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Baseflow dynamics: Multi-tracer surveys to assess variable groundwater contributions to montane streams under low flows

M. Blumstock [a,*], D. Tetzlaff [a,1], I.A. Malcolm [b], G. Nuetzmann [c], C. Soulsby [a,1]

[a] Northern Rivers Institute, School of Geosciences, University of Aberdeen, AB24 3UF, United Kingdom
[b] Marine Scotland Science, Freshwater Fisheries Laboratory, Faskally, Pitlochry PH16 5LB, United Kingdom
[c] Leibniz Institute of Freshwater Ecology and Inland Fisheries, D-12587 Berlin, Germany

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SUMMARY

We monitored changing groundwater-surface water interactions during a drought with a 10 year return period in a 3.2 km^2 catchment in the Scottish Highlands. The montane catchment is underlain by granite and metasediments and has extensive cover of diverse drift deposits (70%), which are up to 40 m deep. Flat valley bottom areas fringing the stream channel are characterised by deep peat soil (0.5–4 m deep) which covers about 20% of the catchment and receive drainage from upslope areas. The drought resulted in small declines in soil moisture and groundwater levels in the valley bottom wetlands, but marked, rapid declines on steeper upland slopes. These coincided with gradual decreases in discharge; however, the chemical and isotopic composition of reduced stream flows showed both temporal and spatial variation. Synoptic hydrogeochemical surveys were carried out on four occasions as flows declined. Each survey repeated sampling of 26 sites along the 3 km long stream network. Samples were analysed for major anions, cations and water isotopes. Initial surveys just after the last winter rain showed relatively homogenous stream chemistry, consistent with dominant near-surface drainage from acidic riparian peat soils. Stream chemistry became increasingly enriched with weathering-derived solutes (e.g. alkalinity, Ca^{2+}, Mg^{2+}, etc.) as flows declined and groundwater dominance of flow increased. However, these changes showed marked spatial variability implying geochemical differences in the bedrock geology and the distribution of storage in drift deposits. Temporal dynamics inferred heterogeneous montane groundwater bodies contributed to flows differentially during the recession. Isotope data indicated that in places the stream was also influenced by evaporative losses from the surface of the peat soils. The largest sources of groundwater appear to be located in the drift in the lower catchment where the most marked increase in weathering-derived ions occurred, and depleted, non-fractionated isotope signatures implied deeper inflows.

1. Introduction

Groundwater is often the sole source of river water during low flow conditions; an issue that is particularly critical in montane headwaters which sustain downstream water supplies and provide many other ecosystem services (Frisbee et al., 2011; Gleeson et al., 2012; Batlle-Aguilar et al., 2014). The geology in montane areas is usually complex, with a high degree of heterogeneity in bedrock types and fracture distributions. Additionally, in areas affected by glaciation, diverse drift deposits vary in size and aquifer properties. These can affect spatial patterns of groundwater recharge, storage, and contributions to stream flow (Soulsby et al., 2004). Such groundwater stores can also have contrasting temporal dynamics as small patchily distributed aquifers in drift deposits may drain relatively quickly and become disconnected. Thus, the quantity and quality of groundwater contributions to stream flow may be highly variable and these are usually poorly understood. This limited understanding is an increasing cause for concern given that climate change has far reaching implications for many montane areas, including reduced snow influences, higher evaporation and increased seasonality of precipitation (Orr and Carling, 2006; Murphy et al., 2009; Kay et al., 2014). Such factors have the potential to affect groundwater recharge and storage and thus to compromise downstream water use.

Investigation of montane groundwater has many challenges: high levels of heterogeneity in the subsurface are difficult to characterise by borehole installation, which is also expensive and often

* Corresponding author. Tel.: +44 (0)1224 273696.
E-mail address: m.blumstock@abdn.ac.uk (M. Blumstock).
[1] Tel.: +44 (0)1224 273696.

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impractical in high altitude terrain (Gabrielli and McDonnell, 2011). Other more spatially integrative techniques such as the use of geophysics are also logistically problematic in mountains, especially if boreholes are not drilled to "ground truth" interpretations (Parsekian et al., 2015). However, in previous studies environmental tracers have been used as tools for identifying groundwater contributions to stream flow and the dynamics of how these change under different flow conditions (Haria et al., 2013; Liu et al., 2013; Batlle-Aguilar et al., 2014; Bertrand et al., 2013; Shaw et al., 2014). This is an approach that can be particularly useful in complex montane areas where geological heterogeneity would be difficult to characterise directly.

Under low flows, when stream water may be entirely supplied by groundwater reservoirs, it will acquire a chemical composition that reflects the geochemistry of its storage origin (Zimmer et al., 2012). For example alkalinity, which integrates the cumulative effects of weathering, has been used to distinguish between contributions of acidic soil water and more alkaline groundwater in montane streams (Haria and Shand, 2004; Rodgers et al., 2004; Birkel et al., 2011b). Sometimes alkalinity, or some other weathering-derived tracers, can also be used to infer the residence time of water, if mineral dissolution is kinetically controlled (Gonzales et al., 2009). In addition, spatial variation of weathering-derived ions can be used to identify streamflow provenance in larger river systems with heterogeneous hydrogeological environments (Szramek et al., 2011). Thus, synoptic surveys of stream water chemistry can provide unique insights into the geographical sources of groundwater contributing to low flows, and how they integrate at larger spatial scales (Soulsby et al., 2004; Froehlich et al., 2008; Heal, 2008; Zimmer et al., 2012; Inamdar et al., 2013; Wirmvem et al., 2014).

Other chemical species, not primarily derived from mineral weathering, can provide additional insights into the hydrological processes influencing groundwater recharge. Atmospheric aerosols, especially Cl^- which is assumed to be conservative, can indicate the timing of recharge and the effects of evaporation (Vuai and Tokuyama, 2007; Froehlich et al., 2008). For example, in maritime regions the dominant source of recharge may occur in winter when salt-rich precipitation is highest and evaporation rates are low (Hrachowitz et al., 2009). Also, labile species heavily regulated by biogeochemical interactions (e.g., SO_4^{2-}, NO_3^-, DOC, DON) can provide insight into runoff sources from soils and the shallow sub-surface (Weiler and McDonnell, 2006).

The stable isotopes of water (^{18}O and ^{2}H) are also useful tracers of groundwater sources and their influence on stream flows (Darling et al., 2003). These behave conservatively in low-temperature environments, due to negligible interactions between ^{18}O and ^{2}H in organic and geologic materials. The processes dictating ^{18}O and ^{2}H composition are phase changes that affect water above or near the ground surface (evaporation, condensation, melting) as well as simple mixing at or below the ground surface (Leibundgut et al., 2009). Thus, isotopes can be used for estimating groundwater recharge, identification of source areas and resolving water flow paths (Koeniger et al., 2009; Leibundgut et al., 2009).

This paper reports the results of a targeted series of synoptic surveys during a prolonged period (4 months) of low flows with a 10 year return period in the Scottish Highlands. The study was based in the Bruntland Burn, an intensively studied sub-basin of the Girnock experimental catchment. Previous field and modelling work has identified dominant sources of runoff at the catchment-scale and the associated landscape controls on their dynamics and associated transit times (Soulsby et al., 2007; Tetzlaff et al., 2007; Birkel et al., 2011a). More recent work has integrated hydrometric and tracer based studies to examine catchment storage dynamics (Birkel et al., 2011b). Whilst these studies have emphasised the importance of riparian wetlands as the dominant source of runoff (Tetzlaff et al., 2014), groundwater discharge provides both an important source of water to these wetlands (as seepage) throughout most of the year, as well as a direct flux into the channel network to sustain the lowest flows (Birkel et al., 2011a, 2014). Groundwater also provides a large store of water that mixes with conservative isotope tracers to affect the attenuation and lag observed in stream waters compared to precipitation (Tetzlaff et al., 2014; Birkel et al., 2015). Nevertheless, little is known about the heterogeneous nature of groundwater storage at the catchment scale and its influence on the spatial variation in stream water quantity and quality.

The aim of this paper was to use synoptic surveys along the river channel network of the Bruntland Burn to infer the dynamics of groundwater contributions as the catchment transitioned from the end of a wet spring to a dry summer with declining flows. With the surveys we sought to answer the following questions:

(i) Is there spatial variability in base flow hydrochemistry and isotopic signatures which could be used to infer differences in groundwater sources and influence?
(ii) Did spatial patterns change over the course of the drought period in a way that could infer the dynamics of groundwater contributions to base flows?
(iii) Can these spatial and temporal patterns be used to better understand groundwater influence on low flow generation at the catchment scale?

2. Site description

The Bruntland Burn is located in the Cairngorms National Park, NE of Scotland, covering an area of 3.2 km^2 (Fig. 1a). More detailed descriptions of the catchment are given elsewhere (Soulsby et al., 2007; Birkel and Tetzlaff, 2010; Birkel et al., 2011a,b). In brief, the main stem (MS) flows approximately 1.2 km in a NE direction from the confluence of three headwater (HW) tributaries before discharging into the larger Girnock Burn. The headwaters (HW1, 0.64 km^2; HW2, 0.39 km^2; HW3, 0.94 km^2) drain from the upper parts of the catchment. The catchment spans an altitude range of 248–539 m.a.s.l. The highest point is located at the south western edge of the catchment at the head of HW3.

The climate is temperate oceanic, with relatively cool summers and winters. Daily mean air and stream temperatures are 7.4 °C and 6.3 °C, respectively (Hannah et al., 2008). Mean annual rainfall is around 1000 mm, usually with limited seasonality. Half of the rain falls in frequent low intensity events of less than 10 mm; <25% of annual rain falls in events with daily totals greater than 20 mm. Mean annual potential evapotranspiration is about 400 mm (Birkel et al., 2011a) based on a simplified Penman–Monteith equation adjusted to aerodynamic and canopy roughness characteristics of the study region (Dunn and Mackay, 1995). Mean annual discharge is 1.8 mm d^{-1}. High and low flow indices, expressed as Q_5 and Q_{95}, are 5.8 mm d^{-1} and 0.4 mm d^{-1}, respectively (for the period June 2011–January 2014).

Due to the glacial history of the landscape, the catchment is characterised by a flat, wide valley bottom and steep hillslopes. HW2 and 3 are dominated by low permeability schist, though some calcium-rich meta-sediments are also present in HW3 (Fig. 1b, Table 1). In contrast, HW1 and the MS are dominated by low permeability granite. Around 70% of the catchment is covered by glacial drift deposits. Recent geophysical surveys have shown that these are typically ~5 m deep on the steeper hillslopes and up to 40 m deep in the valley bottoms (Birkel et al., 2015). Given the poor aquifer properties of the bedrock and the extensive drift cover, these drifts have been identified as the likely largest sources of groundwater storage (Tetzlaff et al., 2014). They are dominated