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The relative role of soil type and tree cover on water storage and transmission in northern headwater catchments

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Abstract:

Soil water storage and stable isotopes dynamics were investigated in dominant soil–vegetation assemblages of a wet northern headwater catchment (3.2 km^2) with limited seasonality in precipitation. We determined the relative influence of soil and vegetation cover on storage and transmission processes. Forested and non-forested sites were compared, on poorly drained histosols in riparian zones and freely draining podzols on steeper hillslopes. Results showed that soil properties exert a much stronger influence than vegetation on water storage dynamics and fluxes, both at the plot and catchment scale. This is mainly linked to the overall energy-limited climate, restricting evaporation, in conjunction with high soil water storage capacities. Threshold behaviour in runoff responses at the catchment scale was associated with differences in soil water storage and transmission dynamics of different hydropedological units. Linear input–output relationships occurred when runoff was generated predominantly from the permanently wet riparian histosols, which show only small dynamic storage changes. In contrast, nonlinear runoff generation was related to transient periods of high soil wetness on the hillslopes. During drier conditions, more marked differences in soil water dynamics related to vegetation properties emerged, in terms of evaporation and impacts on temporarily increasing dynamic storage potential. Overall, our results suggest that soil type and their influence on runoff generation are dominant over vegetation effects in wet, northern headwater catchments with low seasonality in precipitation. Potential increase of subsurface storage by tree cover (e.g. for flood management) will therefore be spatially distributed throughout the landscape and limited to rare and extreme dry conditions. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS hydropedology; isotopes; water storage; soils; land cover; vegetation

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INTRODUCTION

Understanding how vegetation canopies and soils partition, store and regulate water fluxes in the landscape remains a key challenge in water resource research (Hopp *et al*., 2009; Wagener *et al*., 2010; Vivoni, 2012; Mirus and Loague, 2013). Quantifying these effects is crucial for many environmental problems, including the prediction of impacts of changing climate and land use and the associated pressures on ecological habitats (e.g. Poff *et al*., 1997; D'Odorico *et al*., 2010; Tetzlaff *et al*., 2013). In addition, water partitioning, storage and flux processes regulate the generation of stream flow and the time scales for the transport of solutes and contaminants (Kirchner *et al*., 2000; McDonnell *et al*., 2010; Rinaldo *et al*., 2011). The controls on these processes vary depending on the interplay of climate and catchment properties including bedrock type (e.g. Kosugi *et al*., 2008; Gabrielli *et al*., 2012) and depth (Asano and Uchida, 2012), topography (McGuire *et al*., 2005; Tetzlaff *et al*., 2009), pedology (Hrachowitz *et al*., 2009; Hümann *et al*., 2011), snow dynamics (Mueller *et al*., 2013) and vegetation cover (Stumpp *et al*., 2009; Roa-García and Weiler, 2010). Disentangling these controls on storage and release processes is difficult, in particular as the relative significance of different processes is also time variant (e.g. Montaldo *et al*., 2013).

Here, we focus on the relative role of soil and tree cover in northern environments characterized by low seasonality with relatively high precipitation inputs and where the distribution of trees is impacted by a long history of land management practices. Previous studies in humid northern systems have shown that soil water dynamics in certain hydropedological units control hillslope runoff connectivity, streamflow regimes and the resulting water transit time distributions (Soulsby and Tetzlaff, 2008; Hrachowitz *et al*., 2009; Lin, 2010a; Tetzlaff *et al*., 2014). The role of soils has long been recognized as a significant factor for rainfall–runoff

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processes in catchments (Hewlett and Hibbert, 1967), with their physical properties integrating topography, parent material, ecology and climate (Lin, 2010b). However, the influence of vegetation on soil–water interactions in the unsaturated soil zone remains poorly understood. Such inter-relationships are complex, and the dominant processes vary in space and time (Young *et al.*, 2007; Lin, 2010b, 2012). For example, in a semi-arid climate with strong seasonality, Montaldo *et al.*, (2013) found that the dominant ecohydrological controls could switch from a soil-controlled system in late spring when soils are relatively wet to a vegetation-controlled system in summer when soils are dry.

The precise interactions between soils, vegetation and water fluxes remain ambiguous in ecohydrology (e.g. Calder, 2005; D'Odorico *et al.*, 2010; Asbjornsen *et al.*, 2011). The spatiotemporal patterns of soil water availability and flow paths have been identified as key functions of the landscape's vegetation distribution (Thompson *et al.*, 2011; Hwang *et al.*, 2012), which in turn are regulated predominantly by the hydraulic properties of soils. However, others have demonstrated vegetation influence on the movement of surface and soil water, for example, through interception (Holwerda *et al.*, 2010) and stemflow (Li *et al.*, 2009), transpiration (Flerchinger *et al.*, 2010), hydraulic redistribution (Brooks *et al.*, 2006) and changing soil physical hydrological characteristics through root functions (Thompson *et al.*, 2010). This is mainly reported in studies conducted in (semi-)arid areas, whereas it is relatively unknown for wetter climates (Rodriguez-Iturbe *et al.*, 2007) or suggested to be of little importance (e.g. Thompson *et al.*, 2010).

A central limitation to understanding soil–water–vegetation interlinkages is the paucity of data in different environments. Subsurface processes are difficult to measure directly for prolonged periods, although by combining hydrometric and isotopic methods new insights can be gained. Whilst soil moisture data contribute to insights into water storage dynamics, isotope tracers can offer additional insights into water movement, mixing and partitioning processes. Short-term variations in stable isotopes in precipitation, soil water and stream water can be used to understand seasonal dynamics of soil water and related information about transport, storage and mixing processes in the subsurface (DeWalle *et al.*, 1997; Newman *et al.*, 1997; Gazis and Feng, 2004). Fractionation effects of soil water at the top of the soil profile can be linked to evaporation of soil moisture and throughfall of intercepted water on vegetation canopies (e.g. Newman *et al.*, 1997).

Here, we explore the spatiotemporal controls of soil and vegetation characteristics on subsurface water storage and fluxes in a northern headwater catchment in the Scottish Highlands, where the climate is relatively wet and generally has limited seasonality in precipitation. The main soil types naturally support their own specific vegetation communities. However, the Highlands are largely a cultural landscape, and the current spatial distribution of vegetation communities reflects a long history of human management, in particular for game shooting. Red Deer (*Cervas elaphus*) populations are kept artificially high (by winter feeding and historic extinction of natural predators), and grazing inhibits the regeneration of tree species, including Scots Pine (*Pinus sylvestris*), to inaccessible areas where deer are excluded by fencing or steep scree slopes. In addition, the predominant heather (*Calluna* spp.) vegetation is routinely burned to optimize habitat diversity for different life stages of Red Grouse (*Lagopus lagopus scotica*).

The main aim of this study is to investigate the role of soil and tree cover characteristics on subsurface water storage and transmission in a relatively wet climate with limited seasonality in precipitation. More specifically, the following questions are addressed: (1) What are the temporal and spatial dynamics of soil water storage and fluxes for typical soil–vegetation assemblages, (2) what is the significance of soil type and tree cover on the soil water and catchment dynamics and (3) what can be learned about the role of past and future land management on water storage capacities and dynamics in northern environments?

SITE DESCRIPTION

The study was carried out in the Bruntlan Burn (3.2 km^2) tributary of the Girnock Burn (31 km^2), Cairngorms National Park, NE Scotland. The Bruntlan and Girnock Burns are part of longer-term monitoring programmes (Figure 1; Table I), and detailed site descriptions are provided elsewhere (e.g. Soulsby *et al.*, 2007; Tetzlaff *et al.*, 2007). A brief summary of the Bruntlan Burn characteristics is provided here.

The geology is dominated by granite and metamorphic bedrock. Elevations range from 248 to 539 m a.s.l. (mean 351 m a.s.l.), and the mean slope is ~13°. Typical for the Scottish Highlands, the Bruntlan Burn flows through an over-widened glaciated valley with thick drift deposits. The extended riparian zone is largely overlain by peat bogs (histosols), which are up to 4 m deep and thin to around 0.5 m on the footslopes. Humus-iron podzols (spodosols) cover the steeper hillslopes thinning to ranker soils (leptosols) and bedrock outcrops at slopes >25°.

The different soil types largely support their own specific vegetation communities, although vegetation also reflects the long history of red deer and grouse management (Figure 1). The dominant land cover is heather (*Calluna* and *Erica* species) moorland, which

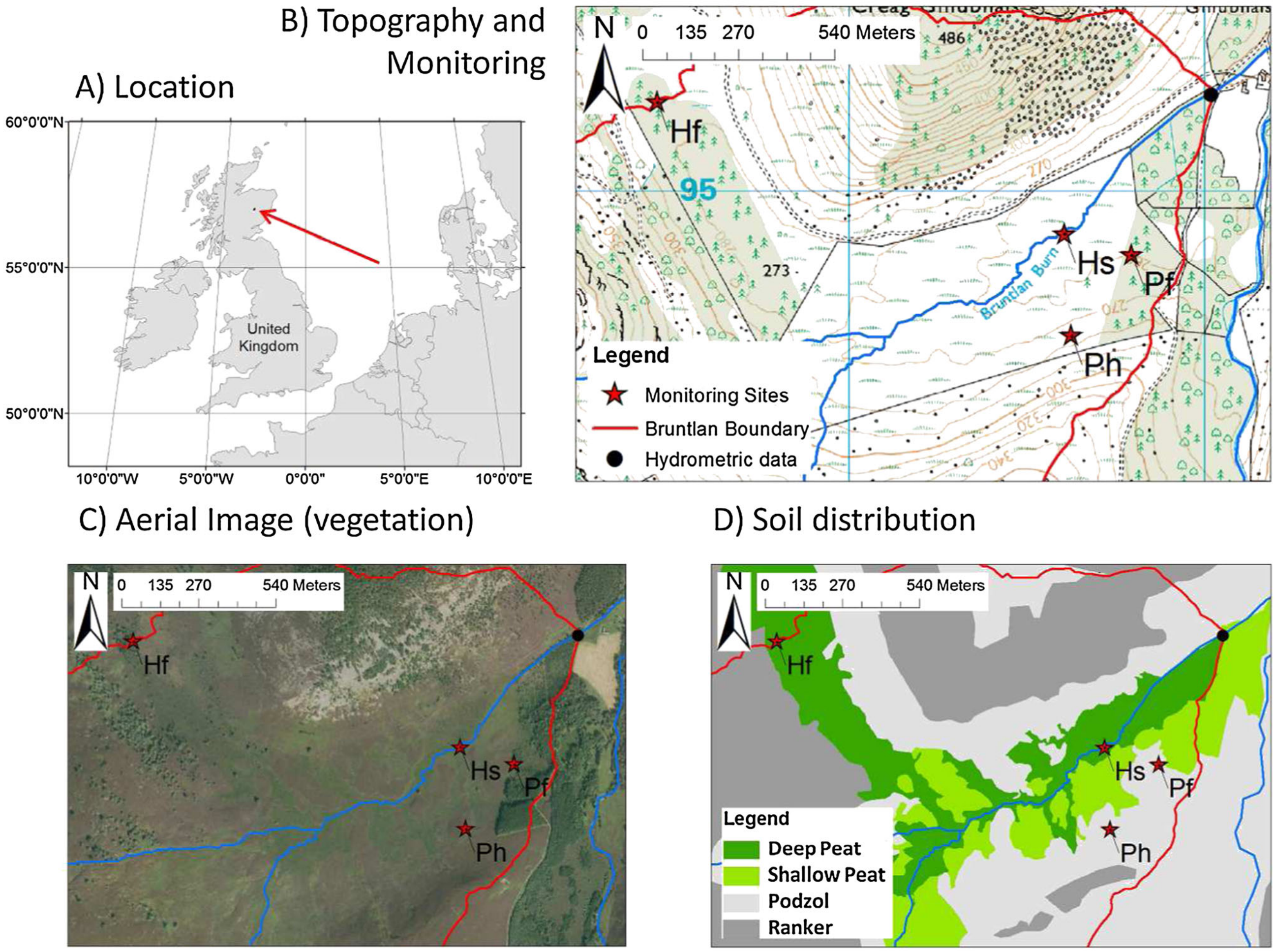


Figure 1. Study area showing (A) the location of the study site and the local (B) topography and monitoring sites, (C) aerial image (vegetation: tree cover (dark green), heather (brown) and peat (light green)) and (D) soil type distribution. The catchment area for the Brunlan Burn is indicated by the red line

mostly coincides with the spatial distribution of podzols. *Sphagnum* and Bog Myrtle (*Myrica gale*) are dominating the histosols, although *Molinia* becomes more common where soils are thinner. Scots Pine (*P. sylvestris*) and other native (incl. Birch (*Betula*), Alder (*Alnus*)) and non-native (e.g. Sitka Spruce (*Picea sitchensis*) and Sycamore (*Acer psuedoplatanus*)) tree species can grow on all soil types but are limited to areas inaccessible for red deer (i.e. behind deer fences and on steeper scree slopes).

The climate is wet with little seasonality in precipitation. Mean annual precipitation is ~1100 mm, which is usually evenly distributed throughout the year (Figure 2). A small proportion of winter precipitation (typically <10%) can occur as snow between October and March. Precipitation greatly exceeds annual potential evapotranspiration (~300 mm) so that evapotranspiration is energy limited. However, there are clear seasons in evapotranspiration rates, driven mainly by large variations in day length and temperature. During the summer months, potential evapotranspiration can therefore exceed precipitation inputs.

The hydrological characteristics of the soil types are strongly linked to their pedogenesis. Porosities and water retention capacities of the histosols are high, resulting in overall large water storage. These wet and poorly draining soils provide a very responsive hydrological regime with runoff generated mainly via surface and near surface horizontal flow in the dynamically saturated riparian zone (Tetzlaff *et al*., 2007; Birkel *et al*., 2010). In contrast, water transmission in more freely draining podzols on the hillslopes is dominated by vertical, deeper flow path recharge with lateral shallow subsurface storm flow in the largest events (Soulsby *et al*., 1998), exhibiting a transient connection to the riparian wetland when water tables are high (Tetzlaff *et al*., 2014). However, because most precipitation events are small (>60% of precipitation falls in events <5 mm), daily runoff coefficients are relatively low (typically less than 10%) and only when podzolic soils are connected to the saturated zone that these can

Table I. Basic physical site characteristics of the Bruntlan Burn

	Bruntlan Burn
Topography	
Area (km^2)	3.2
Mean elevation (m a.s.l.)	351
Min elevation (m a.s.l.)	248
Max elevation (m a.s.l.)	539
Mean slope (°)	12.81
Geology	
Granite	0.46
Metamorphic rocks	0.54
Pedology	
Histosols	0.09
Gleysols	0.12
Podzols	0.36
Leptosols and bedrock	0.43
Land cover	
Peat bog	0.09
Heather	0.41
Woodland	0.21
Bare	0.29

Geology, pedology and land cover are presented as aerial fractions.

exceed 40% (Tetzlaff *et al*., 2014). Tracer studies have indicated that 25–35% of annual runoff comes from groundwater contributions (Soulsby *et al*., 2007). Mean streamwater transit time is on the order of 2–3 years (Tetzlaff *et al*., 2014).

DATA AND METHODS

Soil water storage and transmission dynamics were investigated for four experimental sites with contrasting soil and vegetation types (Figure 1). Two sites for each group were selected so that the first pair was located on poorly drained soil histosols (H sites) and the other pair on freely draining podzols (P sites) (see Table II for soil profile descriptions). The organic horizons of the H sites exhibited high porosities and low bulk densities compared with those of the mineral horizons of the P sites. It is also well known that peats (histosols) have generally high water retention capacities and low hydraulic conductivities (except at the surface) in comparison with other soils (Letts *et al*., 2000). The UK HOST (Hydrology of Soil Types) classification (Boorman *et al*., 1995) provides hydrologically important soil characteristics, including the base flow index (BFI) and the standard percentage runoff coefficient (SPR). The histosols in the study site (HOST'29) are characterized by low BFI (0.232) and high SPR (60). In comparison, for the podzols (HOST 17), a much higher fraction of the annual runoff is ascribed to more slowly responding hydrological stores (BFI = 0.613), and the percentage of storm precipitation that typically appears as runoff is much lower (SPR = 29.2).

Within each of the two soil groups, different vegetation types were included. This allowed for comparisons between forested (Scots Pine; sites Hf and Pf) and non-forested (*Sphagnum* (site Hs) and Heather (site Ph)) locations.

Soil moisture changes and stable isotope dynamics were examined at three depths (−0.1, −0.3 and −0.5 m) that corresponded roughly to the main soil horizons (Table II). Intensive monitoring at the four sites covered one hydrological year between the beginning of October 2012 and the end of September 2013. Longer records (>2 years) for some relevant variables at the non-forested sites (Hs and Ph) are available as part of a larger experimental catchment monitoring programme.

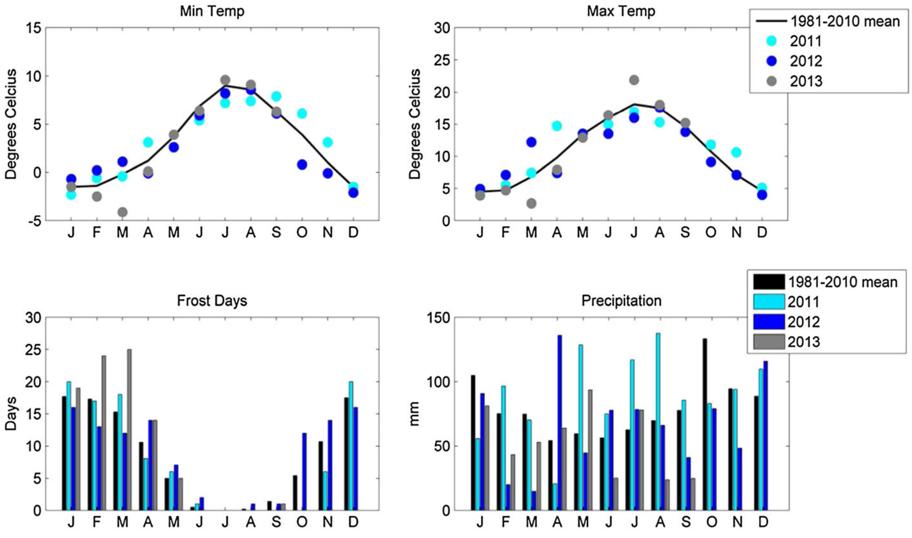


Figure 2. Long term mean (1981–2010) and study period monthly climatic conditions (minimum and maximum temperature, number of frost days and precipitation) for the long-term Braemar monitoring station (330 m AMSL) (data source: UK Metoffice)

Table II. Experimental site properties

Site		Topography				Vegetation	Soil properties					
No.	Reference	Elevation	Slope (°)	Dstream (m)	SAGA (–)	Main types	Soil type	Horizon (depth (m))	Mon depth (m)	ρ (g cm^{-3})	ϕ (–)	OM (–)
Hs	NO 316 949	254	1.47	19	15.80	*Sphagnum*; *Myrica gale*	Histosol	O (0–0.6)	0.1	0.09 (0.02)	0.92 (0.02)	0.57 (0.02)
									0.3	0.08 (0.02)	0.93 (0.02)	0.61 (0.21)
									0.5	0.06 (0.01)	0.95 (0.01)	0.72 (0.01)
Hf	NO 305 953	281	1.93	50	10.67	*Pinus sylvestris*; *Sphagnum*	Histosol	O (0–0.6)	0.1	0.10 (0.03)	0.91 (0.03)	0.59 (0.17)
									0.3	0.07 (0.02)	0.94 (0.02)	0.89 (0.03)
									0.5	0.06 (<0.01)	0.95 (0.01)	0.91 (0.02)
Ph	NO 316 946	277	9.32	228	7.37	*Calluna vulgaris*;	Podzol	O/A (0–0.2)	0.1	0.78 (0.20)	0.73 (0.07)	0.17 (0.10)
								A/E (0.2–0.4)	0.3	1.25 (0.06)	0.47 (0.02)	0.03 (<0.01)
								Bs (0.4–0.6)	0.5	1.47 (0.28)	0.42 (0.03)	0.02 (<0.01)
Pf	NO 318 948	261	3.06	169	8.06	*P. sylvestris*	Podzol	O/Ap (0–0.2)	0.1	0.74 (0.21)	0.68 (0.07)	0.80 (0.06)
								A/E (0.2–0.4)	0.3	1.04 (0.17)	0.60 (0.05)	0.08 (0.02)
								Bs (0.4–0.6)	0.5	1.35 (0.11)	0.45 (0.03)	0.02 (<0.01)

Dstream, distance to the stream; SAGA, SAGA wetness index (Böhner *et al.*, 2006); Mon Depth, monitoring depth; ρ, bulk density; ϕ, porosity; OM, organic matter content.

Volumetric soil moisture (VSM) content was measured at 15-min intervals with *Campbell Scientific* time domain reflectometry (TDR) probes at sites Hs, Ph and Pf, where average values of two replicate probes were used. VSM data were collected for each of the three depths for the podzol sites. VSM was measured at −0.1 m at the histosol sites; the lower soil layers (−0.2 m and beyond) were permanently saturated. Fortnightly spot measurements of soil moisture at Hf were made with a *Delta T* PR2 soil moisture profile probe. These measurements exhibited a strong correlation with the continuous (15 min) TDR soil moisture measurements at Hs ($r^2 = 0.85$). This was used in a linear regression to develop a transfer function to estimate a continuous time series for Hf. In addition, VSM measurements at the ground surface of the four sites were measured fortnightly, by averaging ten replicate measurements using a handheld *Delta T* SM300 soil moisture sensor. All probes were calibrated for the different soil types.

Fortnightly soil water samples from the three depths were collected for all four sites using *Rhizosphere Research Products* MacroRhizon moisture samplers. The water samples were analysed for stable isotope composition with a *Los Gatos* DLT-100 laser liquid water isotope analyser following standard protocols. Data are provided in the δ-notation (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW). The precision of the measurements is ±0.6‰ for δD and ±0.1‰ for δ^{18}O. Owing to an unusually cold winter, there were occasional data gaps in the soil water isotope data during periods where soil frost precluded sampling. Duplicates for each soil layer were collected, and average results are presented here.

Precipitation and discharge were measured at 15-min intervals. Potential evapotranspiration rates were estimated using a simplified version of the Penman–Monteith Equation (*cf* Dunn and Mackay, 1995), on the basis of the data from a *Campbell Scientific* automatic weather station 1 km away. Daily precipitation and stream flow samples were collected for stable water isotope analysis by automatic *ISCO* (3700) samplers. Isotopic fractionation between sampling and collection was prevented by a paraffin seal in the field.

To contextualize the climatic conditions of the sampling period, these were compared with longer-term averages. We used data from a long–term climatic station (at Braemar (330 m), ~15 km west of the site) in addition to those collected in the Girnock catchment area. This allowed for an evaluation of the temporal climatic dynamics within a longer-term context.

Spatial and temporal dynamics in soil moisture were used to estimate dynamic storage changes assuming idealized soil profiles. This involved three 0.2 m deep soil horizons, represented by soil moisture measurements at the centre of each horizon (Table II). Soil moisture deficit (SMD) estimates at time t were derived directly from the VSM data and soil thickness (ST), assuming that maximum observed soil moisture content data ($VSM_{\max}$) represented saturated conditions:

$$SMD_t = \frac{(VSM_{\max} - VSM_t)}{100} * ST \qquad (1)$$

for which SMD_t and ST are represented in millimetres and $VSM_{\max}$ and VSM_t in per cent. The total dynamic soil water storage change was then estimated as the difference between the minimum and maximum SMD values obtained during the observation period.

For each profile of the four soil–vegetation assemblages, SMD estimates were compared with discharge to evaluate threshold behaviour in relation to runoff generation at the catchment scale. The occurrence of overall 'wet' and 'dry' periods was determined by use of a relative Mean Normalized Soil Wetness (MNSW) index, on the basis of the data from all sites ($n = 4$):

$$MNSW_t = \frac{1}{n}\sum_{i=1}^{n} \frac{VSM_t - VSM_{\min}}{VSM_{\max} - VSM_{\min}} \qquad (2)$$

The relationship between discharge and MNSW was then used to establish a cut-off (at an MNSW index of 0.6) between relatively dry and wet conditions (i.e. conditions under which soils are relatively wet and runoff is actively generated *versus* conditions under which soils are relatively dry and runoff is low).

Seasonal input–output catchment dynamics were evaluated using >2 years of precipitation and discharge isotope signatures. These were compared with the isotope dynamics of soil water in the two longer-term site soil profiles (Hs and Ph) to provide an indication of the water storage and transmission with depth in the different soil types. For the 2012–2013 hydrological study year, the variability in isotope signatures of all four soil–vegetation assemblages was investigated in more detail. To identify seasonal/wetness impacts and/or differences between soil and vegetation covers, the evaporative fractionation effects in the top soil horizon (−0.1 m depth) were investigated by comparing isotope signatures against the global and local meteoric water lines for different soil wetness conditions. Similarly, stream water isotopic data were evaluated to assess such impacts at the catchment scale.

RESULTS

Dynamics in hydrometric data

Within the longer-term context, the study year had rather marked seasonality including a relatively dry, warm summer, which provided the opportunity to study the subsurface processes in quite extreme conditions, but ones that may become more common (Murphy *et al.*, 2009; IPCC, 2013). The long-term data showed limited seasonality in the hydroclimate, especially for precipitation, although the study year had several unusual characteristics (Figure 2). Mean monthly temperatures generally varied between −1.5 °C in December and January and 18 °C in July and August. These extremes were more pronounced for the study year (i.e. −4 °C and 22 °C, respectively), indicating a cold winter and warm summer. Other indications of a severe winter included the high number of days with ground frost (Figure 2) and snow cover (Figure 3 B), especially between February and April. During this period, discharge responses were driven by snow melt. The subsequent warm summer months had high potential evapotranspiration rates of up to 5.3 mm day^{-1}, compared with almost nil during the winter period (Figure 3A).

Over the long term, mean monthly precipitation was evenly distributed throughout the year and typically ranged from ~70 mm in February–September to ~100 mm for October–January (Figure 2). Monthly average numbers of days with precipitation >1 mm only varied between ~11 days in June and ~16 days in January. Apart from being unusually warm, the summer that followed the cold 2012–2013 winter was also unusually dry. Precipitation between June and September 2013 comprised only 57% of the long-term average (33% for August–September). Summer discharge responses were very low, with only one significant event at the end of July (Figure 3C).

Spatial and temporal dynamics in soil moisture

There were clear differences between the temporal soil moisture dynamics of the poorly draining histosols and the freely draining podzols. The histosols remained near saturation for most of the year, although some minor drying occurred in the upper soil profile during the summer period (Figure 3D). The VSM in the upper horizon of site Hs ranged from 0.77 to 0.85 (Table III). This suggested that the soil profile of the histosol with *Sphagnum* cover was constantly close to saturation. Indeed, the observed VSM roughly corresponded with the porosity of these soil types (Table II). Assuming idealized soil profiles, dynamic storage changes for the upper 0.6 m profile were only ~15 mm for site Hs. Considering the context of the dry summer, this was remarkably small, suggesting that actual evapotranspiration might be much lower than potential evapotranspiration and/or occurrence of wetland recharge from upland seepage. The extrapolated data to site Hf suggested that, generally, the site was drier, where the VSM ranged between 0.43 and 0.65. This can be related directly to its location in the wetland, as site Hf was located at the edge

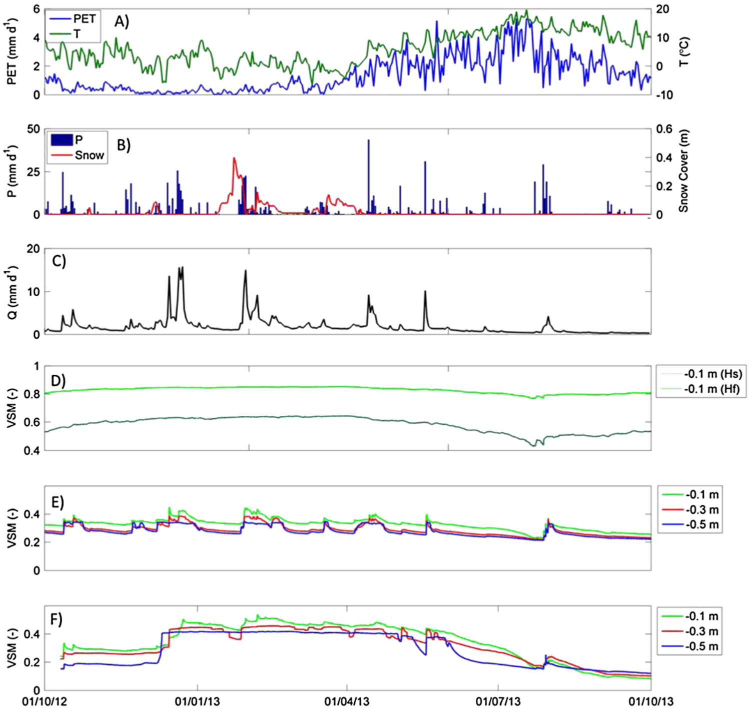


Figure 3. Spatial and temporal variability in (A) evapotranspiration estimated by Penman–Monteith equation (blue line) and mean temperature (green line); (B) precipitation (blue) and snow cover (red line); (C) discharge; and in soil moisture in the (D) poorly draining histosols soils (sites Hs and Hf) and the freely draining podzols under (E) heather (site Ph) and (F) tree cover (site Pt)

Table III. Summary statistics of all soil moisture and isotope data for the 2012–2013 hydrological year

		Volumetric soil moisture (–)						Deuterium isotope signatures (‰ VSMOW)					
Site	Depth	Min	Max	Median	Mean	Stdev	*n*	Min	Max	Median	Mean	Stdev	*n*
Hs	Surface	0.63	1.00	1.00	0.96	0.11	16						
	−0.1	0.77	0.85	0.84	0.83	0.02	35 040	−61.3	−46.9	−52.8	−53.5	4.9	25
	−0.3							−60.7	−57.1	−58.4	−58.4	0.8	25
	−0.5												
Hf	Surface	0.73	0.95	0.91	0.87	0.08	16						
	−0.1	0.43	0.65	0.60	0.58	0.06	[a]	−67.5	−47.9	−52.5	−54.4	5.4	22
	−0.3							−60.1	−54.7	−56.7	−57.0	1.6	22
	−0.5							−59.4	−56.0	−57.1	−57.4	1.0	22
Ph	Surface	0.11	0.63	0.35	0.37	0.14	18						
	−0.1	0.23	0.45	0.33	0.33	0.04	35 040	−64.1	−43.0	−53.5	−52.7	7.4	20
	−0.3	0.22	0.39	0.28	0.29	0.04	35 040	−63.3	−46.9	−55.6	−55.4	4.5	24
	−0.5	0.21	0.35	0.27	0.28	0.04	35 040	−63.4	−49.0	−55.9	−55.7	4.3	24
Pf	Surface	0.12	0.66	0.38	0.38	0.19	19						
	−0.1	0.08	0.54	0.37	0.35	0.13	34 110	−60.9	−45.1	−51.5	−51.7	5.1	21
	−0.3	0.10	0.46	0.32	0.32	0.11	34 110	−62.0	−45.8	−58.1	−55.3	6.0	20
	−0.5	0.12	0.42	0.26	0.29	0.12	34 110	−62.3	−52.7	−55.2	−56.5	3.2	22

[a] Estimated on the basis of the data from site Hs and a linear regression with point measurements.

of the wetland while site Hs was much closer to the stream (Table II). The drawdown of soil moisture during the summer period was also stronger for site Hf. Although still small, dynamic storage changes in the histosol under forest cover (estimated as ~40 mm) were more than double under *Sphagnum* cover.

In contrast, the soil moisture data for the freely draining podzols at sites Ph and Pf showed distinct and frequent wetting and drying cycles in winter and more pronounced drawdown during the drier summer period (Figure 3E and F, respectively). Responses to precipitation inputs were rapid and extended to the deeper soil layers within a short space of time, indicating rapid water flow. As for the histosol sites, observed ranges in VSM in these two podzol sites with contrasting vegetation covers differed markedly. For the upper soil horizon, the ranges were 0.23–0.45 for site Ph and 0.09–0.54 for site Pf (Table III). Correspondingly, total dynamic storage changes for the upper 0.6 m soil profile under tree cover (220 mm) were more than double those under heather (105 mm). It is now accepted that in the UK uplands, the main differences in evapotranspiration between trees and heather are the result of higher interception and higher aerodynamic roughness of forest compared with shorter vegetation (Calder, 2005; Robinson *et al*., 2013). Overall, the dynamic storage variations for the forest cover soil were ~25% of the long-term average annual precipitation. This underlines the anomalously dry nature of the summer and its significance in the Scottish context where moisture deficits are generally low. Whereas the overall range for the forest site (Pf) was larger than that for the heather cover site (Ph), the short-term dynamics of the latter was more pronounced.

For most of the year, the VSM content of the podzolic sites decreased with depth, which was related to variations in soil physical properties with lower porosity in the deeper mineral horizons (Table II). However, for site Pf, this pattern reversed during the dry period, and VSM content increased with depth. Additionally, the response in soil moisture to a large event at the end of July was faster in the lower soil horizon (0.5 m depth) than for the upper layers. Both of these observations suggest significant drying of the upper forested podzolic soil.

Figure 4 shows the relationship between SMD and daily runoff at the catchment scale. In the upper four panels, these are represented for the upper 0.2 m of the soil profile, where dynamic storage changes were largest, in the two panels on the bottom for the total upper 0.6 m for the two podzols sites only. There were four main observations from these plots. First and unsurprisingly, the highest runoff rates coincided with times during which all soil profiles had little available storage. Second, there were clear thresholds in the relationships between SMD of the freely draining podzols and catchment runoff. In contrast, such thresholds were not apparent for the poorly draining histosols (upper two panels), where runoff was low even when these soils were fully saturated. Thirdly, the hysteresis loops in the relationships were relatively narrow for the poorly draining histosols compared with those of the freely draining podzols, suggesting more hysteretic behaviour for the latter. The last main observation showed that the dynamic storage changes under forest cover were generally at least twice as large as for the non-forested sites (see also Figure 3). In addition, the threshold in the relationship between the podzols SMD and runoff for the non-forested site (Ph) was stronger than for the forested site (Pf), suggesting that more potential storage was available under forest cover during some of the larger runoff events.

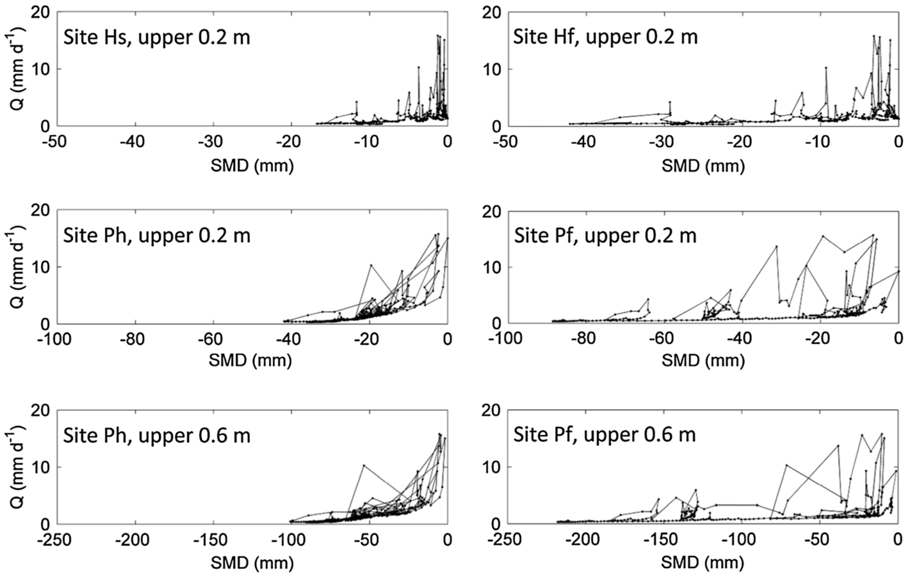


Figure 4. Daily SMD (in mm) *versus* daily runoff for the top 20 cm soil for the poorly drained soils (Hs and extrapolated Hf) and the top 20 cm as well as the total top 60 cm soil profile *versus* daily runoff for the freely draining soils (Ph and Pf). Note the change in scale on the *x*-axis in the vertical direction of the plots

Spatial and temporal dynamics in stable water isotopes

Temporal dynamics of deuterium (δD) for the longer-term monitoring sites are shown in Figure 5 for June 2011 to September 2013. As previously reported for other monitoring periods in the Bruntlan Burn (e.g. Birkel *et al.*, 2011a,2011b), daily precipitation inputs (Figure 5A) were highly variable, ranging between −142.9‰ in winter and −2.5‰ in summer (weighted mean = −59.1‰). In comparison, isotope variation in stream water (Figure 5 B) was strongly damped (−75.2‰ to −49.6‰; weighted mean = −58.1‰). Such strong attenuation of the input signal suggests significant mixing of new event precipitation with older water before it enters the stream. This has been previously linked to large mixing volumes in the riparian zone (Birkel *et al.*, 2011a; Tetzlaff *et al.*, 2014). The longer-term data also demonstrate clear seasonality in the daily stream deuterium signatures with more depleted values in winter and enriched values in summer (Figure 5B).

The soil water isotopes exhibited a similar seasonal pattern at all sites. Precipitation variability was damped for all profiles, with damping generally increasing with soil depth (Figure 5; Table III). Damping was much stronger for the histosol (Figure 5C), for example, at site Hs, than for the podzol at site Ph (Figure 5D). Compared with the previous year, the seasonality in soil water isotopes was more pronounced in the 2012–2013 study year. Considering all four soil–vegetation units, there was consistently more variability in the isotope signatures of the drier, freely draining podzols in response to precipitation inputs than in those of the wet histosols, especially at greater depths (Figure 6; Table III). In the podzols, the influence of depleted winter inputs and enriched summer inputs penetrated through the profile, although these effects were restricted to the surface layers of the histosols and more damped there generally. These differences caused by soil type were greater than the more subtle differences between vegetation types within the same soil class (Figure 6). In particular for the freely draining podzols, the forested site (Pf) showed a delayed response in the upper soil profile to more depleted rainfall inputs at the end of the hydrological year and a more damped profile in the deeper layers during the dry summer period than observed at the non-forested site (Ph; Figure 6).

Possible evaporative fractionation effects on isotope signatures in the upper soil profiles (−0.1 m) were investigated for different soil wetness conditions (Figure 7). The plots for all soil–vegetation assemblages showed that the soil water signatures were more enriched during the periods when soils were drier in the warm summer period reflecting both inputs and evaporative effects (Figure 3). However, there were no marked deviations from the LMWL for any of the assemblages, indicating fractionation was limited, even during the dry warm summer with high potential evapotranspiration rates. In general, such deviations were largest for Hs, where high water content in the upper soil profile might have resulted in the highest apparent fractionation. Regressions through soil water isotope data collected during relatively wet and relatively dry conditions hinted at potential impacts of vegetation (Figure 7). For those soil profiles with tree cover, there appeared to be slightly stronger fractionation effects during the dry period that could perhaps indicate fractionation during interception storage or soil surface evaporation.

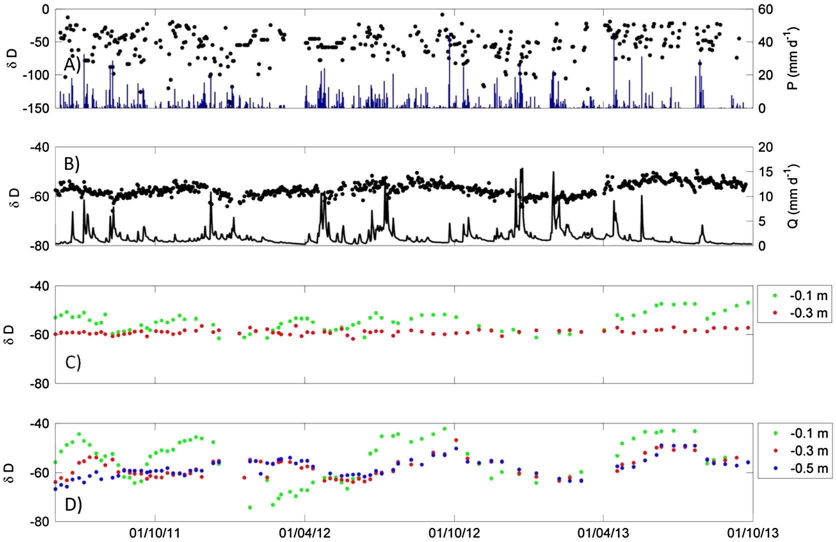


Figure 5. Longer term (>2 years) (A) precipitation and deuterium isotope dynamics, (B) discharge and deuterium isotope dynamics at the Bruntlan catchment outlet, and soil water deuterium isotope dynamics for the non-forested (C) histosol (site Hs) and (D) Podzol (site Ph)

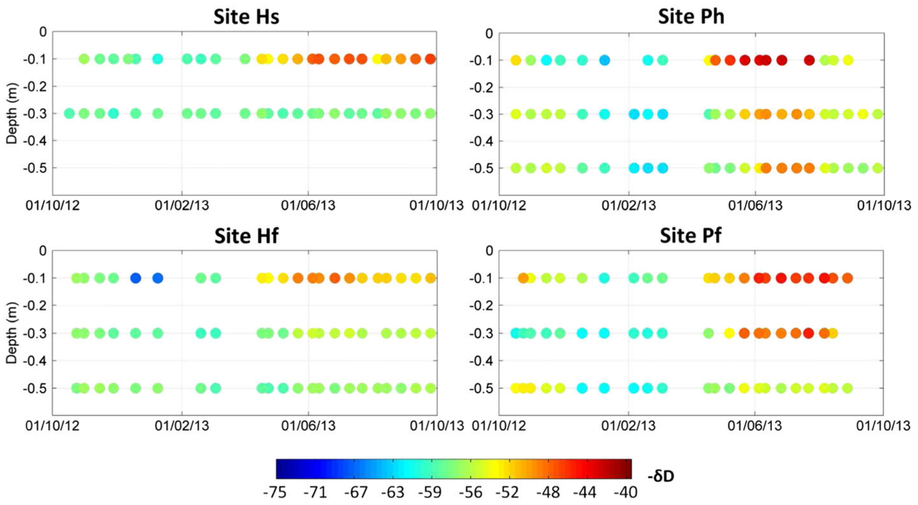


Figure 6. Soil water deuterium isotope dynamics with depth for the four different sites, showing consistently more variability in the isotope signatures of the drier, freely draining podzols (Ph and Pf) than in those of the wet histosols (Hs and Hf), especially at greater depths

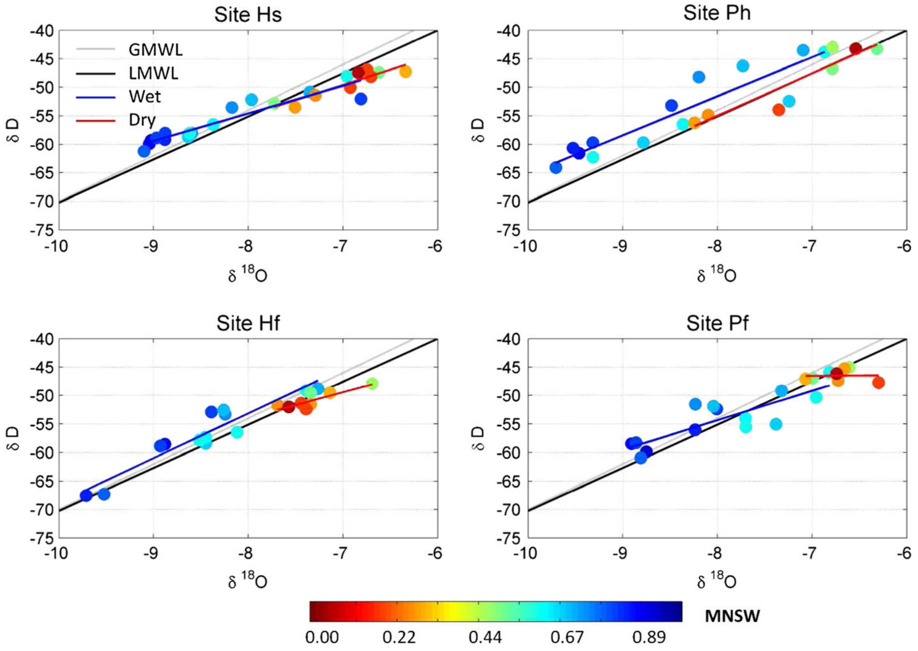


Figure 7. Soil water isotope signatures for the top layer (-0.1 m depth) on the global and local meteoric water lines for the four sites. The colours represent the Mean Normalized Soil Wetness (MNSW) on the day of sampling. Regressions through data from wet (MNSW >0.6) and dry (MNSW <0.6) periods are shown in blue and red, respectively

This is consistent with stream water samples plotting close to the LMWL (Figure 8), suggesting that at the catchment scale, fractionation also had a relatively limited impact. The local meteoric water line lies close to the global meteoric water line. Compared with the clearer distinction of wet and dry samples on the LMWL for the soil plots (Figure 7), there was a larger overlap of wet and dry samples for the stream water samples. For the stream samples, the regression through the data sampled during relatively dry periods was similar to that of the data sampled during relatively wet periods.

DISCUSSION

Temporal and spatial soil water storage and transmission dynamics

Within a typically wet system with limited seasonality in precipitation, the study year was more seasonal with a cold winter followed by a warm and particularly dry summer. This enhanced our ability to assess the potential influence of vegetation on soil–water relations. To some degree, the seasonality was evident at all sites. Both the hydrometric and isotope data showed the clearest

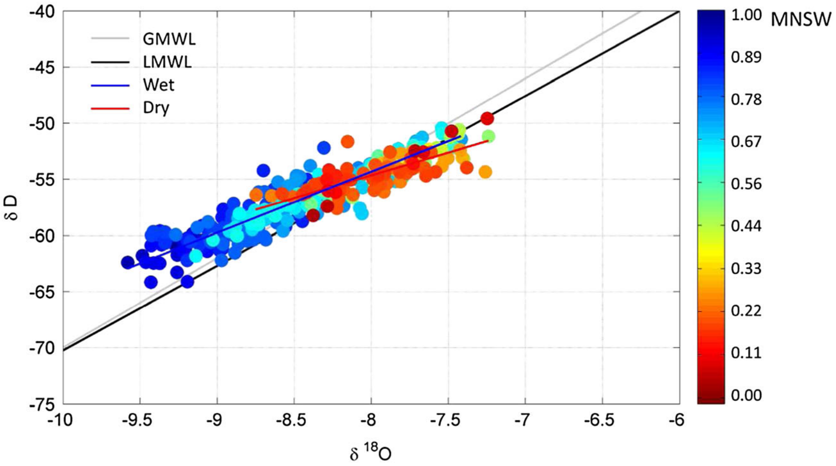
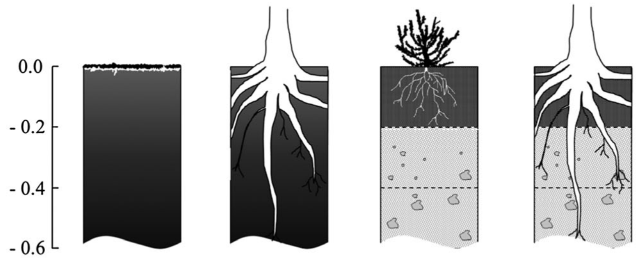


Figure 8. Stream water isotope signatures on the global and local meteoric water lines. The colours represent the Mean Normalized Soil Wetness (MNSW) on the day of sampling. Regressions through data from wet (MNSW >0.6) and dry (MNSW <0.6) periods are shown in blue and red, respectively

difference in soil water dynamics between the poorly draining histosols and freely draining podzols soil types. Figure 9 summarizes the relative total and dynamic storage capacities and provides an indication of soil water residence time in the different profiles, on the basis of the propagation of the soil isotopes with depth and in time in Figure 6. For the histosols where total water storage was large, the dynamic storage changes were particularly small, so that soils were always wet. Consequently, precipitation inputs had a large volume of water to mix with, as demonstrated by the strong damping of the isotope signatures. This is also reflected in relatively long residence times (~2.5 years) that have been estimated by fitting transit time distributions to soil water isotope time series using a gamma function (Tetzlaff *et al*., 2014). Similarly, long residence times have been estimated for histosols in other landscapes with low seasonality in high precipitation inputs (e.g. Crespo *et al*., 2012). In contrast, the dynamic storage changes in the podzols were higher by a factor of around 10, with distinct wetting and drying cycles in winter and significant drying in the summer. The isotope signatures also indicated relatively rapid tracer pulses through these freely draining podzols.

Generally, the differences in soil moisture dynamics were most pronounced during the dry summer. Other variations within soil groups showed the influence of vegetation cover in particular, related to the increased dynamic storage potential in the upper soil horizons under forest cover. The most pronounced soil water differences were observed between the heather (site Ph) and tree cover (site Pf) on the podzols. Although the overall dynamic storage changes were much larger for the forest site, the former showed more rapid water fluxes through the soil profile and quicker responses in the isotope signatures to more depleted rainfall inputs at the end of the observation period. These observa-



Site	Hs	Hf	Ph	Pf
Soil Type	Histosol	Histosol	Podzol	Podzol
Main Vegetation	Sphagnum	Scots Pine	Heather	Scots Pine
Storage Capacity	high	high	low	low
Dynamic Storage Change	17 mm	43 mm	105 mm	221 mm
Residence Time	> 1 yr	> 1 yr	< 6 months	< 6 months

Figure 9. Conceptual graphic showing the four experimental sites, their storage capacities and residence time. Vegetation is not shown according to scale

tions contrast with most other studies where tree roots have been linked to preferred vertical flow paths (e.g. Lange *et al*., 2009; Thompson *et al*., 2010). However, these differences could be attributed to interception and/or more extensive plant water uptake of trees compared with heather during the growing season in the dry summer. As such, the SMD (or storage potential) in the upper soil horizons was much larger under forest cover, thereby slowing down the vertical infiltration of new precipitation inputs during the relatively dry period.

Other explanations for variations between patterns at Ph and Pf could relate to minor differences in soil physical properties alone (e.g. Gazis and Feng, 2004), which may or may not relate to the co-evolution of vegetation cover and soil characteristics, and linked with local differences in topography. Although the different soil–vegetation assemblages represented the main characteristic soil and land cover types of the landscape, we recognize that they do not capture the full extent of natural heterogeneity, for example, from within one of the soil types. Nevertheless, previous work has shown that these are typical for the respective locations of the soil and vegetation distributions and provide an adequate basis for preliminary comparison. There are some subtle variations in topographic characteristics. For example, the slope angle of the forest plot is lower, and there are differences in upslope contributing area and topographical wetness index, indicating that lateral drainage would be less for site Pf. This could explain why during the wet winter months the soils at Pf drained less rapidly than at Ph.

Differences in fractionation between forested and non-forested sites during the dry period may be more directly related to vegetation cover influences. Although small, there is high fractionation resulting from evaporative effects in the soil water under tree cover. This could be explained by a combination of higher surface roughness and interception impacts under forest cover (as shown elsewhere by Ingraham, 1998; Dawson and Simonin, 2012), leading to higher potential for direct soil water evaporation and throughfall of evaporative enriched canopy storage, respectively. While we assume that the water uptake processes by plants does not alter isotope signatures of soil water (Ehrlinger and Dawson, 1992), we might expect that throughfall of interception related enriched water would have been more marked in wetter summers, where evaporation from forest canopies in response to higher amounts of low intensity precipitation inputs would be higher. On the other hand, such wetter summers also have cooler (and cloudier) conditions during which evaporation is more energy limited. Considering these counteracting processes, it seems improbable that much stronger fractionation processes than those observed during the particularly dry and warm summer of the observation period ever occur.

Soil type and forest cover effects on soil water and catchment dynamics

Differences in soil moisture regimes in the soil groups appeared to be greater than the differences between vegetation types within one soil class, suggesting that intrinsic soil hydraulic properties (e.g. the higher water retention capacities of the histosols) exert a stronger control on water storage and transmission dynamics in a wet climate with limited seasonality. These results are consistent with previous findings, where mean transit times in Scottish catchments with mixed land use have been correlated positively with the percentage of freely draining soils (Rodgers *et al*., 2005; Soulsby and Tetzlaff, 2008). Soil type alone has been able to explain up to 80% of the variability in mean transit times across the Scottish Highlands (Hrachowitz *et al*., 2009), probably as soils reflect the integrated effects of climate, topography, parent material and vegetation (as noted generally by Lin, 2010b). For wetter climates with permanently saturated histosols, disentangling the exact role of soil and vegetation properties is difficult, as the vegetation itself is an integral part of the soil. The ability of *Sphagnum* to create its own soil to maintain optimal conditions for its continuation is well known (e.g. Rydin *et al*., 2006). While recognizing these complex interactions of vegetation and soil, overall, the results suggest that in northern headwater catchments, soil type overrides the impact of vegetation (i.e. forested *vs* non-forested) and evapotranspiration on soil water dynamics. This is consistent with the overall energy-limited climate in conjunction with the high storage capacity of the wetter catchment soils, where other processes such as mixing and dispersion prevail (Barnes and Turner, 1998).

Insights into soil water dynamics gained from the different hydropedological–vegetation assemblages also provide better understanding of their role in catchment runoff generation. As expected, higher runoff rates occur when soils are wet, although clear threshold behaviour exists that can be related to soil water dynamics in the drier, freely draining podzols. There are linear input–output relationships when runoff is generated from the permanently wet histosols in the riparian zones. In contrast, nonlinear runoff generation can be related to transient high soil wetness on the hillslopes. As previously shown, such dynamics can be linked to temporary connectivity of the upper podzolic hillslopes to the riparian wetland (Tetzlaff *et al*., 2014). Consistent with these findings, similar threshold behaviour related to increasing connectivity with upper hillslopes has been observed in other headwater catchments (e.g. Sidle *et al.*, 2001; Lehmann *et al.*, 2007; Detty and McGuire, 2010) with different soil types. This highlights the importance of such thresholds in regulating runoff generation dynamics, which has recently been identified and linked to more formal conceptualization of hydrologic connectivity (Lehmann *et al.*, 2007; Spence, 2010; Ali *et al.*, 2013).

The overall strong damping of stream isotopes indicates significant mixing in the poorly draining riparian histosols soils, which signifies a strong connection of the stream with the wetland. As soil and stream data plot close to the GMWL and LMWL, fractionation effects appeared to be limited at the plot and catchment scale. However, the isotope data from the driest period provide some evidence for such evaporative impacts. Typically, stream water is most enriched during higher summer flows. However, as with the soil water in the hydropedological units, stream water is also most enriched during periods where the catchment is relatively dry in terms of soil moisture. Assuming relative groundwater contributions are highest during lowest flows (*cf* Soulsby *et al.*, 2007), such strong evaporative enrichment of stream water during these periods is perhaps initially surprising, as mean groundwater stable isotopes are generally more depleted (approximately δD -61, δ^{18}O -9; Tetzlaff *et al.*, 2014). However, during such dry periods, a proportion of the ground water discharges across the riparian zone and can as such experience ‘open water’ fractionation. In addition, evidence suggests that evaporation within peatlands can be highly spatially variable, and seasonal isotopic enrichment of more permanently shallow water surfaces has been associated with higher isotope fractionating evaporation in northern wetlands (e.g. Birkel *et al.*, 2011b; Levy *et al.*, 2013). These permanently wetter areas are most likely to remain connected with the stream during dry periods, and small increases in flow can be linked with the displacement of the fractionated riparian water. A more extensive dataset (e.g. *cf* Levy *et al.*, 2013) would be needed to provide estimates of the spatial distribution in evaporation throughout the catchment or riparian zones in order to assess such impacts during drier, warmer periods. However, it is noted that compared with the overall storage capacity and water retention properties of these riparian zones, the potential impacts of evaporation on the dynamic storage changes are small, as evidenced by the limited SMD.

Finally, sublimation of snow cover and fractionation processes during melt can also alter isotopic signatures of infiltration (Moser and Stichler, 1980; Cooper, 1998). Such mass-dependent fractionation has previously explained more depleted signatures in the Bruntlan stream during large snowmelt events (Birkel *et al.*, 2011b). The present study year had significant snow cover, which could explain the two unusually depleted values for the north facing site Hf (Figure 6) during the winter period. However, such effects at the catchment scale are not evident. In contrast to the 2008–2009 sampling period (Birkel *et al.*, 2011b), no major shift from the water line was observed for the stream samples during the melt period. However, there was generally less snow, and melt was slower in 2012/2013, which may have resulted in more infiltration rather than direct runoff. As this occurred at a distinctly different time of the year, infiltration of such fractionated melt water could not have obscured fractionation signals related to direct soil water evaporation and evaporative enriched throughfall associated with vegetation cover.

The integration of hydrometric and soil water isotopes data has been invaluable for distinguishing the functional soil water dynamics of the different hydropedological–vegetation assemblages. As both data sets confirmed the overall controls on water storage and flux, a more comprehensive view of these processes could be obtained. Most importantly, the results have shown that such integration of datasets can assist towards translating processes observed at the plot scale to the integrated effect of processes at the catchment scale. This still remains one of the main challenges within catchment hydrology (e.g. Sivapalan, 2003; Tetzlaff *et al.*, 2008). Although the four soil–vegetation assemblages alone do not represent the full spatial heterogeneity within the catchment, they characterize the main functional landscape types. Soil water dynamics within and between the different soil types are consistent with nonlinear threshold behaviour in the runoff response and the mixing and transmission processes reflected in the stream water isotopes.

Management implications of water storage capacities and dynamics

In most places, catchments are becoming increasingly managed, and there is an urgent need for improved understanding of the cumulative impact of human intervention on the quantity and quality of water resources (Montanari *et al.*, 2013; Thompson *et al.*, 2013). Concurrently, there is increasing interest in actively designing land management strategies – typically involving increased forest cover – for flood mitigation (Wheater and Evans, 2009; Parrott *et al.*, 2010), for climate change adaptation (Aldous *et al.*, 2010; Wilby and Keenan, 2012) and to improve or sustain rural livelihoods and other catchment ecosystem services (Bosso *et al.*, 2010; Tetzlaff *et al.*, 2013). For evidencebased decision making, managers need improved understanding of how land use affects soil–water–vegetation linkages through generating storage capacity in catchment soils and encouraging increased flow partitioning along slower, deeper pathways (Asbjornsen *et al.*, 2011; Vivoni, 2012; Thompson *et al.*, 2013).

In the context of the study catchment, the Scottish government is planning large scale afforestation projects (>100 M trees; Scottish Government, 2010) principally to enhance biofuel and timber production. In addition, increased afforestation is being promoted to 'create' storage for flood mitigation (Wheater and Evans, 2009; Aldous *et al.*, 2010; Wilby and Keenan, 2012). The scientific evidence for such potential, although primarily from small scale studies (typically less than 1 km^2) and for up to medium size events only, comes from a long history of studies linking the impacts of deforestation practices to flooding across the world (e.g. Bosch and Hewlett, 1982; Calder, 1990; Andréassian, 2004). However, these have not always been received without some controversy (e.g. Hewlett and Bosch, 1984; Bruijnzeel, 1990; Calder, 2005), and the local impacts of such land use changes are now perceived to depend on a catchment's physical properties, the (antecedent) hydroclimatic conditions and the location of impacts in the landscape (e.g. Bruijnzeel, 2004; Calder, 2005).

For northern environments with wet and low seasonality in precipitation, this study has re-emphasized the importance of soils in regulating water storage and flux dynamics in upland catchments (Soulsby and Tetzlaff, 2008; Hrachowitz *et al.*, 2009; Lin, 2010a; Tetzlaff *et al.*, 2014). For land management strategies in Scotland and other areas with similar landscapes and climates, this suggests that soil type and their integrated control on runoff generation could dominate the effects of past and future changes in vegetation cover on water storage and transmission. The results suggest that the potential augmentation of subsurface storage by tree cover will therefore be spatially distributed throughout the landscape, where efforts are likely to be more effective for podzolic soils, but are also limited to unusually dry conditions. In addition, for catchments similar to the Bruntlan Burn, even with extensive forest cover on the steeper slopes, the impacts at the catchment scale are likely to be modulated by the large storage of water and quick runoff generation in riparian wetlands. In general, this suggests that vegetation management strategies are, for example, unlikely to result in flood reduction, particularly in the largest events. On the other hand, attempting to create such additional storage may come with a potential threat of decreasing water availability for downstream flows and wider ecosystem services especially during drier conditions as seen elsewhere (Chen *et al.*, 2010). It is noted that the exceptionally dry nature of the study year shows an extreme situation that is unlikely to be replicated in wetter summers. Given that the forested podzols have limited dynamic storage in wetter periods, this will limit the effectiveness of vegetation management for mitigating the largest floods during the winter and wetter summers. However, future climate projections for Scotland suggest that prolonged warm, dry periods, such as that experienced during the study period, are likely to become more frequent (Murphy *et al.*, 2009; IPCC, 2013; Capell *et al.*, 2013), leading to longer growing seasons and associated reduction in water availability and potentially increasing the relative importance of vegetation controls on water storage dynamics. Notwithstanding, wider interpretation of the preliminary results presented here needs caution; for a full assessment of the relative impacts of large scale forestry, analyses should include a wider spectrum of evaluations such as effects on the longer-term water balance (e.g. Muñoz-Villers and McDonnell, 2013) or short-term volume and timing of runoff generation (e.g. Kalantari *et al.*, 2014), as well as other factors such as the influence of tree species and catchment characteristics (e.g. Chen *et al.*, 2010).

CONCLUSIONS

The relative influence of soil type and tree cover was examined on water storage and transmission processes in a northern headwater catchment in Scotland, UK. These environments typically have limited seasonality in precipitation. However, the study year showed distinct seasonality, with a particularly warm and dry summer, allowing for a thorough assessment of the potential impacts of vegetation on soil–water interactions. Subsurface soil water dynamics were investigated for different soil–vegetation assemblages that included poorly draining histosols in riparian zones and freely draining podzols on the hillslopes, as well as forested and non-forested sites. Hydrometric and isotope data both showed that for soil water dynamics and their integrated influence on runoff generation, soil type dominates over vegetation impacts. The permanently wet histosols have large storage capacities and showed only small dynamic storage changes, even during the dry summer. In comparison, the dynamic storage changes within the more freely draining podzols were at least one order of magnitude larger. Temporary high soil wetness in the podzols on the hillslopes was associated with nonlinear runoff generation at the catchment scale. Owing to higher evapotranspiration rates, tree cover appeared to temporarily increase the dynamic storage potential in summer, although these differences were generally smaller than those observed between soil types. The results suggest that vegetation management has limited potential for increasing soil moisture storage and moderating large floods in these landscapes.

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