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How does landscape structure influence catchment transit time across different geomorphic provinces?

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Abstract

Despite an increasing number of empirical investigations of catchment transit times (TTs), virtually all are based on individual catchments and there are few attempts to synthesize understanding across different geographical regions. Uniquely, this paper examines data from 55 catchments in five geomorphic provinces in northern temperate regions (Scotland, United States of America and Sweden). The objective is to understand how the role of catchment topography as a control on the TTs differs in contrasting geographical settings. Catchment inverse transit time proxies (ITTPs) were inferred by a simple metric of isotopic tracer damping, using the ratio of standard deviation of δ^{18}O in streamwater to the standard deviation of δ^{18}O in precipitation. Quantitative landscape analysis was undertaken to characterize the catchments according to hydrologically relevant topographic indices that could be readily determined from a digital terrain model (DTM). The nature of topographic controls on transit times varied markedly in different geomorphic regions. In steeper montane regions, there are stronger gravitational influences on hydraulic gradients and TTs tend to be lower in the steepest catchments. In provinces where terrain is more subdued, direct topographic control weakened; in particular, where flatter areas with less permeable soils give rise to overland flow and lower TTs. The steeper slopes within this flatter terrain appear to have a greater coverage of freely draining soils, which increase sub-surface flow, therefore increasing TTs. Quantitative landscape analysis proved a useful tool for inter-catchment comparison. However, the critical influence of sub-surface permeability and connectivity may limit the transferability of predictive tools of hydrological function based on topographic parameters alone. Copyright © 2009 John Wiley & Sons, Ltd.

Key Words catchment transit times; landscape structure; geomorphic provinces; isotopic tracers; quantitative landscape analysis; northern temperate regions

Introduction

Over the past decade there has been increasing interest in using the input–output dynamics of conservative tracers to explore the concept of transit times (TTs) in catchment hydrology. TT characteristics can be used as simple hydrological descriptors that can be very insightful in terms of conceptualizing flow paths and mixing processes at the catchment scale (McGuire and McDonnell, 2006). As a result, a number of studies have tried to identify and assess the controls on catchment transit time distributions (TTDs) and resulting mean transit times (MTTs) estimates. Empirical studies have investigated the influence of topography (McGlynn *et al*., 2003; McGuire *et al*., 2005), soil hydrology (Soulsby *et al*., 2006; Tetzlaff *et al*., 2007; Dunn *et al*., 2008) and geology (Vitvar and Balderer, 1998; Viville *et al*., 2006) as first order controls on catchment TTDs or MTTs. Recent theoretical studies have also made progress in quantifying the physical processes that may underpin such controls (Kirchner *et al*., 2001; Cardenas, 2007). Inevitably, these empirical studies have generally been restricted to individual nested catchments, or single geomorphic provinces, and thus it is unclear how findings from individual investigations may be extrapolated to other catchments or different geographical regions (Tetzlaff *et al*., 2009). Indeed there are convincing arguments suggesting that the 'uniqueness of place' and scaling issues may ultimately frustrate attempts to develop transferable, macroscale laws in hydrology (Beven, 2000); despite equally persuasive arguments of the need to search for such laws (McDonnell *et al.*, 2007). Recent international efforts such as the Prediction in Ungauged Basins (PUB) initiative from the International Association of Hydrological Sciences (IAHS) call for the development of process-based catchment classification schemes that relate metrics of hydrological function to quantifiable measures of catchment form (Wagener *et al.*, 2007). If successful, such schemes could be invaluable in developing transferable, predictive tools that could be applied to ungauged basins.

This Scientific Briefing focuses on assessing the degree to which simple indicators of catchment mean TT (MTT) can be related to topographic indices derived from quantitative landscape analysis using digital terrain models (DTMs). Catchment DTMs—unlike other environmental data (e.g. soil cover, geology and land use)—are often readily available and are particularly useful in assessing the properties of ungauged basins. Analysis of DTMs offers the opportunity to relate behavioural metrics (such as MTT) to topographic indices which capture the characteristics of landscape organization that control hydrological function (McGuire *et al.*, 2005).

Analysis of the input–output dynamics of conservative tracers has been particularly useful in assessing hydrological function in catchments, reflecting the integration of process interactions at fine spatial and temporal scales (Tetzlaff *et al.*, 2008).

In this way, tracers offer insight into the 'averaging' which characterizes the emergent behaviour of catchment systems at larger spatial scales (Soulsby *et al.*, 2000, 2008; Laudon *et al.*, 2007). Thus, there is considerable potential in using tracers to derive simple metrics of catchment function that can then be used to develop catchment typologies and classification schemes that may be useful in assessing ungauged basins (Soulsby and Tetzlaff, 2008).

In this context, we applied quantitative landscape analyses to DTMs of 55 catchments (varying in area from 0·04–230 km^2) where there was at least 12 months of stable isotope data regularly sampled (i.e. at weekly or fortnightly intervals) in precipitation and stream flow. These catchments are located in three countries and five contrasting geomorphic provinces in northern temperate regions (Figure 1): Scotland (the Cairngorms), Sweden (Fennoscandian shield) and the United States of America (the Western Cascades, Appalachian Plateau, Valley and Ridge Province). In all catchments, previous research had established some degree of process-understanding to contextualize data interpretation. The specific objectives of this briefing are (i) to characterize the damping in conservative (isotopic) tracer input–output relationships to develop simple TTs indices or inverse transit time proxies (ITTPs) in each catchment; (ii) to assess the degree to which such damping can be related to quantitative measures of catchment landscape organization reflected in topographic indices and (iii) to examine the intra- and inter-regional variation in such relationships for the different geomorphic provinces.

Figure 1. Location of the eight study catchments in the northern temperate region: I HJA (Western Cascades, US); II Catskills (Appalachian Plateau, US); III Mahantango (Valley and Ridge Province, US); IV Black Burn; V Feugh; VI Girnock; VII Feshie (all The Cairngorms, Scotland); VIII Krycklan (Fennoscandian shield, Sweden)

Study Catchments

The characteristics of the catchments investigated are summarized in Table I. Briefly, the HJ Andrews catchments in the Western Cascades of Oregon are steep and mountainous, receiving 2500 mm of annual precipitation, but this mainly falls in the winter period and summers are very dry. The geology is volcanic and soils are deeply weathered and freely draining. The catchments are non-glaciated and are mainly covered by coniferous forest (McGuire *et al.*, 2005). The Catskill catchments represent the most north-eastern extent of the Appalachian Plateau. This region is also montane and steep, but glaciated and somewhat drier than the HJ Andrews (*ca* 1500 mm annual precipitation). The geology is sandstone with interbedded shales and siltsones; soils tend to be free-draining (Burns *et al.*, 1998). The catchments are also afforested, though deciduous species dominate. The Mahantango catchments in Pennsylvania are less mountainous with about 1100 mm of annual precipitation. These catchments are agricultural with forested land on the ridges, and non-glaciated with relatively shallow (<1·5 m) soils, predominantly well-drained silt loams, that cover folded and faulted bedrock (O'Driscoll *et al.*, 2005). The geology is sedimentary and characterized by shale in the lower elevation reaches and interbedded shales, siltstones and sandstones, becoming increasingly coarse-grained in the higher elevation reaches (Gburek and Folmar, 1999). The Scottish sites are located in the glaciated Cairngorms or (in the case of the Black Burn) similar East Grampian Mountains of Scotland (Soulsby

Table I. Catchment characteristics of the eight study catchments and their associated sub-catchments in the northern temperate region

Region	Area range km^2	Mean δ^{18}O stream water (‰)	Mean annual precipitation mm	Mean annual discharge l s^{-1} km^{-2}	Mean altitude m	Dominant geology (%)	Dominant land use (%)
HJ Andrews, Western Cascades, OR, USA[a]	0·1–62·4	−11·36	2514	55·2	985	Andesitic-basaltic lava flows/ashflow tuffs/volcaniclastics	100 Forest
Catskills, NY, USA	0·2–23·1	−9·07	1530	40·2	902	Sandstone	100 Forest
Mahantango, Pennsylvania, USA[a]	0·1–7·3	−8·63	1090	14·6	287	Sandstone/shale	45/53 Forest/crop
Black Burn, NE Scotland[a]	0·8–25·6	−8·59	1100	26·3	222	Metamorphic/sandstone	Rough grazing/arable
Feugh, East Grampians, Scotland[a]	1·3–233	−8·61	1130	24·8	329	78 Granite	68 Moorland/peat
Girnock, E Cairngorms, Scotland[a]	0·8–30	−8·95	1100	17·7	403	46 Granite	81 Moorland/peat
Feshie, W Cairngorms, Scotland	10·0–44·9	−9·74	1300	34·6	865	70/30 Schist/granite	79 Moorland/Peat
Krycklan, Northern Sweden[a]	0·04–66·8	−13·55	646	10·2	242	Meta-sediments	88/8 Forest/wetland

[a] Smaller catchments are nested within larger mesoscale basins.

et al., 2004; Tetzlaff *et al.*, 2007; Dunn *et al.*, 2008). Of this group, the Feshie catchments have the highest altitude and are the most montane, with altitude declining in the order Feshie>Girnock>Feugh>Black Burn. Annual precipitation decreases from *ca* 1300 mm at Feshie to 1100 mm at Black Burn. The geology is mainly granite with schists, though the Black Burn catchment has sandstone in its lower reaches. All the Scottish catchments are dominated by montane heath vegetation or *Calluna* dominated moorland. The soil cover varies: peat soils dominate most flatter areas and more freely draining podzols can be found on steeper slopes. The Krycklan catchments are located on the Fennoscandian shield (Buffam *et al.*, 2007); these are the lowest altitude catchments and have the lowest precipitation, of which 40% falls as snow in winter. The geology is dominated by meta-sediments and peat soils. In most places, coniferous forest is the dominant vegetation, though where the peat is deepest, *Sphagnum*-dominated wetlands occur. At all sites, with the exception of the Catskills and Feshie, the smaller sub-catchments were nested within a larger mesoscale catchment (Table I).

Methodology

Topographic analysis

Raster DTMs with a pixel resolution of 10 m were used for analysis of topographic characteristics. A number of topographic indices were used to derive quantitative descriptors of the landscape structure that were then related to catchment hydrological function. A raster-based stream network was generated from the digital elevation data based on the accumulated upslope area (UA) 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 each geomorphic region and provided consistency across the catchments. Using this stream network, the median sub-catchment area [(MSC), ha] was computed. MSC is defined as the median of the local catchment areas of all stream pixels upstream of the catchment outlet. MSC is a measure of drainage structure (with lower values indicating more dendritic networks and higher values indicating more linear networks) and has been found to be related to MTT in some studies (McGlynn *et al.*, 2004).

Each pixel was linked to the stream pixel to which it drained by assuming that the flow path follows the surface topography. On the basis of this flow path, 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 flow path 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 are 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 ($\mathrm{TWI}_{\mathrm{d5}}$) $\ln(a/\tan\beta)$ where a is the UA per unit contour length and $\tan\beta$ is the local slope. However, we used the downslope index, d5, instead of the local slope to compute the $\mathrm{TWI}_{\mathrm{d5}}$ {[ln(m)]} (Hjerdt *et al.*, 2004). For each of these indices, catchment-wide distribution functions and median values were computed to allow comparison between catchments.

Transit time proxies

Time series analysis of isotopic tracers in precipitation and stream water has been widely applied to explore TTs and TTDs (McGuire and McDonnell, 2006). However, this approach usually involves using inverse modelling with lumped parameter convolution models in time or frequency domains and requires extensive datasets to estimate parameters that describe the TTD (McGuire and McDonnell, 2006). In this case, we developed a simpler approach that can be readily applied to different sites particularly within inter-catchment comparison studies. Results of earlier work by the authors identified strong relationships between estimates of MTT from lumped parameter models and a simple ITTP derived from the ratio of the standard deviation of δ^{18}O stream flow samples to the standard deviation of δ^{18}O in the precipitation samples (Maloszewski *et al.*, 1983; DeWalle *et al.*, 1997; McGuire *et al.*, 2005; Soulsby and Tetzlaff, 2008). These ITTPs—although based on a very simple measure of tracer damping—were correlated with MTT estimates based on convolution integral methods (Figure 2). The correlations were negative with a higher ITTP equating to less damping and lower TTs (of *ca* <0·5 years). Conversely, lower ITTPs are evidence of greater damping and higher TTs (of up to a few years). Despite some scatter, this simple ratio may be a convenient, transferable semi-quantitative ITTP, which can be quickly derived for large numbers of catchments. Such indices can only be viewed as simplified representations of TT, and interpretation should be suitably cautious. For example, the standard deviations will vary with the length of sampling interval and the longevity of the data record; moreover, tracer fluctuations in precipitation can be variable between years, thus different data sets may not be truly comparable in space and time (e.g. Hrachowitz *et al.*, In press). Nevertheless, the relationships shown in Figure 2 suggest that the ITTP may at least provide a first approximation of possible differences in flow paths and mixing processes in different catchments.

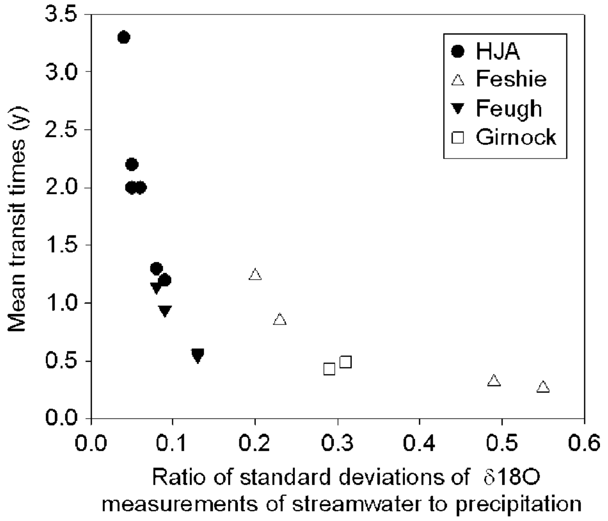

Figure 2. The relationship between mean transit times (MTT) and inverse transit time proxy ITTP (ratio of standard deviations of δ^{18}O measurements of stream water to precipitation) for the HJ Andrews (Western Cascades, US), the Feugh, the Girnock (E Cairngorms, Scotland) and the Feshie (W Cairngorms, Scotland) (based on McGuire *et al*., 2005; Rodgers *et al*., 2005a,b; Tetzlaff *et al*., 2007)

Results

Figure 3 summarizes the ITTP (derived from the ratio of the standard deviation in streamwater to the standard deviation in precipitation) for each catchment in relation to the topographic indices described above. The ITTP is low (<0·1)—and imply TT is high—in the HJ Andrews sites, and in the Mahantango and Black Burn catchments. Higher ITTPs—(>0·1)—were found in the Feshie, Krycklan, Girnock and Catskill catchments, as well as most of the Feugh sites, implying lower TTs. Intra-catchment variation in the ITTP for individual regions differed; the ratio varied by a factor of two or more at HJ Andrews, Mahantango, the Feugh, Feshie and Krycklan. In contrast, the Catskill, Black Burn and Girnock sites showed much more restricted intra-catchment variability.

A principal component analysis (PCA) was carried out using the topographic indices to differentiate the catchments on the basis of landscape structure (Figure 4). Catchments within different geomorphic provinces tend

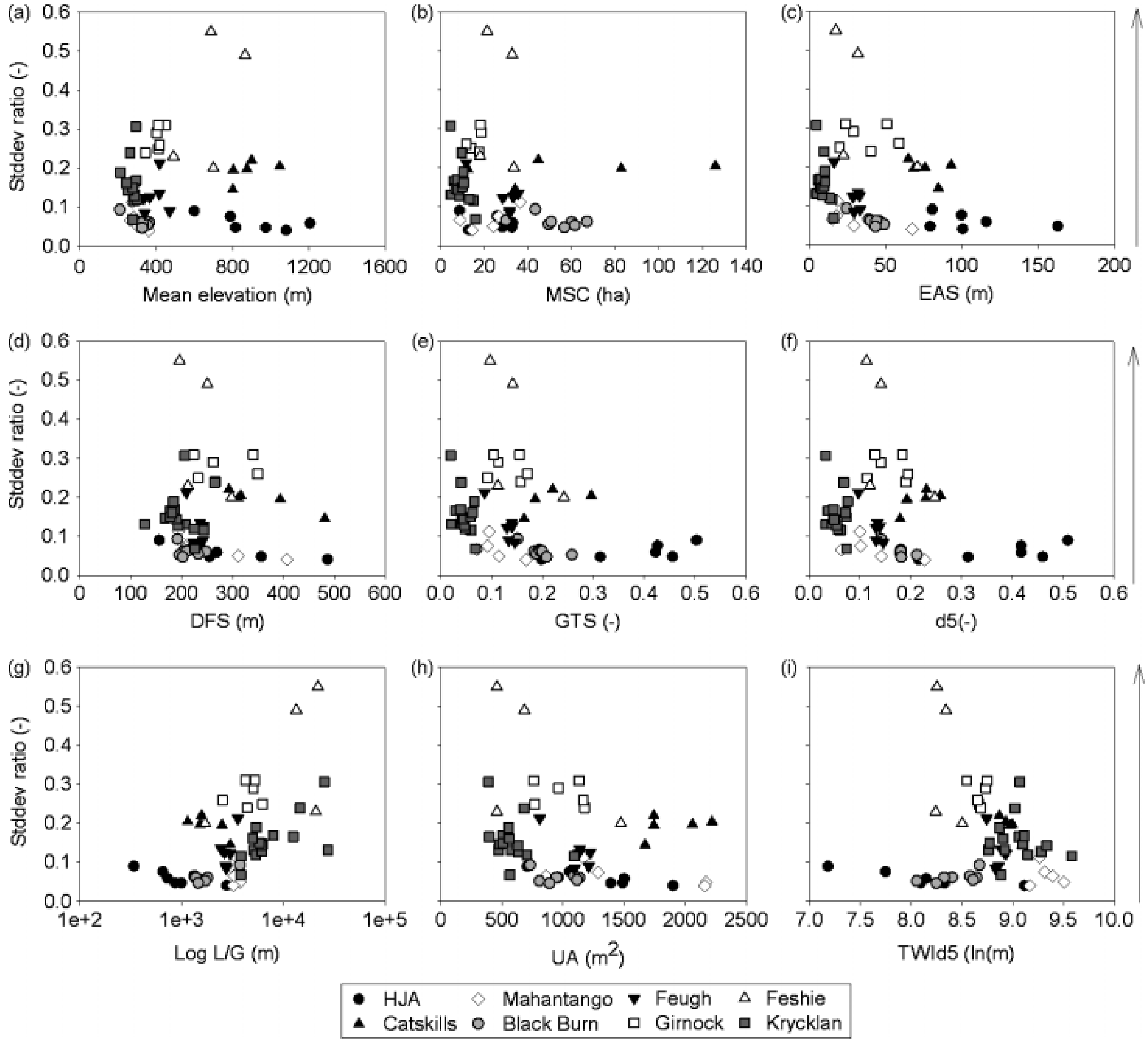

Figure 3. Relationships between topographical indices (EAS, elevation above stream; DFS, distance from stream; GTS, gradient to stream; d5, downslope index gradient; L/G, Flow path length/gradient; MSC, median sub-catchment area; UA, upslope area; TWI_{d5}, topographic index) and inverse transit time proxy ITTP (ratio of standard deviations of δ^{18}O measurements of stream water to precipitation) for the eight catchments and their associated sub-catchments

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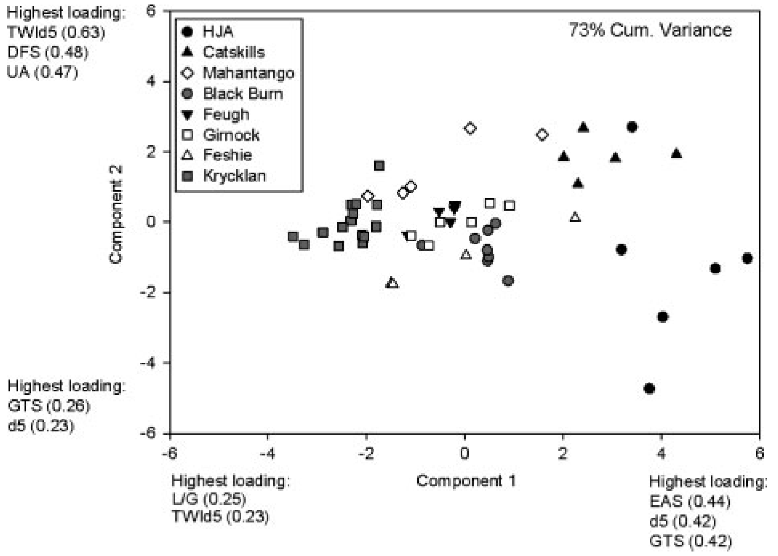

Figure 4. Principal component analysis (PCA) for the eight catchments and their associated sub-catchments. Each catchment was characterized using a total of nine topographical indices (ME, mean elevation; MSC, mean sub-catchments size; EAS, elevation above stream, DFS; distance from stream; GTS, gradient to stream; d5, gradient; L/G, flow path length/gradient ratio; UA, upslope area; TWI_{d5}, topographic index). The indices with the highest component loadings are shown adjacent to respective axes

to cluster together in the plot, though there is some overlap. Most of the HJ Andrews sites tend to separate out, along with most of the Catskill sites in terms of having high elevations, steep gradients, long flow path lengths and high UAs. One of the Mahantango sites and the Allt a' Mharcaidh (Feshie catchment) have similar topographic characteristics and also plot in this cluster of catchments. At the other extreme, the Krycklan catchments in Sweden have lower elevations and gentler gradients. The sites of the Black Burn, Feugh and Girnock catchments group closely together, occupying intermediate positions in relation to the main components.

The relationships between the ITTPs and various topographic indices shown in Figure 3 are expressed as correlation coefficients in Table II. Due to the small sample sizes, the correlations for individual catchments are indicative rather than necessarily of statistically significance. The correlations when all sites are pooled are relatively weak, reflecting major differences in the nature of these relationships in different geomorphic provinces. For example, in the HJ Andrews and Catskill catchments, there were strong positive relationships between the ITTP and median flow path gradient, but negative relationships between ITTP and the TWI_{d5}, median flow path length and the L/G index. In other words, TTs appeared lowest in catchments with steeper, shorter slopes. In contrast, in the Krycklan catchments and the Feshie, there were negative relationships between the ITTP and the median flow path gradient, but strong positive relationships with the L/G index, indicating that TTs are lowest when slopes are gentlest.

The Scottish sites of the Girnock, Feugh and Black Burn show intermediate values for many of the topographic indices, and the sites cluster together in the PCA shown in Figure 4. The Girnock and Black Burn catchments show poor correlations with most topographic indices, possibly as a result of the limited variability in the ITTP despite differences in sub-catchment topographic characteristics. The ITTP is poorly correlated with the L/G index at all three sites, though for the Feugh and Black Burn, stronger negative correlations are apparent with the slope-related indices of flow path gradient and the d5. In the Girnock, only UA is correlated—negatively—with the ITTP.

The Mahantango also shows a strong inverse relationship between the ITTP and slope-related indices, but a weak positive relationship with the L/G index. In the PCA (Figure 4), the Mahantango sites exhibit considerable overlap with other sites, and two catchments have topographic characteristics similar to those of the Catskill catchments, whereas others are more similar to the subcatchments of the Feugh and the Krycklan sites. Sites from other geomorphic provinces also show overlap. For example, the Allt a' Mharcaidh in the Feshie plots closer to some of the Andrews sites.

There was no relationship between catchment size and ITTPs, although such relationships have sometimes been assumed (Wolock *et al.*, 1997). The ratio was generally most variable in smaller catchments within each province (Figure 5). Where catchments were nested, this variability was averaged at larger scales, though there is insufficient data from larger catchments to say whether this reflects linear or non-linear averaging. Median subcatchment size—rather than catchment size *per se* is sometimes more strongly correlated with MTT in headwater catchments; for example, at Maimai in New Zealand this index gave a useful measure of landscape structure believed to reflect hydrologic connectivity (McGlynn *et al.*, 2004). However, in this study MSC was correlated with ITTP only in the Mahantango and Catskill catchments, and these correlations were weak.

Table II. Relationships between topographical indices and inverse transit time proxy ITTP (ratio of standard deviations of δ^{18}O measurements of stream water to precipitation): (a) Correlation coefficient (r$_p$) and (b) Spearman rank correlation coefficient (r$_s$)
(a)

	N	Elevation	EAS	DFS	GTS	d5	L/G	MSC	UA	TWI$_{d5}$
All catchments	55	0·13	−0·25	−0·02	−0·28	−0·24	0·55	−0·17	−0·27	−0·05
HJA	6	−0·69	−0·37	−0·82	0·73	0·73	−0·69	−0·39	−0·94	−0·91
Catskill	5	0·53	−0·41	−0·93	0·62	0·74	−0·81	0·31	0·39	−0·96
Mahantango	5	−0·69	−0·65	−0·79	−0·58	−0·61	0·10	0·72	−0·68	−0·13
Black Burn	8	−0·83	−0·91	−0·27	−0·73	−0·83	0·86	−0·43	−0·39	0·6
Feugh	6	0·17	−0·85	−0·66	−0·89	−0·91	0·74	−0·82	−0·83	−0·56
Girnock	6	0·65	−0·05	0·06	−0·18	−0·18	0·07	0·56	−0·24	−0·07
Feshie	4	0·57	−0·61	−0·52	−0·60	−0·60	0·50	−0·05	−0·55	−0·45
Krycklan	15	−0·09	−0·49	0·10	−0·49	−0·25	0·57	−0·3	−0·35	−0·08

(b)

	N	Elevation	EAS	DFS	GTS	d5	L/G	MSC	UA	TWI$_{d5}$
All catchments	55	0·08	−0·32	0·00	−0·37	−0·29	0·56	−0·28	−0·33	0·02
HJA	6	−0·66	−0·14	−0·83	0·83	0·86	−1·00	−0·26	−0·77	−0·94
Catskill	5	0·90	−0·30	−0·90	0·70	0·90	−0·70	0·60	0·40	−0·90
Mahantango	5	−0·70	−0·60	−0·90	−0·60	−0·70	0·30	0·70	−0·60	0·00
Black Burn	8	−0·33	−0·74	−0·07	−0·62	−0·60	−0·12	−0·45	−0·05	0·62
Feugh	6	0·31	−0·37	−0·34	−0·54	−0·54	0·03	−0·03	−0·14	−0·09
Girnock	6	0·40	−0·06	−0·29	−0·34	−0·34	−0·17	0·51	−0·69	−0·06
Feshie	4	0·00	−0·80	−0·80	−0·80	−0·80	0·80	−0·40	−0·80	−0·40
Krycklan	15	−0·09	−0·44	−0·21	−0·45	−0·12	0·60	−0·24	−0·52	−0·23

(EAS, elevation above stream; DFS, distance from stream; GTS, gradient to stream; d5, downslope index gradient; L/G, flow path length/gradient; MSC, median sub-catchment area; UA, upslope area; TWI$_{d5}$, topographic index).

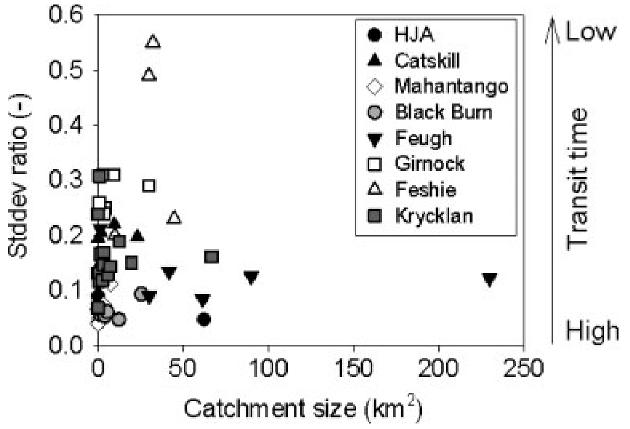

Figure 5. Relationship between catchment size and the inverse transit time proxy ITTP (ratio of standard deviations of δ^{18}O measurements of stream water to precipitation) for the eight catchments and their associated sub-catchments

Discussion

Despite a relatively simple method of estimating ITTPs in this study, the results indicate that the topographic controls on TTs are different—both in terms of characteristics and degree of influence—among these contrasting geomorphic provinces. Topographic controls are most obvious and intuitive in steep montane catchments, such as HJ Andrews and in the Catskills, where gravitationally driven sub-surface flow paths dominate and TTs decline as slopes become increasingly steep (McGuire *et al.*, 2005). In catchments where topography is more subdued, such as at Krycklan or some of the Scottish sites, flatter, poorly drained areas often result in the development of peat soils where runoff is dominated by overland flow and TTs are lower when gradients decline and the L/G ratio increases (Soulsby *et al.*, 2004, 2006; Laudon *et al.*, 2007).

It is perhaps not surprising that a landscape analysis based on surface topography alone is not always useful in predicting metrics such as TTs because sub-surface permeability and connectivity are also potentially important determinants of hydrologic response. For example, in catchments like the Feshie, Feugh and Krycklan, where a counter-intuitive negative relationship between TT and slope measures was observed, the response may reflect isotopic mixing that is less damped in flat, peat-covered areas with greater overland flow, and more damped where slopes are steeper and better drained allowing greater sub-surface mixing.

Moreover, in other catchments such as the Girnock and the Black Burn, ITTPs were very similar despite some differences in landscape characteristics. Local process knowledge suggests that this relates to extensive drift cover in these glaciated catchments. In the Girnock, the drift is poorly drained glacial till resulting in responsive peat and gleyed soils, which may explain low TTs (Tetzlaff *et al.*, 2007). In the Black Burn, the drift is more free-draining, mixing processes are more effective, and the isotopic response is strongly damped (Dunn *et al.*, 2008).

Similarly, geological differences can affect flow paths and mixing processes. For example, in the Mahantango catchments, the lack of confining layers in intensely jointed and fractured sandstone results in significant groundwater storage and a strong groundwater influence on stream flows (O'Driscoll *et al.*, 2005), which is consistent with the damped tracer responses observed at this site and the poor correlation between the ITTP and topographic characteristics. In contrast, in the Catskill catchments, vertically fractured bedrock with confining layers cause extensive spring systems that may contribute to the apparently lower TTs in this steeply sloping province, which is consistent with the higher ITTPs which show good correlation with many topographic indices (Burns *et al.*, 1998).

Despite the ambiguities of the relationships between topographic indices and ITTPs, the quantitative landscape analysis proved to be a useful way of characterizing catchment topography in a way that could be elucidated through PCA (Figure 4). This suggests PCA analysis has value in inter-catchment comparisons that link geomorphic structure to hydrological function both within and between geomorphic provinces. This may prove to be a useful tool in hydrologically meaningful catchment classification (Wagener *et al.*, 2007). Despite the success here, these results suggest that transferable approaches to predicting metrics of hydrological function based on topographic analysis alone, may be most useful primarily in the steepest terrain. We regard these results as preliminary, and further work is needed to examine the relationships between simple metrics of hydrological function such as TT and landscape characteristics at a wider range of sites. Such an analysis would require an international collaborative effort based on sharing data sets and analytical tools as for example, the PUB initiative. Finally, most studies are restricted to relatively small headwater catchments, which are, at best nested only at the mesoscale (*ca* 10^1-10^2 km^2), as was the case with the nested sites reported in this study. Although these nested sites showed averaging of TT's with scale, there is a need for further upscaling to larger catchments (*ca* 10^3-10^4 km^2) to establish how the nature of such averaging might change as larger lowland landscape units exerting an increasing influence on hydrological response (Bishop *et al.*, 2008; Tetzlaff and Soulsby, 2008).

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