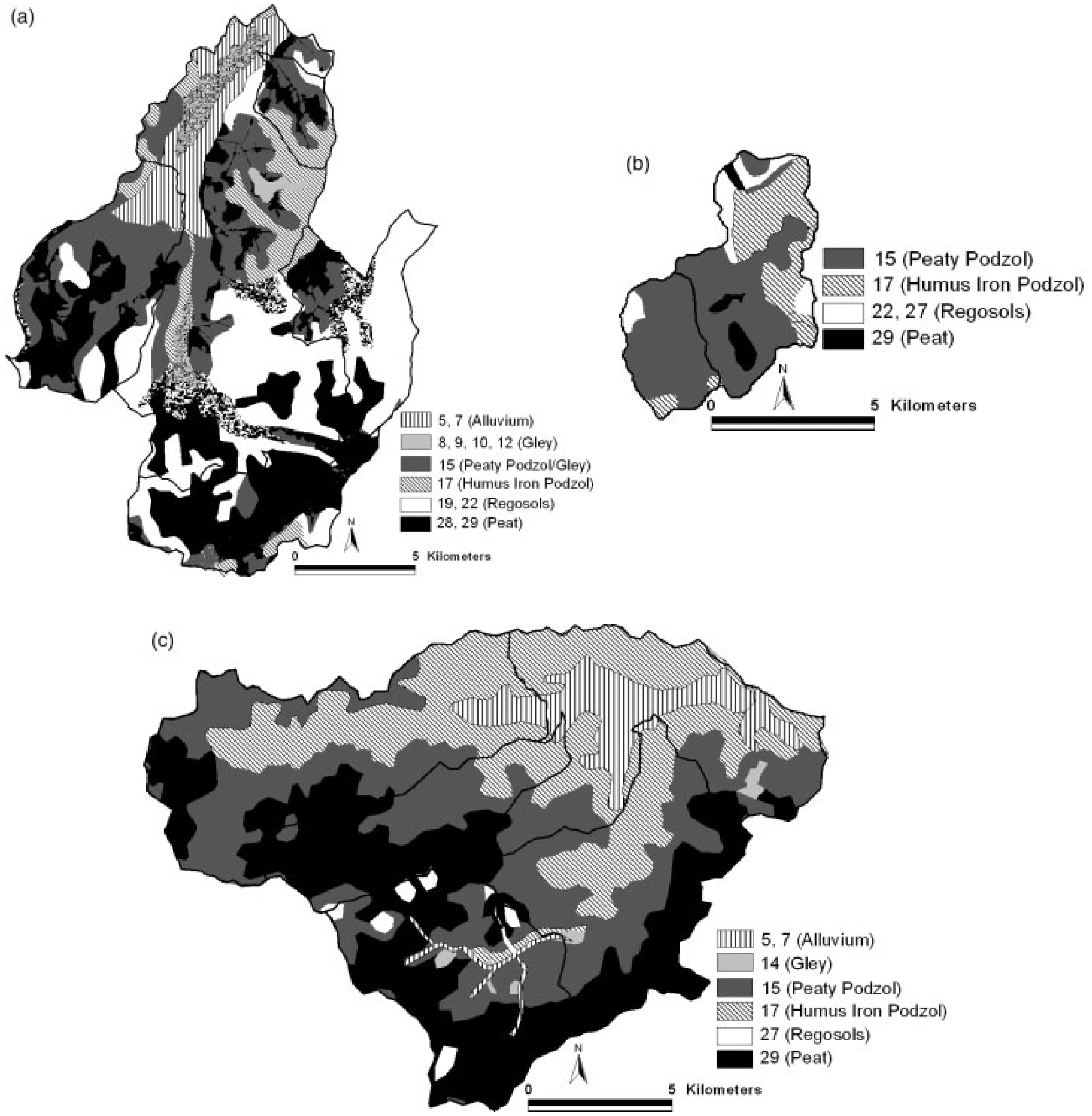

Figure 2. HOST maps of the (a) Feshie, (b) Girnock and (c) Feugh (HOST classes 5, 7: alluvial soils; HOST classes 8, 9, 10, 12, 14: gleysols; HOST class 15: peaty podzols and peaty gleys; HOST class 17: humus iron podzol; HOST classes 19, 22, 27: regosols; HOST classes 28, 29: peats)

Feugh

Altitudes in the 230 km^2 Feugh catchment are lowest (Figure 1) and the annual precipitation averages 1150 mm. Large plateau areas occupy the catchment interfluves where extensive areas of deep peat are the dominant soil (Soulsby *et al.*, 2003) (Figure 2c). Four sub-catchments of the Feugh were analysed: Charr (Ch) and Bogendreip (Bg) form nested sub-catchments at scales of 41 and 90 km^2 (Waldron *et al.*, 2007). These catchments are both dominated by peaty headwaters on gentle interfluves, with free draining podzols on steeper hillslopes and valley bottom alluvium. The Water of Aven (Av) has a similarly incised catchment, with peat headwaters, whilst the sub-catchment of Powlair (Po) has a much smaller area of peat and is dominated by more freely draining soils in the wide open valley. Work by Rodgers *et al.* (2005a) showed that MTTs and groundwater contributions to annual runoff were highest in the Powlair and Water of Aven sub-catchments at *ca* 1 year and 42–55%, respectively (Table I). The MTTs were shorter (6 months) and groundwater contributions lower (35–40%) at Charr and Bogendreip.

DATA AND METHODOLOGY

Topographic analysis

Raster DTMs with a pixel resolution of 10 m were used for a quantitative analysis of topographic characteristics. These DTMs were derived from the digitised benchmark maps of the UK Ordnance Survey. A number of topographic indices were used to derive quantitative descriptors of the landscape structure. These indices ranged from simple metrics such as elevation and slope to more comprehensive measures such as the median sub-catchment (MSC) size (described below). A raster-based

Table I. Catchment characteristics and hydrological descriptors of (a) the Feshie, (b) the Girnock and (c) the Feugh and their associated sub-catchments

	Area (km^2)	Responsive soils (%)	GW contribution (%)	Range GW contribution (%)	MTT (months)	+/− 95th Percentile (months)
(a) Feshie						
Cho	44·9	49	45	42–46	10·2	6·0
UpFes	32·3	84	29	24–33	3·2	2·2
Eid	29·9	87	41	38–49	3·8	2·5
Mh	10	33	51	46–57	14·8	7·3
(b) Girnock						
LM	29·9	73	30	27–33	5·1	3·3
IB	9·1	93	36	30–41	5·9	3·1
(c) Feugh						
Bg	90·1	49	36	32–40	6·8	4·1
Po	60·1	19	55	51–58	13·7	7·5
Ch	41·8	66	37	34–40	6·5	4·1
Av	30·1	55	41	32–49	11·3	6·7

stream network was generated from the digital elevation data based on the accumulated upslope area (US) and assuming a threshold area of 5 ha for stream initiation. Comparison with streams (particularly the location of stream heads) in the field indicated that the elevation-based stream network generally agreed well with the real stream network in this geomorphic region. Using the derived stream network we computed the drainage density (DD) for each sub-catchment. DD, as well as some of the other indices we computed, is obviously quite sensitive to the chosen stream initiation threshold. While this choice influences the absolute value of these indices, the relative differences between different catchments are less affected.

Catchments differ in the way contributing area accumulates along the stream network and, thus, in the area distribution of subcatchments upstream the catchment outlet. To quantify these differences in catchment structure, the MSC area (ha) was computed. MSC is defined as the median of the local catchment areas of all stream pixels upstream the catchment outlet. MSC is a measure of drainage structure (with lower values indicating more branching, dendritic networks and higher values, more linear networks) and has been found to be related to MTT (McGlynn *et al.*, 2003). MSC depends on the chosen stream initiation threshold, but again we were more interested in relative differences between the study catchments than in absolute values. For the computation of the local catchment areas for each stream pixel, we used a combination of a multiple flow direction algorithm (Seibert and McGlynn, 2007) and a single (steepest) direction algorithm. The latter was used when the accumulated area exceeded the stream initiation threshold, i.e. for stream pixels.

Each pixel was linked to the stream pixel to which it drained by assuming that the flowpath follows the surface topography. Here we used the single direction steepest gradient approach to determine flowpaths. In the flatter parts of the catchment the assumption that flowpaths follow the surface topography might not be fully valid, but still provides a useful approximation given the available data. Based on this flowpath, five indices were computed for each pixel: the elevation above stream [EaS, (m)], the distance from stream [DfS, (m)], the average gradient along the flow pathway to the stream [GtS, (−)] and the ratio of flowpath length (L) and gradients (G), which is a proxy for travel times, summed along the entire flow pathway (L/G). The lengths (L) were the grid size lengths depending on flow direction (10 m for cardinal and 14 m for diagonal directions) and the gradients (G) were computed as the elevation difference of the two respective cells divided by L.

Other commonly used indices were also computed. The downslope index d5 ([−], Hjerdt *et al.*, 2004) was defined as the gradient towards the closest point which is at least 5 m (in altitude) below the pixel in question. The UA draining through each pixel was calculated using the algorithm suggested by Seibert and McGlynn (2007). UA and slope were combined into the topographic wetness index [TWI, $\ln(a/\tan\beta)$] where a is the UA per unit contour length and $\tan\beta$ is the local slope. The contour length was computed based on the circumference of a cell and the number of downslope flow directions. For the computation of TWI we used the downslope index, d5, instead of the local slope to compute the TWI_{d5} [ln(m)], because this index considers downslope conditions and, thus, is assumed to provide a better estimate of local groundwater gradients (Hjerdt *et al.*, 2004). For each of these indices, catchment wide distribution functions and median values were computed to allow comparison between catchments.

Soil maps

Recognition of the potential influence that soil coverage can have on catchment hydrology has resulted in numerous initiatives to develop approaches to utilize soil information in standardised, transferable ways. A key tool has been the development of hydrologically meaningful soil maps (e.g. Scherrer and Naef, 2003). In the UK, the Hydrology of Soil Types (HOST) system was developed over a decade ago as a digital spatial data set based on a national hydrological classification scheme (Boorman *et al.*, 1995; www.macaulay.ac.uk/host/). In upland areas, the HOST system has been shown to be a useful means of grouping soils on the basis of hydrological responsiveness (Soulsby *et al.*, 2006b). Responsive soils include peats, gleys and regosols that rapidly generate storm runoff by overland flow or shallow sub-surface storm flow. In contrast, freely draining soils (such as podzols and alluvium) facilitate deeper sub-surface flows and recharge of groundwater which sustain recessions and baseflows (e.g. Tetzlaff *et al.*, 2007b). This information has allowed catchment wide HOST maps to be used as apparently good predictors of MTTs estimated from tracer data (Soulsby and Tetzlaff, 2008).

MTT calculations and hydrograph separations

MTT and percentage groundwater contribution as descriptors of the hydrological response of the various catchments were taken from previous studies (Rodgers *et al.*, 2005a,b; Tetzlaff *et al.*, 2007a) (Table I). In these studies, MTTs were estimated based on fitting sine waves to seasonal δ^{18}O variations in precipitation and streamwater. Subsequent work has shown that, at least for upland Scottish catchments, this approach provides MTT estimates comparable to more complex TTD models such as the gamma function (cf Kirchner *et al.*, 2001) or using parallel linear reservoirs (Shaw *et al.*, 2008). The uncertainties of the estimated MTT are generally significant, especially for larger MTT values and caution needs to be exercised in interpretation (McGuire and McDonnell, 2006). The MTTs were derived using data for the same hydrological year—2001/2002—for the Feugh and Feshie catchments, whereas the values for the Girnock catchments were derived using data for the hydrological year 2003/2004. Both years were similar in being slightly above average precipitation with a wet summer and, thus, the estimated values were assumed to be comparable and to give a reasonable approximation of the differences in MTT for the different catchments.

Percentage groundwater contributions to annual runoff were estimated from chemically based hydrograph separation. Here we used weekly stream alkalinity samples; the lowest baseflows were used to define catchment scale groundwater end members and direct soil water samples were used to define storm flow end members derived from upper organic soil horizons (Soulsby *et al.*, 2003; 2004).

Statistical analysis

The calculated topographic indices and percentage cover of responsive soils (defined as the sum of shallow regosols, gleysols and histosols) were then used to investigate the relationship between variables describing the landscape structure of the various catchments and hydrological function in terms of MTT. For this, Pearson correlation coefficients (r_p) and Spearman's rank correlation coefficients (r_s) were computed given the problems of establishing normality with a small data set. Data were also ordinated by principal component analysis (PCA) using topographic indices to characterise the structure of each catchment as a basis for comparison and spatial differentiation. Two PCA ordinations were produced. First, only the 11 topographic indices were included in the PCA as variables to identify those that differed most between the catchments and sub-catchments to assess the relative importance for spatial differentiation of topographic conditions. The second PCA considered percentage of responsive soil cover and percentage of groundwater contribution as additional variables. This provided additional insight into differences in soil cover and hydrogeology compared to those of topography. Thus, PCA indicates the way in which the topographic indices, soil cover and groundwater contribution interact in a multi-dimensional space.

RESULTS

Topographic characteristics

While there was a general agreement on the order of magnitude for the calculated topographic indices in the different catchments, there were some interesting differences (Table II). These differences can be seen in the PCA results (Figure 3). The loadings of the indices are illustrated by the length of their respective arrows, i.e. highest loadings refer to highest inter-catchment differences. The Feshie sub-catchments separate out and the most obvious is the Mharcaidh, which has the steepest mean slope and highest EaS. However, the Eidart is distinct in having the highest mean elevation, and the Eidart and Chomraig have by far the largest L/G index, a low TWI$_{d5}$ index and higher drainage densities. The high loadings of these indices are illustrated by the length of their respective arrows. The two Girnock catchments at IB and LM separate on the basis of having low gradient indices and relatively low elevation above the stream indices. The Feugh catchments cluster closely together, with high TWI$_{d5}$ values. However, the Aven is distinct with high indices for mean elevation, DfS and UA, whilst the Powlair site has lower mean elevation, low DfS and a low UA.

The median values of the topographic indices (Table II) are only one measure of the catchment wide distributions and do not always show the sometimes large differences in the distributions. A closer look at the distributions—exemplary shown for GtS, DfS and log L/G in Figure 4—shows that all the catchments are upland in character, with relatively steep slopes covering a significant part of each (Figure 4a). However, the Allt a' Mharcaidh is clearly distinct, being the steepest overall; this reflects the Mharcaidh having the smallest catchment area, but highest altitudinal range. The flatter nature of the lower valleys of the Chomraig and Upper Feshie are also apparent in the distributions, with the Eidart's steeper sections also evident. The distributions for the Girnock at IB are broadly similar to the Eidart and Upper Feshie in terms of expansive low gradient

Table II. Topographical indices

	DD $(\mathrm{km/km}^2)$	ME (m)	MSC (ha)	EaS (m)	DfS (m)	MS (−)	GtS (−)	d5 (−)	L/G (m)	UA (m^2)	$\mathrm{TWI}_{\mathrm{d5}}$ ln(m)
(a) Feshie											
Cho	2·92	490	18·1	22·4	212	0·13	0·11	0·12	20 844	459	8·24
UpFes	3·21	686	21·2	17·4	196	0·13	0·10	0·11	21 914	458	8·25
Eid	2·11	865	32·7	31·7	250	0·16	0·14	0·14	13 404	683	8·34
Mh	2·00	699	33·5	71·0	298	0·26	0·24	0·25	1702	1473	8·50
(b) Girnock											
LM	2·39	405	18·6	28·8	262	0·16	0·11	0·14	5092	963	8·73
IB	2·90	469	18·2	23·6	224	0·15	0·1	0·13	4250	759	8·55
(c) Feugh											
Bg	2·11	365	33·2	32·9	242	0·15	0·14	0·14	2637	1224	8·92
Po	2·49	339	31·6	29·3	223	0·16	0·15	0·15	2747	1095	8·83
Ch	2·19	415	35·7	31·8	236	0·15	0·14	0·13	2438	1137	8·88
Av	2·08	469	31·6	33·2	242	0·16	0·13	0·13	2721	1210	8·86

DD, drainage density; ME, mean elevation; MSC, median sub-catchment; MS, mean slope; median values are given for all the following indices: EaS, elevation above stream; DfS, distance from stream; GtS, gradient to stream; d5, downslope index; L/G, flowpath integrated length/gradient (travel time proxy); UA, upslope area; $\mathrm{TWI}_{\mathrm{d5}}$, topographic index.

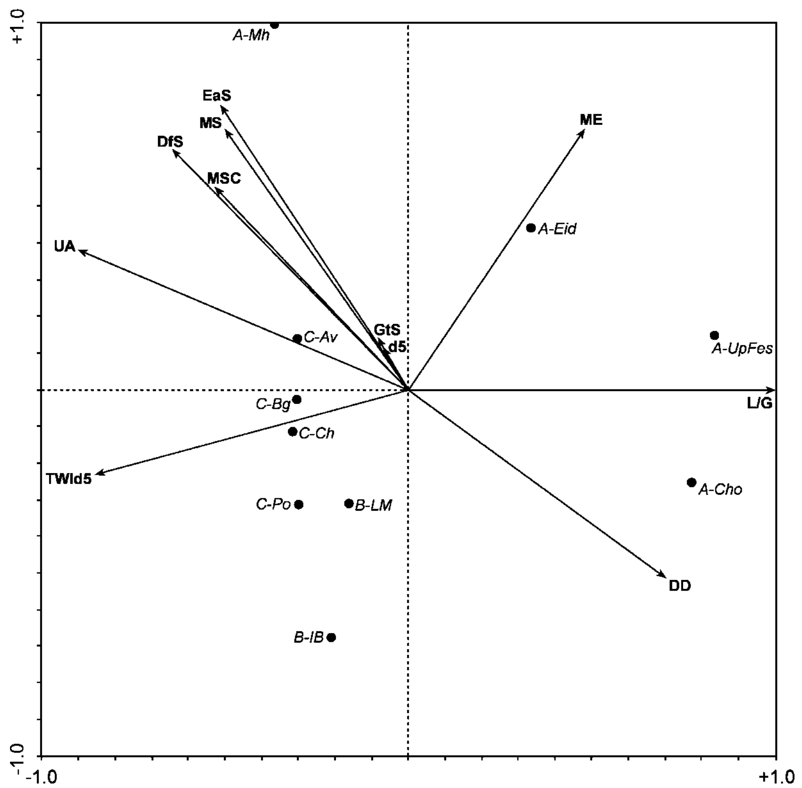

Figure 3. Principal component analysis (PCA) for the three catchments (A: Feshie, B: Girnock, C: Feugh) and associated sub-catchments (81% cum. variance). Each catchment was characterised using a total of 11 topographical indices [DD, drainage density; ME, mean elevation; MSC, median sub-catchment; MS, mean slope; EaS, elevation above stream; DfS, distance from stream; GtS, gradient to stream; d5, downslope index; L/G, flowpath integrated length/gradient (travel time proxy); UA, upslope area; $\mathrm{TWI}_{\mathrm{d5}}$ topographic index]. The component loadings of the indices are illustrated by the length of their respective arrows

areas fringing the stream. The LM site is more complex, with some steeply sloping sections in certain parts of the catchment. The Feugh sites have similar distributions, although the extended, low gradient valley bottom at Powlair is distinct.

The distributions of the DfS index again highlight the Mharcaidh as having the longest mean flow path lengths (Figure 4b and Table II). The Chomraig and Upper Feshie are once more distinguished by short median flow path lengths. The Girnock at LM has relatively long flow paths, though these are in the catchment downstream of IB, where this index is relatively low. The Feugh sites are intermediate and all similar, though shorter flow path lengths at Powlair are again evident.

The differences between catchments are more obvious for the L/G values, which also are reflected by the high loadings in the PCA analysis (Figure 3). There is a greater proportion of high values in the Chomraig, Upper

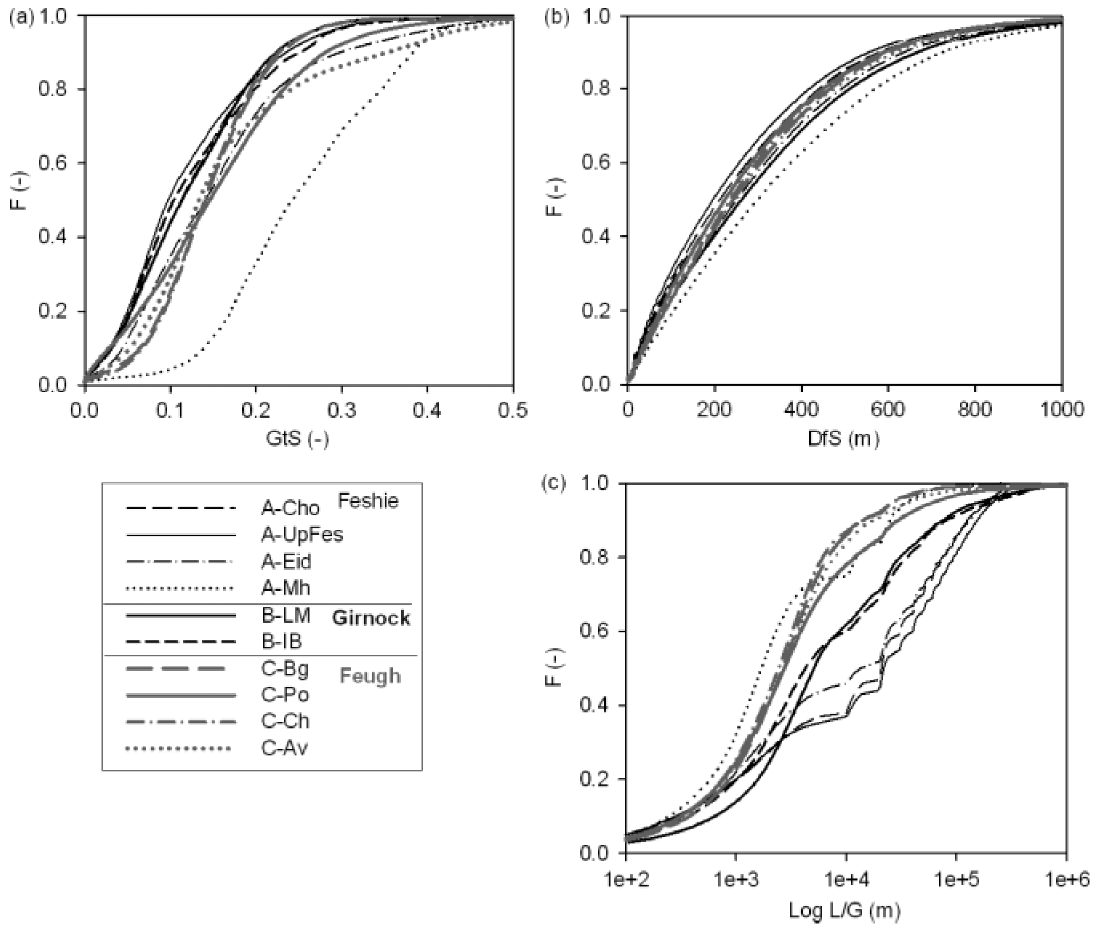

Figure 4. Frequency distributions of (a) gradient to stream (GtS), (b) distance from stream (DfS) and (c) log flowpath length/gradient ratio (L/G) (abbreviation A for Feshie sub-catchments; abbreviation B for Girnock sub-catchments; abbreviation C for Feugh subcatchments)

Feshie and Eidart reflecting the effect of the low gradient valley bottom areas. Conversely, similar distributions are evident for the steeper Mharcaidh and Feugh sites, though both the steepness of the former and low gradient areas of the Powlair sites are distinct. The Girnock sites plot intermediately, though the steeper parts of the lower catchment at the LM site become apparent.

Topographic controls on MTT

The various topographic indices (Table II) and the estimated MTTs (Table I) were correlated to a varying degree with correlations coefficients r_s up to $-0{\cdot}66$ (Table III and Figure 5). The complex differences in the topographic structure of the different catchments may result in a lack of simple relationships, because many of the indices were, as expected, inter-correlated (Table IV). Given the relatively small sample size, the Spearman's rank correlation coefficients r_s were assumed to be most instructive, because they are less affected by individual outliers. In this regard, the MTT shows the strongest (negative) correlation with the L/G metric (Figure 5g). However, the median UA shows a positive correlation of similar strength, with the median flow path gradient and median UA also quite strongly correlated though not statistically significant (Figure 5e and h). The main anomaly on the correlations between MTT and L/G is the Allt Chomraig, with a relatively high L/G gradient and a long transit time. The Chomraig was also the main outlier on the correlation between MTT and UA. The relationship between the GtS and MTT is mainly influenced by the high gradient and long transit time of the Mharcaidh, and quite a lot of scatter at intermediate gradients of *ca* 0·15.

Soil controls on MTTs

The relationships between estimated MTT and percentage responsive soil cover show that sub-catchment soil distribution has a strong effect on MTT (Figure 6). Indeed, it exhibits a stronger correlation than any of the individual topographic indices (Table III). Despite this, the percentage responsive soil cover did not appear to provide greater spatial differentiation of catchment characteristics in the PCA (Figure 7). Responsive soil cover was, however, negatively correlated with slope indices, such as median flow path gradient (Table IV). The negative correlation between slope and responsive soil cover most likely results from that the most responsive peat and gleyed soils are found on flatter hilltops or in valley bottom areas, whilst more freely draining soils are on steeper hillslopes. Simply stated, higher peat coverage on flatter catchment interfluves results in rapid hydrological responses to precipitation (via overland flow

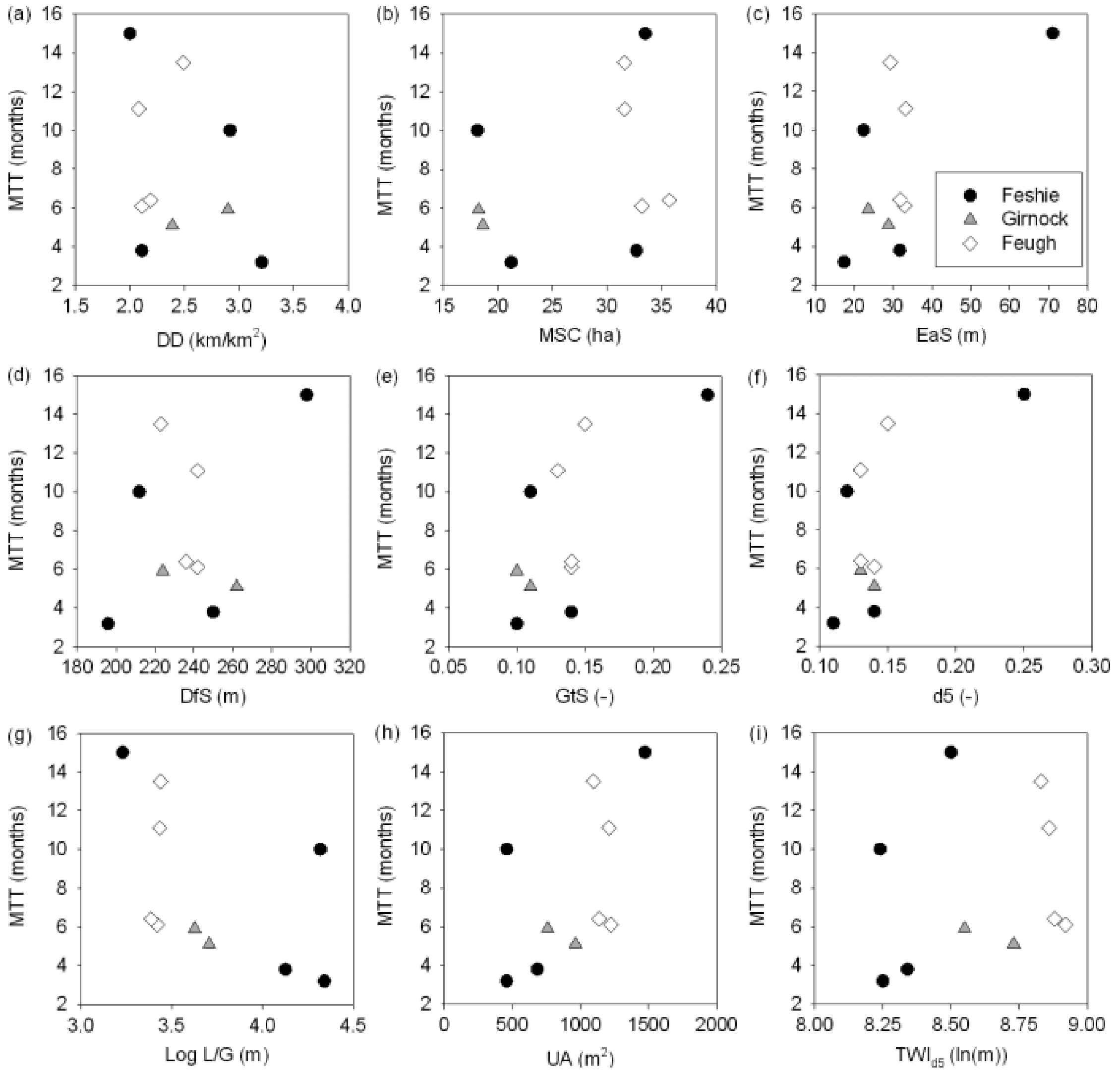

Figure 5. Relationships between topographic indices [DD, drainage density; MSC, median sub-catchment; EaS, elevation above stream; DfS, distance from stream; GtS, gradient to stream; d5, downslope index; L/G, flowpath integrated length/gradient (travel time proxy); UA, upslope area; TWI$_{d5}$, topographic index] and MTT

Table III. Relationships between topographical indices and MTT

	r_p	r_s
Area	−0·02	0·12
DD	−0·32	−0·44
ME	−0·22	−0·19
MSC	0·29	0·33
EaS	0·60	0·58*
DfS	0·36	0·16
MS	0·61	0·44
GtS	0·65*	0·58*
d5	0·60	0·36
L/G	−0·41	−0·66**
L/G log	−0·53	−0·66**
UA	0·57	0·66**
TWI$_{d5}$	0·23	0·26
% Responsive soils	−0·87***	−0·80****

Pearson correlation coefficient (r_p) and Spearman's rank correlation coefficient (r_s); DD, drainage density; ME, mean elevation; MSC, median sub-catchment; MS, mean slope; EaS, elevation above stream; DfS, distance from stream; GtS, gradient to stream; d5, downslope index; L/G, flowpath integrated length/gradient (travel time proxy); UA, upslope area; TWI$_{d5}$, topographic index. * Significant as $p < 0·05$ (for r_p) and *** $p < 0·05$, *** $p < 0·025$, **** $p < 0·01$ (Von Storch and Zwiers, 1999).

or shallow sub-surface storm flow), leading to reduced recharge, lower groundwater contributions and shorter MTTs (Rodgers *et al.*, 2005a). Higher coverage of freely draining podzols on steeper hillslopes increases recharge, produces higher groundwater contributions to annual flow and longer transit times, as shown by the Allt a' Mharcaidh.

DISCUSSION

This paper sought to use an inter-catchment comparison to examine the degree to which topographic indices can be used to characterise catchments and as a basis for predicting MTTs in contrasting parts of the geomorphic province of the Cairngorm mountains, Scotland. The topographic indices were found to be useful for characterising the catchments and for differentiating their landscape properties in the PCA. This provided a more integrated perspective on their landscape characteristics than has been previously been possible for these catchments.

Table IV. Inter-correlations between topographical indices (Pearson correlation coefficient r_p)

	DD	ME	MSC	EaS	DfS	MS	GtS	d5	L/G	UA	TWI_{d5}	% Responsive soils
DD	1·00	−0·03	−0·80	−0·67	−0·79	−0·59	−0·67	−0·54	0·69	−0·81	−0·58	0·35
ME	−0·03	1·00	0·10	0·27	0·20	0·29	0·28	0·28	0·48	−0·29	−0·72	0·36
MSC	−0·80	0·10	1·00	0·54	0·43	0·42	0·64	0·42	−0·52	0·69	0·51	−0·43
EaS	−0·67	0·27	0·54	1·00	0·88	0·97	0·98	0·98	−0·51	0·76	0·13	−0·48
DfS	−0·79	0·20	0·43	0·88	1·00	0·88	0·81	0·85	−0·60	0·73	0·25	−0·27
MS	−0·59	0·29	0·42	0·97	0·88	1·00	0·94	0·98	−0·50	0·70	0·08	−0·44
GtS	−0·67	0·28	0·64	0·98	0·81	0·94	1·00	0·96	−0·47	0·74	0·13	−0·58
d5	−0·54	0·28	0·42	0·98	0·85	0·98	0·96	1·00	−0·45	0·68	0·04	−0·47
L/G	0·69	0·48	−0·52	−0·51	−0·60	−0·50	−0·47	−0·45	1·00	−0·89	−0·85	0·36
UA	−0·81	−0·29	0·69	0·76	0·73	0·70	0·74	0·68	−0·89	1·00	0·75	−0·57
TWI_{d5}	−0·58	−0·72	0·51	0·13	0·25	0·08	0·13	0·04	−0·85	0·75	1·00	−0·37
% Responsive soils	0·35	0·36	−0·43	−0·48	−0·27	−0·44	−0·58	−0·47	0·36	−0·57	−0·37	1·00

DD, drainage density; ME, mean elevation; MSC, median sub-catchment; MS, mean slope; median values are given for all the following indices: EaS, elevation above stream; DfS, distance from stream; GtS, gradient to stream; d5, downslope index; L/G, flowpath integrated length/gradient (travel time proxy); UA, upslope area; TWI_{d5}, topographic index.

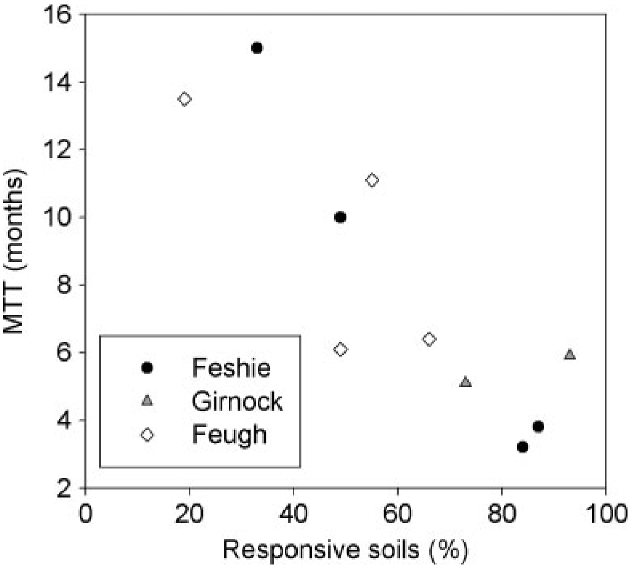

Figure 6. Relationship between percentage responsive soil coverage and MTT

Correlations between individual topographic indices and MTT were not convincing and few proved statistically significant. Thus, the potential use of such relationships to predict metrics of hydrological function, such as MTT, seems much more limited in the Cairngorms than has been found in other geographical regions (e.g. McGuire *et al.*, 2005). There was a weak correlation between MTT and GtS, although this was strongly influenced by the steep outlier of the Allt a' Mharcaidh. On intermediate slopes of 12–13%, the estimated MTT varied between 4 and 14 months. The correlations improved when the median flow path gradient was combined with the flow path length in the L/G statistic. However, the relationship was clearly nonlinear. Catchments with a low L/G index (<4000 m) were generally steeper catchments in the Feugh and Allt a' Mharcaidh and MTTs varied between 6 and 15 months. The higher indices (>4000 m) were found in the Girnock and Feshie catchments with extensive low gradient valley bottom areas which had MTTs of <6 months. An exception was the obvious outlier of the Allt Chomraig, where the MTTs are estimated at *ca* 10 months. The Chomraig was also an outlier in the correlation between mean UA and MTT which was as strong as that with L/G. This mainly reflects the effect of the low gradients over much of the lower Chomraig formed by extensive areas of freely draining alluvium. This contrasts with catchments like the Girnock, Upper Feshie and Eidart where the valley bottoms have poorly drained drift and responsive peaty soils and hence shorter MTT.

Interestingly, in this study negative and positive correlations were observed between MTT and L/G and slope indices, respectively. This is somewhat counterintuitive and in contrast with results for steep catchments in the Cascades (Oregon, USA) (McGuire *et al.*, 2005) and Maimai (New Zealand) (McGlynn *et al.*, 2003), where negative correlations with slope indices and positive correlations with the L/G index were found. This apparent paradox seems most likely explained by the dominance of deeper freely draining soils in the Cascade catchments, resulting in hydraulic gradients being strongly driven by gravity and deeper impeding layers and therefore closely reflecting topography. In contrast, in the Cairngorm region, the predominance of more responsive peat and gley soils in flatter valley bottom areas, and free draining podzols on steeper slopes means that higher gradients are often associated with deeper flow paths, more marked mixing and longer transit times. Despite this, even the longer MTTs (*ca* >1 year) derived for the Cairngorms are somewhat shorter (generally *ca* >1·5 years) than those found at sites in the Cascades, possibly as a result of shallower soils and more even distribution of precipitation in Scotland.

These findings highlight the importance of recognising that in different geomorphic provinces, different controls on runoff generation processes will result in different relationships between hydrological metrics such as MTT and mapped landscape indices relating to topography. These anomalies appear to reflect the complex geomorphic evolution of each catchment, which although producing similar general landscape patterns, results in

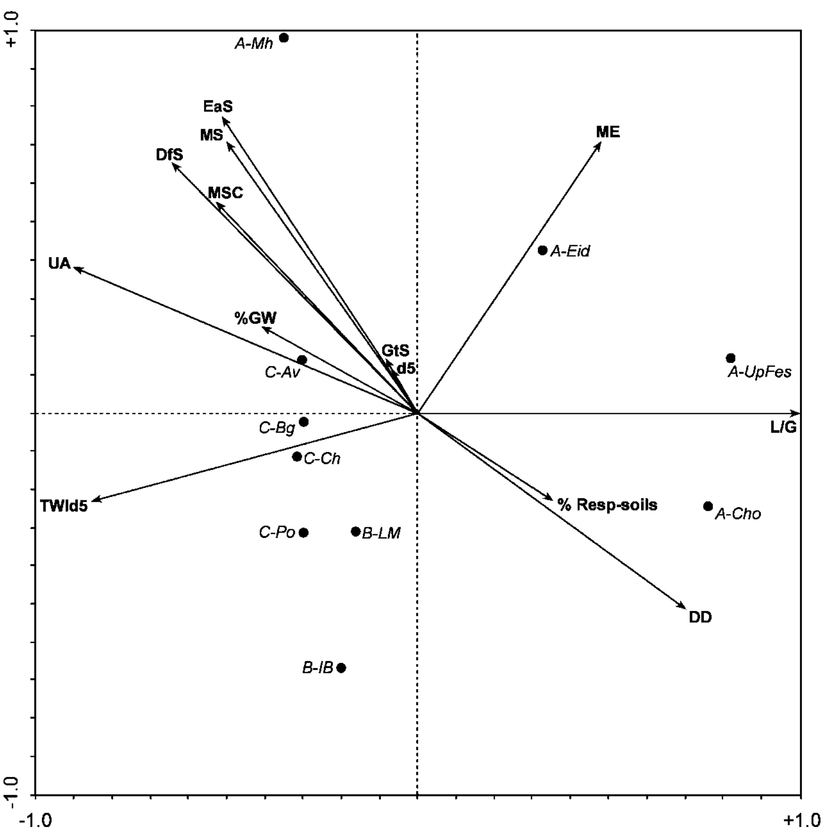

Figure 7. Principal component analysis (PCA) for the three catchments (A: Feshie, B: Girnock, C: Feugh) and associated sub-catchments (77% cum. variance). Each catchment was characterised using a total of 13 indices: 11 topographic indices [DD, drainage density; ME, mean elevation; MSC, median sub-catchment; MS, mean slope; EaS, elevation above stream; DfS, distance from stream; GtS, gradient to stream; d5, downslope index; L/G, flowpath integrated length/gradient (travel time proxy); UA, upslope area; TWI_{d5}, topographic index], percentage responsive soil cover and percentage groundwater contribution. The component loadings of the indices are illustrated by the length of their respective arrows

a unique combination of topographic features. In broad terms this seems to relate to the distribution of different glacial and periglacial drift deposits, which have different properties in terms of permeability and porosity that are better reflected in soil characteristics. None of the topographic indices showed as strong a correlation with MTT as percentage responsive soil cover, which is significant for r_p and r_s. However, it must be stressed that the UK is fortunate in having national digitised maps of soil hydrology.

In this study, we deliberately focussed on mesoscale (i.e. >10 km^2) catchments to try and reduce the more marked small-scale heterogeneity that is apparent in catchments of $<5-10$ km^2 and examine emergent behaviour at larger scales (Laudon *et al.*, 2007; Tetzlaff and Soulsby, 2008). At a finer level of scale resolution, McGlynn *et al.* (2003) found that mean sub-catchment area was a useful measure of structure in small (<10 km^2) catchments at Maimai in New Zealand, and one that was a good predictor of MTT. However, this was not evident at these Cairngorm sites, perhaps as larger scale emergent properties of catchments became more important at the mesoscale.

This investigation has also demonstrated the potential of DTM-based quantitative landscape analysis in conjunction with hydrological tracer studies to understand the differences between the catchment structure and the linkages with hydrological function. In this particular case, the results highlighted some of the constraints on the inferences that can be made on the basis of topographic analysis alone. This has wider implications, such as highlighting the need for critical thinking when applying hydrological models based on topographic indices. Nevertheless, the analysis gave a much better quantitative understanding of how catchment characteristics vary. There are many fruitful avenues of further research from such analysis. For example, analysis of both smaller and larger catchments within the Feshie, Feugh and Girnock systems would be instructive in terms of examining how topographic indices and landscape organisation might change at different spatial scales and it may be possible to relate this to dominant hydrological processes. This might provide further insight into how to discretize catchment landscapes to optimise field sampling programmes and the structure of semi-distributed models. Finally, using such DTM-based analysis for catchment comparison between different geographical regions would help quantify in a more integrated way how topographic characteristics of landscapes with different evolutionary histories might differ in a hydrologically meaningful way (Tetzlaff *et al.*, 2009). This could be a useful screening tool in identifying the different ways in which hydrological classification schemes could be regionalised in relation to their hydrogeomorphic characteristics (Wagener *et al.*, 2007).

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