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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

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A longer-term perspective on soil moisture, groundwater and stream flow response to the 2018 drought in an experimental catchment in the Scottish Highlands

Chris Soulsby[1] | Bernhard Scheliga[1] | Aaron Neill[1] | Jean-Christophe Comte[1] | Doerthe Tetzlaff[1,2,3]

[1]Northern Rivers Institute, School of Geosciences, University of Aberdeen, Aberdeen, Scotland, UK

[2]IGB, Berlin, Germany

[3]Department of Geography, Humboldt University, Berlin, Germany

Correspondence
Chris Soulsby, Northern Rivers Institute, School of Geosciences, University of Aberdeen, Elphinstone Road, Aberdeen, AB24 3FX, UK.
Email: c.soulsby@abdn.ac.uk

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Abstract

The drought of summer 2018, which affected much of Northern Europe, resulted in low river flows, biodiversity loss and threats to water supplies. In some regions, like the Scottish Highlands, the summer drought followed two consecutive, anomalously dry, winter periods. Here, we examine how the drought, and its antecedent conditions, affected soil moisture, groundwater storage, and low flows in the Bruntland Burn; a sub-catchment of the Girnock Burn long-term observatory in the Scottish Cairngorm Mountains. Fifty years of rainfall-runoff observations and long-term modelling studies in the Girnock provided unique contextualisation of this extreme event in relation to more usual summer storage dynamics. Whilst summer precipitation in 2018 was only 63% of the long-term mean, soil moisture storage across much of the catchment were less than half of their summer average and seasonal groundwater levels were 0.5 m lower than normal. Hydrometric and isotopic observations showed that ~100 mm of river flows during the summer (May-Sept) were sustained almost entirely by groundwater drainage, representing ~30% of evapotranspiration that occurred over the same period. A key reason that the summer drought was so severe was because the preceding two winters were also dry and failed to adequately replenish catchment soil moisture and groundwater stores. As a result, the drought had the biggest catchment storage deficits for over a decade, and likely since 1975–1976. Despite this, recovery was rapid in autumn/winter 2018, with soil and groundwater stores returning to normal winter values, along with stream flows. The study emphasizes how long-term data from experimental sites are key to understanding the non-linear flux-storage interactions in catchments and the "memory effects" that govern the evolution of, and recovery from, droughts. This is invaluable both in terms of (a) giving insights into hydrological behaviours that will become more common water resource management problems in the future under climate change and (b) providing extreme data to challenge hydrological models.

KEYWORDS

drought, Girnock burn, groundwater, long-term experimental catchment, Salmon, soil moisture

1 | INTRODUCTION

Extreme weather outside of previously measured climatic variations is becoming more common in many parts of the world. It is important to understand how these changes force catchment hydrological function and the processes which regulate stream flow generation. Long-term experimental catchment studies have always been essential for recognizing and contextualizing such extremes, and that importance is likely to increase in the future (Tetzlaff et al., 2017). The drought in the summer 2018, which affected much of Northern Europe, resulted in low river flows and threats to water supplies across extensive areas (Kleine et al., 2020). Elsewhere, similar unusually prolonged and extended droughts have set new records for low rainfall and high temperatures (Wanders et al., 2015), and the concurrent increased risk of catastrophic fires is becoming apparent (Turetsky et al., 2015).

Whilst many classic runoff generation studies in catchment hydrology focus on storm events, we have much poorer understanding of how droughts develop and evolve (e.g. Huang et al., 2017). In particular, we need to better understand how the fluxes of "green" water (evaporation and transpiration) during dry and warm hydrometeorological conditions interact with catchment soil moisture and groundwater storage dynamics to affect "blue" water fluxes (to recharge and stream flows) that regulate the runoff generation processes that sustain low flows (Orth & Destouni, 2018). Additionally, there is a need to know how "memory effects"—or the persistent influence of antecedent conditions—affect catchment storage over longer periods preceding droughts and during them (Bales et al., 2018). Often in drought studies, analysis focuses on precipitation and stream flow time-series from national hydrometric networks. However, there is a need to relate these to the catchment context of sensitive soil moisture and groundwater dynamics and other proxies of runoff generation such as tracer dynamics.

The definitions of droughts vary, but relate to extended periods where the effects of below-average rainfall (meteorological drought) become apparent and propagate through hydrological systems (Huang et al., 2017). Droughts can extend over short periods of weeks-months, but usually have more serious implications when they extend across seasons or even years. The Highlands of Scotland are not a region where extended droughts have historically been a matter of major concern (Spinoni et al., 2018). The country's latitude and proximity to the North Atlantic are associated with a predominance of maritime westerly weather systems and frontal rain, with prolonged periods of dry stable atmospheric conditions being relatively uncommon (Burt and Howden, 2013). Moreover, rainfall is generally high, and energy limited conditions and frequent high humidity supress atmospheric moisture demand and evapotranspiration. That said, short-term monthly or seasonal negative rainfall anomalies can occur throughout the year, but usually positive anomalies soon follow and replenish moisture deficits (Wang et al., 2017). Despite the generally wet conditions characterizing the Scottish hydroclimate, it has been shown that slower changes in mesoscale atmospheric circulation and teleconnections with Atlantic storm tracks generally lead to clustering of "wetter" and "drier" years (Werritty & Sugden, 2012). Over the past 50 years, these drier periods have tended to occur at roughly decadal intervals. Under such drier conditions, usual seasonal drawdown of soil moisture and groundwater levels may not be rapidly replenished by late summer/autumn rains. However, rarely are such deficits carried into the following year, unless low summer precipitation is followed by a drier-than-average winter (Soulsby, Birkel, & Tetzlaff, 2016). Even then, deficits are fully replenished by the start of the following spring at the latest (Soulsby et al., 2015). However, recent years leading up to the 2018 drought in the Scottish Highlands resulted in an unusual sequencing of two drier than average winters and two very dry summers, with associated low river flows (Fennell et al., 2020). Climate change projections suggest such changes in seasonal rainfall patterns are likely to be more common in future, with greater distribution of rainfall towards winters and higher summer temperatures (Capell et al., 2014). Additionally, land management pressures in upland areas are changing, with policy drivers creating trends towards increased forest cover which may also increase water use from increased interception evaporation and transpiration (Geris et al., 2015; Haria & Price, 2000; Soulsby, Braun, et al., 2017).

Consequently, as these environmental and climate changes occur over protracted periods, long-term experimental catchments provide important repositories of information sources and data to examine how droughts affect moisture storage and fluxes and better understand and predict the likely effects of future change (Tetzlaff et al., 2017). Here, we use long-term hydrometric data from the Girnock Burn observatory in the Scottish Highlands to examine the 2018 drought in terms of the depletion of soil moisture and groundwater stores within the Bruntland Burn sub-catchment. This is supplemented with use of stable isotopes to understand how catchment function changes as the catchment transits between wet and dry conditions. We also estimate the storage changes in relation to output fluxes and contextualize the 2018 drought in the longer term perspective of rainfall variability over the past 50 years. This addresses three research questions.

1. To what extent are extreme droughts identifiable by extreme soil moisture and groundwater anomalies and do these vary spatially?
2. Are isotopes of value in drought studies in terms of identifying changing hydrological pathways?
3. What are the future implications of such droughts and how can catchment monitoring evolve to better understand them?

The latter question is particularly important in the context of the Girnock Burn, as the catchment is an important long-term fisheries monitoring site, particularly for Atlantic salmon (*Salmo salar*) (Glover et al., 2020). In Scottish rivers, Atlantic salmon is a key biodiversity component which is also economically important as a sports fishing resource. It is also a cold water species that is sensitive to various aspects of river flow and stream temperature and hence future droughts (Glover et al., 2020). Hence, an evidence base to guide conservation management and mitigation measures is urgently required.

2 | STUDY SITE

The Bruntland Burn (BB) (Figure 1) is a small 3.2 km^2 montane headwater catchment in the Cairngorms National Park in NE Scotland, UK. It is a sub-catchment of the 31 km^2 Girnock Burn, which is a tributary of the larger ~2108 km^2 River Dee catchment. The Dee is the main drinking water supply for 300 000 people and is economically critical for Atlantic salmon (*Salmo salar*) fishing (Tetzlaff et al., 2008). The predominant climate can be described as transitional between northern temperate and boreal, but with a maritime influence that leads to generally cool, wet summers and mild, wet winters with an annual average temperate of 6°C. Average daily temperatures during summer and winter season are 12 and 1°C, respectively. Half of the ~1000 mm annual precipitation (P) falls during frequent, low-intensity events of <10 mm day^{-1}. There is no major distinct seasonality in the distribution of precipitation events, with heavy rain possible all year round, though winter is usually wetter. The annual potential evapotranspiration (ET) and run-off (R) are around 400 and 700 mm, respectively (Birkel, Soulsby et al., 2011). Between May and August, ET is usually the dominant water flux out of the catchment (Kuppel et al., 2020). During drier conditions, direct groundwater (GW) inflows to the stream sustain baseflow (Ala-Aho et al., 2017). GW contributions account for ~30–40% of the annual discharge, with the remainder coming from storm runoff (Birkel, Soulsby et al., 2011; Birkel, Tetzlaff et al. 2011).

The topography of the catchment is marked by its glacial origin (Figure 1a). Steep hillslopes up to 61° encompass a wide and flat valley bottom which covers around 20% of the catchment. Mean gradient for the catchment is 14°; and its elevation ranges from 238 to 539 m above sea level (a.s.l.). Granite dominates the underlying bedrock, fringed by Si-rich and Ca-rich meta-sediments (Figure 1b). The solid bedrock is overlain by an extensive low-permeable glacial drift deposit which covers up to 70% of the catchment area (Soulsby et al., 2007). This drift deposit is up to 40 m deep in the valley bottom, in contrast to the steeper hillslope, where shallower (<5 m) more lateral moraines and ice marginal deposits prevail (Soulsby, Bradford, et al., 2016). These deposits have been identified as the main GW source in the catchment (Scheliga et al., 2017).

The local vegetation is typical for the Scottish Highlands: the vegetation on the hillslopes and drier areas is predominantly 30–50 cm high heather shrubs (*Calluna vulgaris*), while the wetter areas and riparian zone are covered with *Sphagnum spp*. mosses and grass (*Molinia caerulea*). Just 11% of the catchment is covered by Scots Pine (*Pinus sylvestris*) forest to be found mostly on steeper hillslopes (Wang et al., 2017). Freely draining peaty podzols prevail on the upper and steeper hillslopes where heather dominates (Tetzlaff et al., 2014).

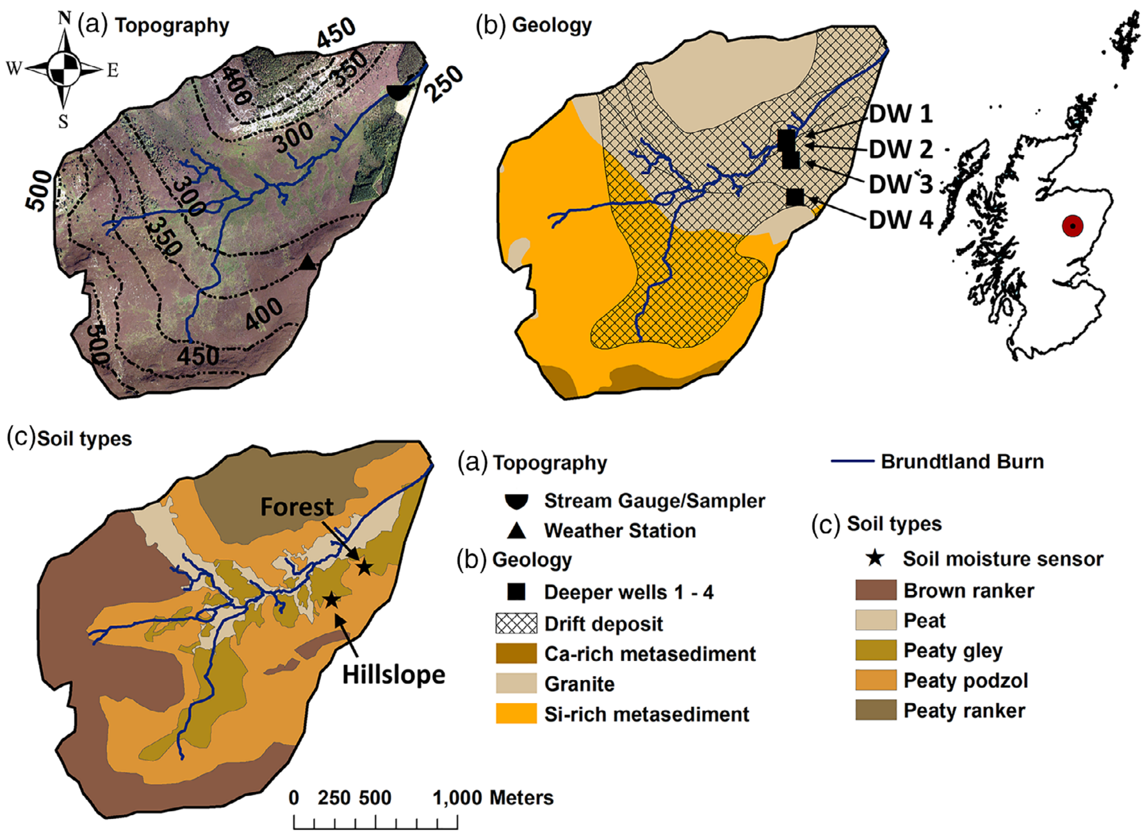

FIGURE 1 The Bruntland burn catchment in the NE of Scotland; (a) topography with the location of the automatic weather station, stream gauge and water sampler (which is also where precipitation is sampled for isotopes); (b) geology of the study site with extent of the drift deposit including the locations of the deeper wells 1–4; (c) soil types distribution with location of the soil moisture sensor in the forest and on the upper hillslope

Here, the GW table is often >1 m below the soil surface (Blumstock et al., 2016; Scheliga et al., 2018). The catchment interfluves and steeper hillslopes have been identified as the main areas for GW recharge. On the lower hillslopes and valley bottom, peats and peaty gley soils characterize the subsurface with shallower GW tables close (<0.3 m) to the ground surface (Blumstock et al., 2016). These wet conditions are sustained by subsidy from groundwater discharge on the lower slopes and the saturated peaty soils generate overland flow in storm events.

The response of the volumetric soil moisture content (VSMC) in the upper hillslope has been shown to have a more distinct drying and rewetting pattern between storm events compared to very conservative responses in the quasi-permanently saturated riparian zone and lower hillslopes (Tetzlaff et al., 2014). The hillslopes can contribute rapid storm run-off once they become hydrologically connected to the stream network, via the wetlands, during prolonged storm events (Soulsby et al., 2015). However, it has been shown that during summer, in particular, soils under forest are substantially drier than those under heather (Geris et al., 2015) due to higher interception and transpiration losses (Kuppel et al., 2020).

3 | DATA AND METHODS

This study focussed mainly on the evolution of the 2018 drought, which has been the driest prolonged period since detailed hydrometeorological monitoring started in the Girnock Burn in 2001 (Table 1). The hydrometric and isotopic data has been collected in the Bruntland Burn sub-catchment since 2011. Additionally, rainfall in 2018 was compared to the most recent 50 years from a local yearlong precipitation record which started at Balmoral Castle in 1918 and is available on the Centre of Environmental Data Analysis (CEDA) webpage. This site is around 5 km west of the catchment itself and at an altitude of around 300 m, similar to the catchment outlet.

Hydro-meteorological monitoring in the catchment includes precipitation from a mountain automatic weather station (AWS), stream flow at the catchment outlet, volumetric soil moisture at two long-term stations (one under heather, one forest) and deeper groundwater levels in four permanent wells in contrasting landscape positions (Figure 1). In addition, the site benefits from daily sampling of isotopic signatures in precipitation and stream at the catchment outlet (Figure 1).

The stream stage height was monitored at the catchment outlet with an Odyssey capacitance probe (resolution of 0.8 mm) (Figure 1a). Regular discharge measurement of the outlet cross-section ensured an up to date stage-discharge rating curve to estimate the stream discharge. The volumetric soil moisture content (VSMC) was monitored with Campbell time-domain reflectometery (TDR) probes connected to a CR800 Campbell logger at 10, 30 and 50 cm depth. Both soil moisture sites, Forest and Upper Hillslope (Figure 1c), are in peaty podzols. The site Forest is located in a 30 year old Scots pine plantations in a lower slope area. Each VSMC monitoring site has a duplicate set TDR probes 2 m away from the first set of probes. The deep groundwater wells (DW) were installed along a representative hillslope transect following more spatially extensive sampling with shallower wells (Blumstock et al., 2016) (Figure 1b). All DW were drilled to reach into the drift deposits and are screened in the lower 30 cm (Table 2). For more details on the construction and installation of the DW see Scheliga et al. (2018). The GW levels were monitored with micro-divers which measure the pressure of the water column above itself. The measurements were compensated for atmospheric pressure before deriving the height of the water column using a barodiver near the catchment outlet. The respective ground surface at each DW site was used as height reference point. The recorded GW levels were regularly (every 2 months) verified using manual dip meter measurements.

Daily samples of precipitation and stream water were collected with ISCO 3700 auto-samplers located near the outlet and later

TABLE 1 General precipitation statistics for 2018 and long-term average

Season	Month	2018	Mean $_{\text{long-term}}$ (mm)	Percent of mean $_{\text{long-term}}$ (%)
Spring	Mar–May	149.4	172.5	87
Summer	June–Aug	119.2	188.3	63
Fall	Sep–Nov	329.2	245.3	134
Winter	Dec[a]–Feb	167.8	230.2	73

[a]December is from the same year.

TABLE 2 Characteristic of the deeper groundwater wells and soil moisture stations in the Bruntland burn catchment, NE Scotland

ID	Elevation (m a.s.l.)	Depth of sensor (cm)	Soil type
DW 1	254	330	Peat
DW 2	254	264	Peat
DW 3	259	160	Peaty gley
DW 4	284	187	Peaty podzol
Forest site	261	10/30/50	Peaty podzol
Upper hillslope site	284	10/30/50	Peaty podzol

analysed in the laboratory for their isotopic composition. A layer of paraffin oil was applied to the autosampler bottles before sampling to prevent evaporation fractionation of the collected water samples. Samples were extracted with a syringe from below the paraffin and filtered (0.2 μm, cellulose acetate) then stored at 8 °C in the laboratory.

To complement the routine monitoring of isotopes in precipitation and stream flow, synoptic sampling of stream water along the channel and the three headwaters was conducted under contrasting flow and wetness conditions. During a summer campaign (1st August 2018), sampling was undertaken under very dry conditions and the daily discharge was 0.86 mm day^{-1}. During wet conditions in late-autumn (28th Nov. 2018), the daily discharge was 7.15 mm day^{-1}. All samples were collected in 250 ml PVC bottles, completely filling the bottle with no head space. The collected samples were stored in a refrigerator in the laboratory until their isotopic composition—namely, deuterium(δ^2H) and 18-oxygen (δ^{18}O)—and Gran alkalinity were analysed. Gran alkalinity can be used in UK uplands to distinguish hydrological sources, as it closely approximates the conservative acid-neutralizing capacity of sampled water (Neal, 2001). The alkalinity was determined on the spatial samples using a three-point acidimetric Gran titration to end points pH 4.5, 4.0, and 3.0 following the guidelines provided by Neal et al. (1997).

The results of the isotopic analysis are reported in the δ-notation (in ‰) which is the abundance ratio of heavy to light isotopes in the sample relative to the Vienna Standard Mean Ocean Water (VSMOW). A Los Gatos TIWA-45-EP Laser Spectrometer (precision of ±0.3‰ for δ^2H; ±0.1‰ for δ^{18}O) was used to analyse the isotopic composition. During the analysis, a standard was analysed for every three water samples. The Los Gatos Post Analysis Software did not detect organic contaminations in the water samples.

The relationship between δ^{18}O and δ^2H in the isotope signal of the global precipitation forms the global meteoric water line (GMWL) (Dansgaard, 1964).The local precipitation can deviate from the GMWL (Scheliga et al., 2017) and forms the local meteoric water line (LMWL) (Equation 1):

$$\delta^2 H = 7.6‰\, x\, \delta^{18} O + 4.9‰. \quad (1)$$

We further calculated the line-conditioned excess (short lc-excess) defined by Landwehr and Coplen (2006) which defines the unconformity with the local meteoric water line (LMWL) as

$$\text{lc} - \text{excess} = \delta^2 H - a‰\, x\, \delta^{18} O - b, \quad (2)$$

where a is the slope and b the intercept of the local amount weighted precipitation (a = 7.6‰; b = 4.9‰).

The Standardized Precipitation Index (SPI) is a simple and temporally flexible drought index which was developed for drought detection and monitoring, it solely relies on precipitation data as input (Hayes et al., 1999). However, a long-term data time-series is required (>30 years) and is fitted to a probability distribution. This is then transformed into a normal distribution so that the median SPI for a particular site and period is zero. In other words, half of the previous precipitation amounts are below the median and half above. Positive SPI values are indicative of periods greater than the median precipitation (i.e. wet conditions), and negative values are less (i.e. dry conditions). A dry period anomaly is considered to occur when the SPI value is ≤ −1 and continues until SPI becomes positive (Tigkas et al., 2015). Table 3 shows the drought conditions according to the SPI. The SPI was calculated for each month (for short-term anomalies) and quarterly (for longer-term) during each hydrological year (Oct–Sep) using the Drought Indices Calculator (DRINC; Tigkas et al., 2015). Additionally, a 6-month running mean for the monthly and quarterly SPI values was calculated to reduce the noise from extreme values.

4 | RESULTS

4.1 | Long-term perspective from standard precipitation index

To set the catchment response to the 2018 drought in context, the SPIs over the last 50 years were analysed. These were plotted as monthly and quarterly (3 month) anomalies (Figure 2a,c), which were then both averaged with 6 month smoothing windows (Figure 2b,d). The monthly plots highlight the hydroclimatic variability in Scotland with individual months alternating between significantly above and below average rainfall. However, when smoothed over 6 months, the longevity and clustering of wetter and drier periods as well as the -longer-term context of the 2018 drought became apparent.

In terms of droughts, the mid-1970s corresponded to severe drought periods across the whole of the UK, particularly through 1975–1976. Less severe and shorter droughts periods occurred in the mid-1980s and mid-1990s, prior to a major drought that affected much of Europe in 2003. What is notable about the 2018 drought are the antecedent conditions in the preceding years, especially 2016–2017, but also throughout most of 2016, following a very wet January at the start of the year. Although severely dry conditions have not been persistent, and individual months have had positive anomalies, most months have had negative anomalies. The longevity of the dry conditions was particularly apparent in the smoothed quarterly data. This analysis provides a longer-term context for understanding the internal catchment dynamics over the past few years since the start of 2016.

TABLE 3 Drought conditions corresponding to the standardized precipitation index (SPI)

SPI values	Drought condition
≥2.0	Extremely wet
1.5–1.99	Very wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.0 to −1.49	Moderately dry
−1.5 to −1.99	Very dry
≤ −2.0	Extremely dry

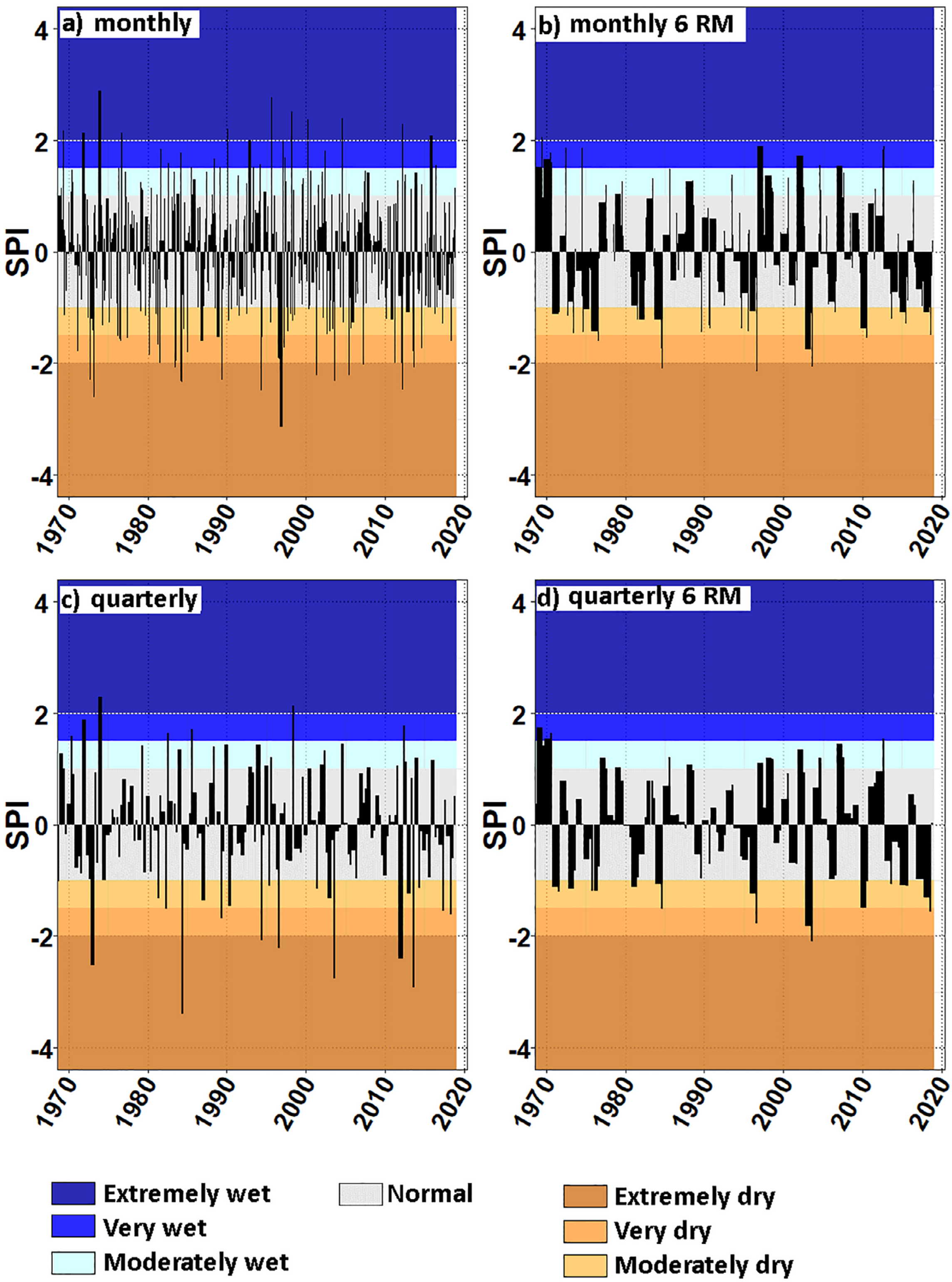

FIGURE 2 The standardized precipitation index (SPI) for (a) monthly precipitation totals, (b) 6 month running mean of the monthly precipitation, (c) quarterly (Oct–Dec, Jan–Mar, Apr–Jun, Jul–Sep) precipitation totals, and (d) running mean over two quarterly precipitation totals

4.2 | Rainfall and discharge dynamics

The year-round distribution of rainfall in the Scottish Highlands dictates that prolonged dry spells of no rainfall for a few weeks are extremely rare, even during the drought of 2017–2018 (Figure 3). Most rainfall events are small, with 50% of annual precipitation occurring on days of <10 mm; there are typically ~230 rain days per year. Even in the longer-term record, days with rainfall exceeding 25 mm are rare, typically 3–4 times per year

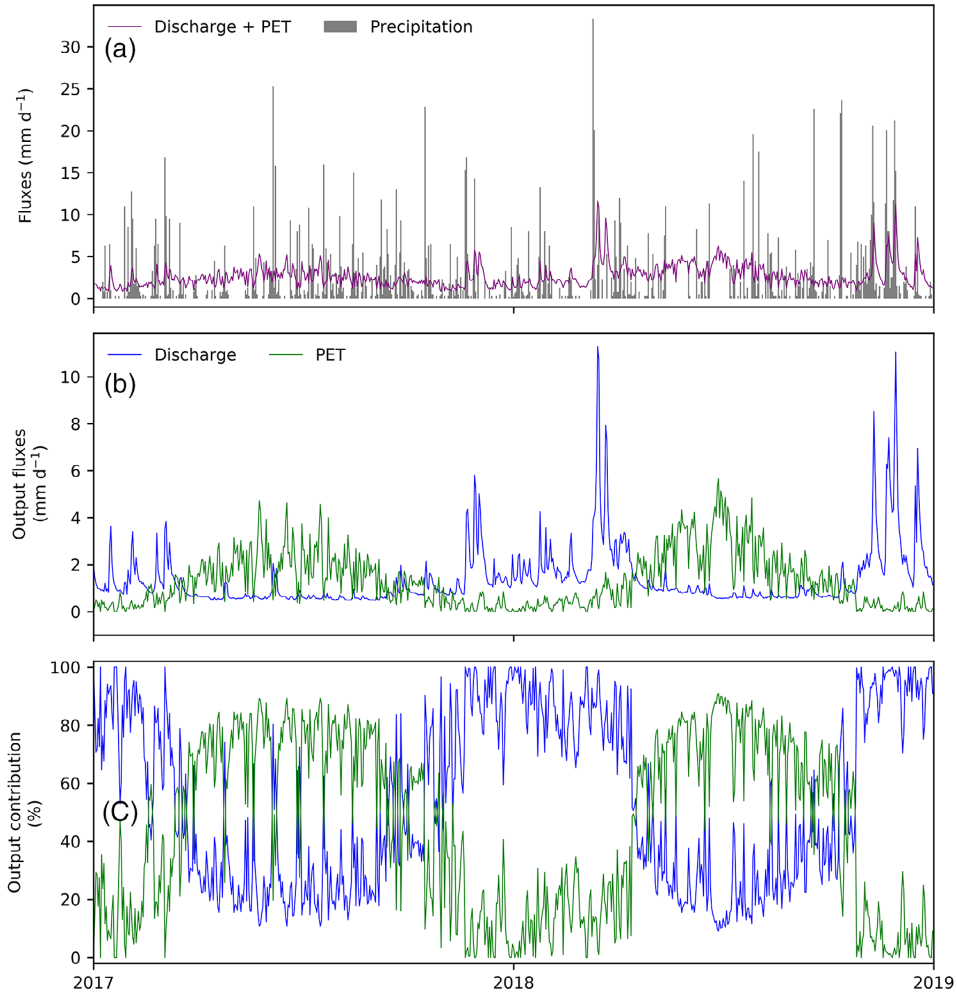

FIGURE 3 Hydrological fluxes in the Bruntland burn 2017–2018: (a) precipitation inputs and outputs, (b) zoomed in discharge and potential evapotranspiration as daily fluxes (middle panel), (c) discharge and potential evapotranspiration as a daily percentage outputs (lower panel)

and usually cluster in wetter periods of frontal weather such as in the winters of 2013/2014 and 2015/2016 (Figure 4a). However, 2017 and 2018 were notable for a lack of such high rainfall events, even in the winter, despite the overall number of rain days remaining high (Figure 3).

Streamflow in the catchment is closely coupled to rainfall; with even small (<5 mm) rainfall events usually initiating a runoff response from the valley bottom wetlands (Figures 3 and 4). Streamflow is generally seasonal and is usually highest in winter, though this more reflects the effects of higher ET and greater soil water storage availability in summer—before reaching field capacity (Kuppel et al., 2020). Figure 3 shows this for 2017 and 2018, where ET was the dominant flux out of the catchment in the summer. However, summers can have high flows such as in 2011 and 2012 (Figure 4a). But in the period of record, the winters of 2016/2017 and 2017/2018 were notable for relatively low flows in response to rainfall inputs. Even the highest flows were only modest compared to the longer term record.

4.3 | Soil moisture and groundwater levels

The two long-term soil moisture sites showed quite different storage regimes due to different landscape positions and landcover (Figure 4b,c). On the Upper Hillslope under heather, soil moisture variability was much more dynamic than under forest, largely as a result of higher net precipitation in the absence of a forest canopy. Forest A is in a lower slope position and the subsoil is wetter in winter and drier in summer as a result of seasonal variations in the watertable, which are driven by upslope subsidies in winter recharge.

Generally, fluctuations in the Upper Hillslope ranged between 25 and 45% in the organic surface horizon (10 cm), and 25 and 40% in the mineral subsoil (30 and 50 cm). This followed a distinct seasonal pattern with a summer minimum and winter maximum, though the soil moisture was dynamic in response to rainfall events in summer. The low soil moisture content in the summer of 2018 in response to low rainfall and high evapotranspiration was a clear outlier in the 2011–2018 time-series. In the summer of 2018, all three horizons dropped to ~15% soil moisture content following some re-wetting in the winter 2017/2018. Summer precipitation only had a small effect in replenishing deficits, and rewetting did not occur until late autumn/early winter.

At the Forest site, previous soil moisture variations since 2012 have been more distinctly seasonal and more marked compared to the Upper Hillslope (Figure 4c). The forested nature of the site greatly reduced effective rainfall in the summer due to higher interception

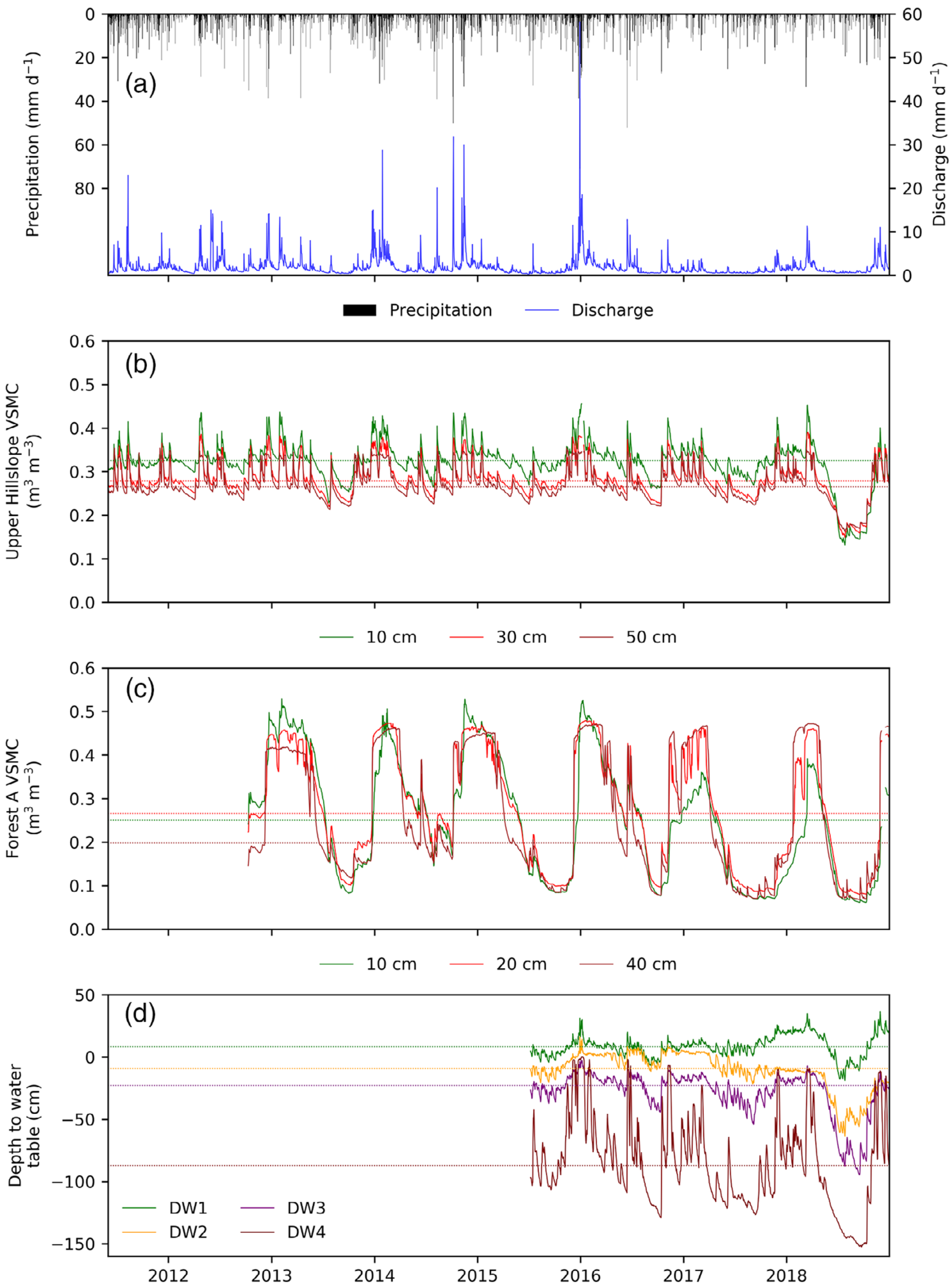

FIGURE 4 (a) Daily precipitation and discharge; volumetric soil moisture content on (b) the upper hillslope and (c) the forest site; (d) groundwater tables in the deeper wells along the hillslope transect. Horizontal lines show median values for each sensor

and transpiration losses, and the position in a lower slope area results in a distinct, seasonal groundwater influence in the subsoil during the winter. Consequently, although the soil moisture levels in the summer of 2018 were the lowest recorded, they were only marginally lower than in previous years. However, the prolonged nature of the summer drying in 2017 which also delayed and reduced the degree and longevity of re-wetting in late winter 2017/2018 was apparent. This also coincided with drier than usual conditions in the winters of 2016/2017 and 2017/2018.

The dramatic effect of the summer 2018 drought was also apparent in the monitored groundwater levels (Figure 4d). On the upper hillslope (DW4), groundwater levels usually fluctuated between 1.2 m below the ground surface in winter, to within 0.2 m in the wettest period. However, in 2018, the minimum level dropped by a further 0.5–1.5 m below the surface. Similarly, on the lower valley slopes, all wells exhibited anomalously low water levels. DW1, which is usually artesian (as it is on the north side of the stream and has direct connectivity with a short steep scree slope above it) had a water level 15 cm below the surface. Similarly, DW2 and DW3, which are south of the stream, were about 40 cm lower than previous summer levels. This is unusual, as previous soil moisture and shallow groundwater monitoring showed that the valley bottom peaty soils usually remain very close to saturation in summer with water tables very close to the surface (Tetzlaff et al., 2014). Although the groundwater wells showed a transient period of high levels in the late winter of 2017/2018, apart from the artesian DW1, winter levels in the other boreholes were lower throughout this winter compared to previous ones, consistent with lower recharge.

4.4 | Cumulative outflows and storage changes

The cumulative discharge fluxes were assessed over seven hydrological years and plotted against the cumulative precipitation for the catchment (Figure 5). The low precipitation of the 2017–2018 year was evident, though clearly 2016–2017 was also a dry year. It is striking that the winters of 2016/2017 and 2017/2018 lacked high precipitation and runoff events, though the impacts on stream flow were more dramatic in the reduction in 2017–2018 (Figure 5a). The high precipitation year of 2015–2016 also stood out in the time-series, largely reflecting the impact of Storm Frank at the end of 2015, which locally led to the highest stream flows since 1829.

Given the usual, year-round high frequency of precipitation events, long periods where storage in the catchment is drawing down to sustain stream flow are uncommon. The drier summers of 2013, 2015, 2017 and 2018 stand out in this regard, where precipitation inputs were lower. Lack of precipitation in these periods pushed the catchment into periods of overdraft where for lengthy periods, stream flow and evapotranspiration fluxes out of the catchment exceeded precipitation inputs. This is evident in the daily storage changes over each water year estimated from the water balance (P-PET-Q), though it should be noted that these are qualitative assessments in the sense that PET is an overestimate of actual ET in drier summers. The large storage deficits for 2018 became clear, and much greater than for 2017, as there was more summer rainfall in 2017. The low positive winter storage over 2017/2018 is also clear, emphasizing the late, brief and less marked re-wetting of soils and groundwater that winter (Figure 4).

The effects of this drawdown on the catchment were evident from phase space plots for the soil moisture sensors on the upper hillslope (Figure 6). Note the forest site is not shown, and the influence of forest vegetation and low elevation landscape position (see above) resulted in limited inter-annual variability in storage. The hillslope plot shows the normalized variation of moisture content of each horizon on the x-axis, and the daily rate of change of soil moisture content on the y axis; this is positive when the soils were re-wetting and negative when drying (cf. Maneta et al., 2018). The anomalous slow, prolonged soil moisture depletion across the profile for the spring and summer of 2018 was evident, with only 2012–2013 showing similar substantial deviations from the more predictable conditions in the other years. These plots typically show wettest conditions in the winter, and most rapid replenishment (+ve changes) in the late-summer to winter period, with drawdown starting in spring and continuing in the summer, despite occasional re-wetting.

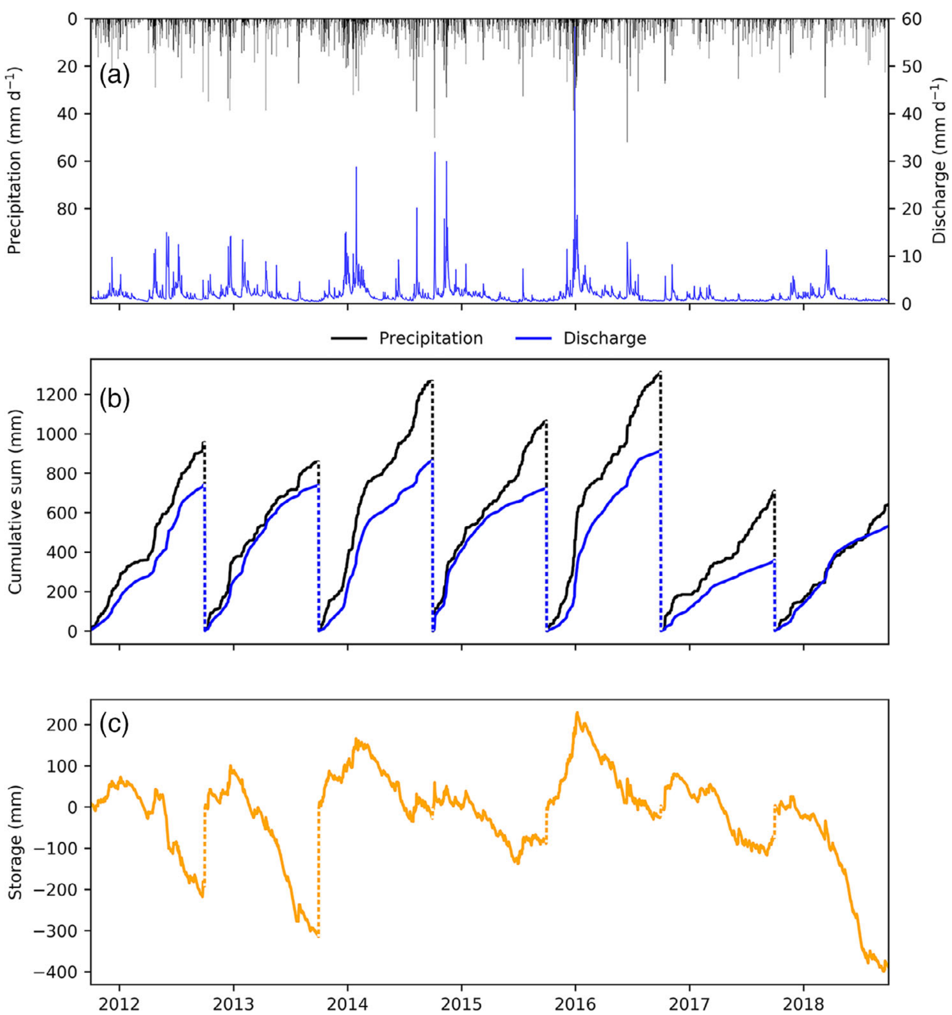

FIGURE 5 (a) Daily precipitation and discharge; (b) cumulative sum of the daily precipitation and discharge for each hydrological year (Oct–Sep) and (c) storage (at each timestep calculated as $S(t) = S(t - 1) + P(t) - Q(t) - PET(t)$, with S reset to 0 at the start of each water year)

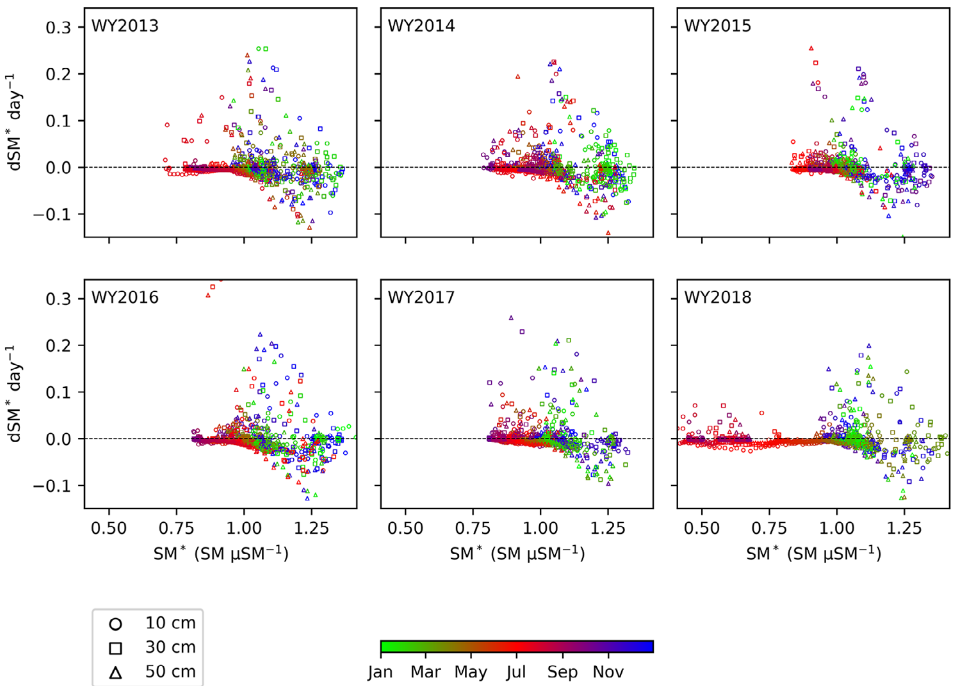

FIGURE 6 Phase-space plots of soil moisture at the upper hillslope monitoring site for each monitoring year. The plots show normalized soil moisture variations (x axis) through months (colour coded) against daily changes in soil moisture (y-axis) as soil moisture increases (+ve values) or decreases (−ve values)

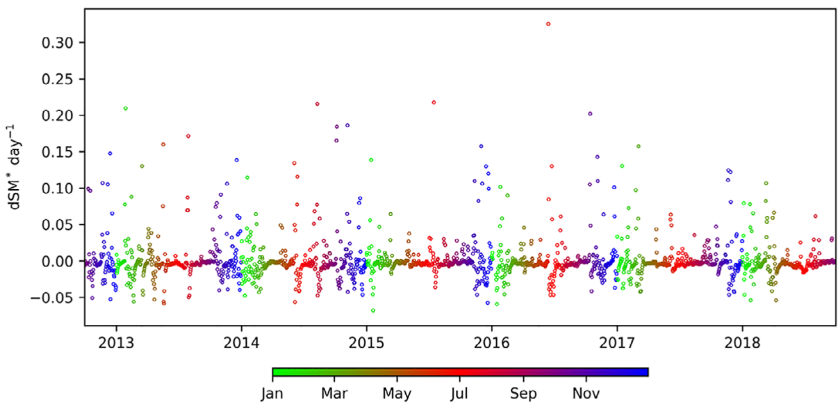

FIGURE 7 Time-series plots of soil moisture dynamics at the upper hillslope monitoring site show daily changes in soil moisture (y-axis) as moisture content increases (+ve values) or decreases (−ve values)

It is also notable that the evapotranspiration was high, but drainage was very slow in the summer of 2018. The early soil water drainage, together with groundwater depletion roughly match the cumulative outflow of discharge (Figure 5).

The dynamics of soil moisture change are plotted as a time-series for the whole soil profile in Figure 7. This again highlights the general seasonality of soil moisture dynamics, but shows that some of the highest rates of replenishment came in large summer storm events, such as in 2013, 2014, 2015 and 2016. However, this was not evident in 2017 or 2018, though the autumn re-wetting in 2018 was very clear.

Previous work during the 2013 drought in the catchment showed that soil moisture deficits at the upper hillslope site were around 100 mm, whilst under the forest site they reached 200 mm (Geris et al., 2015). In 2018, the latter remained similar, but even under heather, the soil moisture data indicated that deficits were close to 200 mm (Figure 4). Further, the additional groundwater drawdown at the wells, if extrapolated to the catchment scale (making assumptions based on measured characteristics of depths and porosities of the different soils and drifts), indicated up to 100 mm of groundwater depletion over the summer of 2018. This more or less matches the cumulative discharge over the summer (Figure 5), again confirming the sole groundwater sources of stream flow.

4.5 | Stable water isotope and alkalinity dynamics

Stable isotopes complemented the hydrometric data by providing useful insights into how the drought affects water flows paths (Figure 8). Daily isotope dynamics in rainfall showed marked variation over the 2 years of 2017 and 2018 (Figure 8b). Seasonal patterns were evident being more enriched in heavier isotopes in summer and more depleted in winter, though day-to-day variability was marked throughout the year. This variability was much more damped in stream flow, though the seasonality was still apparent, and small shifts of the stream isotopic composition in the direction of rainfall occurred

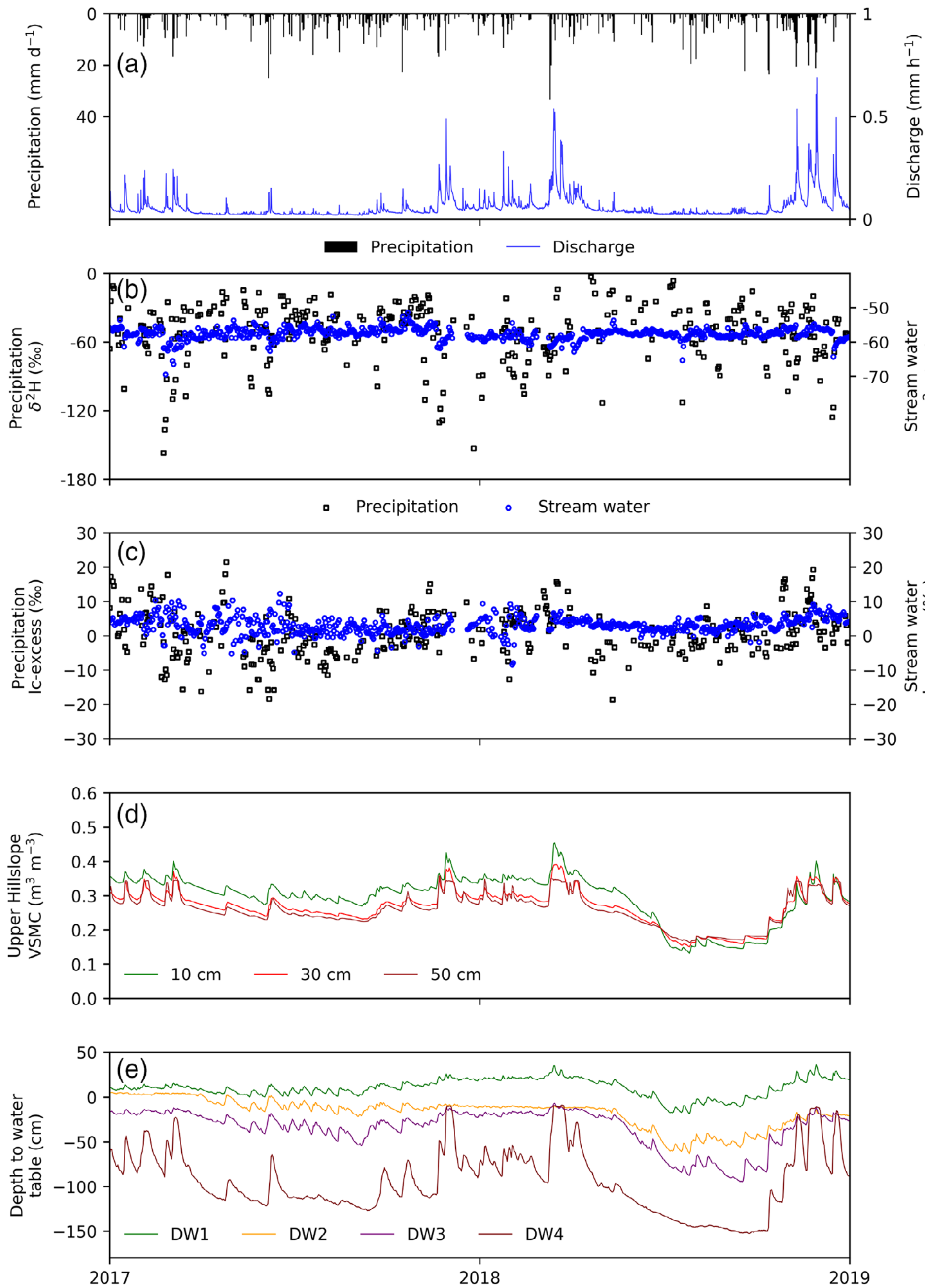

FIGURE 8 (a) Daily precipitation and discharge; (b) deuterium signal of the precipitation and stream; (c) lcexcess signal of the precipitation and stream; (d) volumetric soil moisture content at the upper hillslope site; (e) groundwater table in the deeper wells along the hillslope transect

during larger events. These were usually winter events where the stream became more depleted. Previous work has shown that this damping is explained by the large storage of water in the valley bottom wetlands that is largely displaced by incoming rainfall. The smaller scale event-based variations were associated with increasing breakthrough of new water in rapid runoff responses when the soil moisture and groundwater levels were highest (Figure 8d,e). The isotopic composition of base flow was fairly constant, with δ^2H values around −58 to −59‰, which is close to the composition of groundwater in the valley bottom (Scheliga et al., 2017).

The lc-excess in precipitation was generally positive especially in winter, with some negative values in usually small summer events (Figure 8c). Stream water values were generally positive, reflecting the predominance of unfractionated runoff sources. Lower (slightly negative) stream water values were occasionally evident in the summer of each year, when evaporative fractionation in valley bottom peatlands occurs, though more so in 2017 than 2018. These lower lc-excess values corresponded to periods where the catchment was drying out through evaporative losses, and fractionation of water draining through interconnected pools on the surface of the valley bottom wetlands affects the stream (Sprenger et al., 2016). The less frequent occurrence of negative lc-excess values in the drier summer of 2018 was consistent with any surface water fractionation being disconnected from drainage to the stream network due to the drier soils and lower groundwater levels (Figure 8d,e).

For better spatial assessment of isotope patterns and the influence of groundwater inflows under drought conditions, two synoptic surveys were undertaken (in August and November 2018) along the main stem of the BB downstream of the confluences of its three main headwater tributaries (Figure 9). During the dry August sampling, the headwaters showed small differences in δ^2H, with HW1 and HW3 being similar, but HW2 being depleted by almost 3‰ in comparison (Figure 9a). At the sample point immediately downstream of the confluence of HW3 (BB17), the stream isotope signal showed a ~ 1‰ increase moving towards that of HW3, which is the largest headwater catchment. However, by BB16, δ^2H signaturesfell by ~2‰. They then increased slightly between B15-B13 before falling to that of B16, and remained constant until B4 where after they increased by ~1‰ at the catchment outlet. The lc-excess remained positive, with only B17 falling to zero (Figure 9b). Interestingly, the Gran alkalinities (Figure 9c) were high and showed a general increase downstream of the HW1 confluence. This overall pattern is consistent with depleted groundwater inflows in the valley bottom sustaining low flows, with limited inflow from wetlands that would increase δ^2H and decrease the lc-excess and Gran Alkalinity.

In contrast, sampling when the catchment was re-wetted on 28th November 2018 showed higher and more consistent δ^2H (between ~−56 to −55‰) moving in the direction of recent rainfall, more positive lc-excess and a consistently low Gran Alkalinity (<100 μeq L^{-1}) along the entire stream network. In contrast to the drought conditions, this clearly showed that surface and near surface flow paths dominated runoff generation, and groundwater influences were overprinted in the tracer signals.

5 | DISCUSSION

5.1 | Drought dynamics and storage changes

The dynamics of water storage in the Bruntland Burn prior to, and during, the 2018 drought are highly instructive for understanding how the effects of periods of moisture stress propagate through the catchment's hydrological compartments. The humid hydroclimate of Scotland dictates that storm runoff generation processes and floods have been much more extensively researched than droughts (Werritty, 2019). However, the widespread impacts of the 2018 drought and future climate change forecasts, with more marked seasonal distribution of rainfall and warmer drier summers, call for a new focus on drier periods and their hydrological impacts (Capell et al., 2014; Spinoni et al., 2018).

In many environments, the increased dominance of green water fluxes, relative to blue water fluxes, occurs as catchments are drying down, and this is also the case in the Scottish Highlands (Kuppel et al., 2020). With increased evapotranspiration in the summer, the

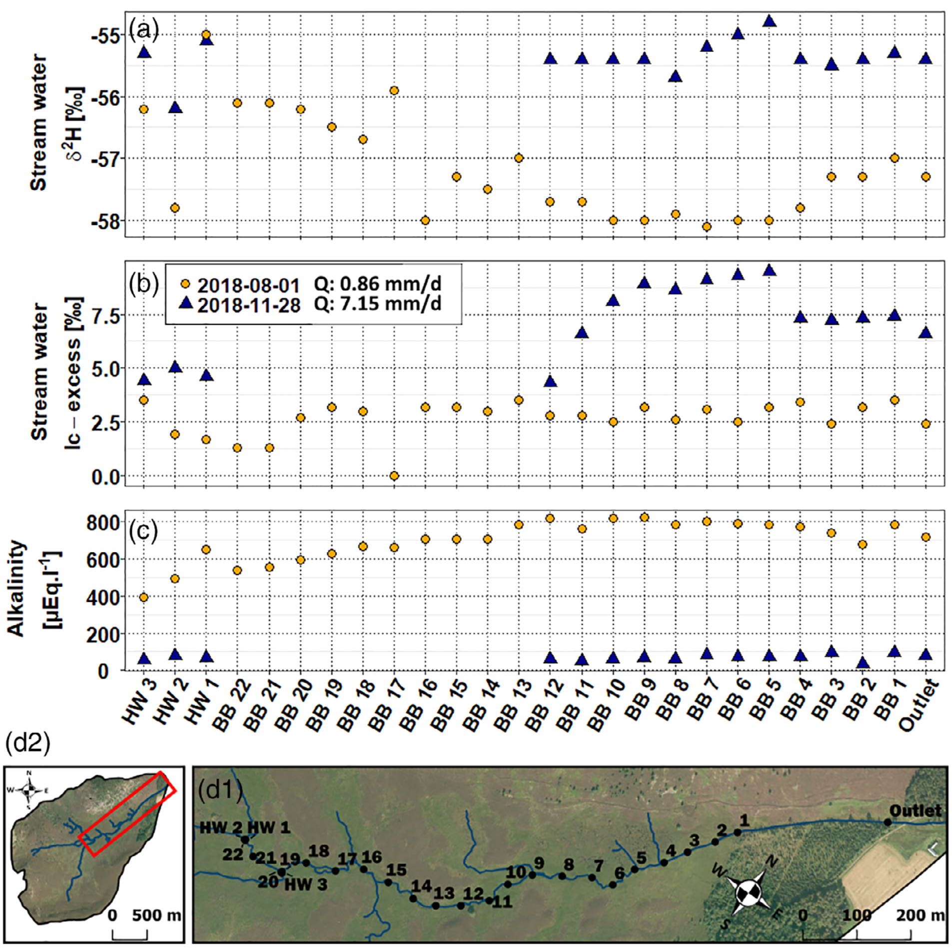

FIGURE 9 Results of the synoptic sampling along the Bruntland burn (BB) main channel in August 2018 and November 2018; (a) deuterium composition; (b) lc-excess and (c) gran alkalinity; (d.1) sampling locations along the Bruntland burn stream, (d.2) full extent of the Bruntland burn catchment with the red rectangle indicating the extent of (d.1). Please note that the gap between outlet and location BB 1 is due to inaccessibility to the stream channel due to a deer fence

upper soils begin to dry as atmospheric demand is met, and transpiration of the shallow-rooting heather and Scots Pine vegetation is sustained (Haria & Price, 2000). The resulting cessation of drainage through the soil profile, even though the organic, upper soil profile may retain moisture storage, restricts recharge, which is then mainly focused during winter (Scheliga et al., 2017). As a result, groundwater sustains stream flows and water tables fall as groundwater storage becomes depleted. In most years, recharge in the late autumn and early winter replenishes soil moisture deficits and groundwater depletion. However, in more severe dry spells with insufficient winter precipitation, "memory effects" of the previous year(s) can result in moisture deficits before summer green fluxes increase (Soulsby, Birkel, & Tetzlaff, 2016). That seems to have happened in 2017–2018, indeed, the effects of the relatively dry 2017 summer still seemed to be evident in the late, brief and less marked rise in watertables that winter, especially on the more extensive hillslopes (Figure 4). These two winters of lower recharge and limited replenishment of catchment-wide storage deficits (see Figure 5c) appear to have played a key role of increasing the catchment's vulnerability to the 2018 drought.

Although the catchment is only sparsely forested, the forest site showed dramatic effects of increased interception and canopy evaporation on evapotranspiration losses in summer (A. A. Smith et al., 2020). Indeed, even without the extreme conditions of the 2018 drought, the soil becomes very dry throughout its profile in most summers. This, together with the effect of more limited seasonal water subsidy from upslope, mitigated the specific effects of the drought in 2018 as the soil could not get much drier. Nevertheless, the findings highlight the significance of forest cover in enhancing green water fluxes, which will reduce blue water fluxes, especially during summer low flows (Douinot et al., 2019; Haria & Price, 2000; A. Smith et al., 2021).

5.2 | Insights into runoff generation and storage changes during droughts through isotopes

The use of isotopes to better understand the drought evolution was highly informative. Traditionally, the rapid changes in the isotopic composition of precipitation and stream flow during storm events have been used to understand runoff generation processes (Soulsby et al., 2015). Isotopic changes are less obvious for droughts and for slower responding parts of catchment hydrological systems. However, some recent studies, at a range of scales, have used isotopes to assess green water fluxes and runoff generation. These vary from assessing sources of plant water uptake in droughts at the plot scale in Mediterranean environments (e.g. Barbeta et al., 2015) to assessment of groundwater inputs to larger catchments under low flow conditions in geographical regions as diverse at the Italian Alps (Chiogna et al., 2018), Costa Rica (Birkel et al., 2020) and upland areas in central India (Noble & Arzoo Ansari, 2019). In the BB, the trajectory to more stable, intermediate isotopic ratios was consistent with the dominance of groundwater inflows, which increase in the valley bottom (Scheliga et al., 2017). This was confirmed by the spatial plots, which also underlined the value of using other tracers in conjunction with isotopes as the Gran Alkalinity data supported the influx of deeper waters downstream of the confluence with the main headwater tributaries.

The high lc-excess values were also consistent with the composition of groundwater sources which were mainly recharged by winter rainfall. Any evaporative signal from the upper soil horizons is lost in mixing as water percolates through the usually wet winter soils (cf. Tetzlaff et al., 2014). Runoff storm event runoff coefficients in the catchment are typically 10–40%, with higher values only occurring in winter storms (Soulsby et al., 2015). New water fractions are typically <10%, so precipitation isotope and lc-excess signals are not transferred directly to streams due to mixing processes in the wetlands (Tetzlaff et al., 2014). Consequently, in summer, absence of low lc-excess in stream water indicates that surface drainage from peats has stopped (Kuppel et al., 2018). Water in peaty pools usually evaporates in summer and affects the stream isotope composition, but the cessation of inflows of peat waters indicated a very dry catchment state in the drought of 2018, fed only by groundwater.

5.3 | Past and future context of the 2018 drought

Clearly, the drought of 2018 was an unusually widespread event throughout Europe (e.g. Imbery et al., 2018). In the Scottish Highlands, the prolonged period of lower-than-average rainfall over the two preceding years with two dry winters created antecedent conditions that forced the catchment into a very low state of storage. The degree to which summer soil water and groundwater levels dropped across the BB catchment was not previously seen in the years of monitoring. In the context of the 50 year long-term record, the drought was not unprecedented, with the mid-1970s being similarly characterized by a run of dry years and warm summers between 1975–1977. Although recovery was rapid following high autumn rainfall in 2018, a major concern is the increasing likelihood that such events become more frequent in future given the severity and implications of climate change impacts forecast for northern Europe in general, and the Scottish Highlands in particular (Capell et al., 2013).

The effects of drought-induced storage deficits on water fluxes, especially for stream flow, potentially have profound implications for upland Scottish rivers. Low summer flows reduce the thermal capacity of streams via lower volumes to heat which renders them more vulnerable to warming (as a result of lower volumes of water to heat), particularly in the context of climatic change (Fabris et al., 2018; Garner et al., 2014). Many streams in the Scottish Highlands support important cold-water ecosystems, most notably sustaining Atlantic salmon, which locally is the focus of an economically-important sports fishery. Salmon suffer growth inhibition and sub-lethal stress at temperatures >22.5°C and lethal effects when temperatures >32°C (Fabris et al., 2018). In recent years in the Girnock Burn, maximum temperatures have exceeded 22.5°C, though such headwater streams are especially vulnerable to warming through climate change (Hrachowitz et al., 2010). Reduced summer flows and the resulting lower thermal capacity could reduce both available physical habitat in stream channels from reduced wetted areas and increase thermal stress.

Drought-induced storage deficits may also be compounded by land use policies that are seeking to encourage tree planting both in general terms of increasing timber and biofuel production, but also to specifically mitigate against increased temperature effects from climate change (Scottish Government, 2019). While trees reduce short wave radiation reaching streams and wetlands, they also increase green water fluxes such as interception losses and transpiration, again at the expense of groundwater recharge and stream flow generation (Soulsby, Braun, et al., 2017; Wang et al., 2017). There is currently interest in the degree to which such evaporative losses can increase moisture storage capacity and provide a nature-based solution to flood management. However, it is clear that any such gains, which are likely limited to small and moderate summer floods (Soulsby, Dick, et al., 2017), will have a trade off in terms of potentially lower stream flows, especially during the summer, exacerbating climate change and drought effects.

Even under current land management conditions in the Scottish Highlands, more frequent, dry conditions may create wider potential problems. Usually peaty soils are highly water retentive and retain high soil moisture content throughout the year in the Scottish hydroclimate. However, under dry conditions, they can become a fire risk. This is a particular risk as moorlands are often burned under management regimes to create habitat for grouse or red deer populations which are managed for game hunting (Davies et al., 2016). It is increasingly recognized that burning moorlands in headwaters can have wide-ranging effects on downstream river systems including altered hydrological regimes (Brown et al., 2015). Increased risk of managed fires getting out of control, or accidental fires in summer, which can affect extensive areas is increasingly recognized as a climate change effect in Scotland and beyond (Turetsky et al., 2015). After burning, carbon losses can occur, and the loss of vegetation cover decreases green water fluxes, increasing runoff (Brown & Holden, 2020). It is clear that climate change will force a fundamental rethink of land and water management in the Scottish Highlands and elsewhere. As ever, long-term catchments provide a vital evidence base to inform decision making.

5.4 | Wider implications

Experimental catchments with long data time-series are valuable resources for drought assessment and will be crucial in monitoring the effects of climate change in the coming decades. There is potential in focusing more data collection on catchment storage dynamics, rather than flux measurements. This can be facilitated by new, more integrated tools for monitoring storage over a larger footprint using, for example, cosmic ray neutron sensors (Dimitrova-Petrova et al., 2020), hydrogeophysics (Dick et al., 2018) and micro-gravity changes (Kennedy et al., 2014). In addition, such tools can be used in catchments to assess the spatial distribution of storage in relation to landscape position (e.g. Soulsby, Bradford, et al., 2016), identification of important recharge zones, discharge areas and regions of important dynamic storage change to understand the non-linear responses of stream flows in both wet and dry periods (Soulsby et al., 2015). Such new insights can complement more traditional hydrometric monitoring in providing new data times series of extreme conditions such as droughts. Such data are also invaluable for challenging environmental models, as often these perform well under "average" conditions. In most spatially hydrological modelling, correctly capturing re-wetting after dry periods is usually the most challenging aspect (e.g. Soulsby et al., 2015), but crucial to understand the effects of droughts and their recovery periods. Thus, data streams from long-term catchments have a key role to play in improving models and making better projections for future climate change and land use scenarios (Ala-Aho et al., 2017). In particular, the combination of hydrometric and isotope data has the potential for improved representation of water storage—flux—age dynamics (A. Smith et al., 2021).

6 | CONCLUSION

The 2018 drought reduced soil moisture and groundwater storage levels to their lowest recorded in 10 years of research at the experimental Bruntland Burn catchment in the Scottish Highlands. However, these conditions reflected both the particular conditions during the summer of 2018 as well as antecedent conditions over the preceding 18 months. The slow depletion of storage mainly reflected lack of winter groundwater recharge and gradual evaporative losses through the spring and summer that created the large storage deficits. Although these deficits were modest and rapidly replenished in the wet autumn of 2018, they resulted in low river flows generated from groundwater drainage. Such conditions are likely to become more common in future, as drier, warmer summers for Scotland are a predicted consequence of climate change, though winters are expected to remain wet. This raises questions over future land and water management as flows from headwater catchments provide water that sustains a wide range of ecosystem services, from public water supplies to economically important Atlantic salmon fishing. Moreover, land management trends in the Scottish Highlands, like increasing forestry, increase green water fluxes and reduce blue water fluxes, so may exacerbate climate effects during low flows. Additionally, drier soil conditions may increase fire risk in dry peaty soils and require more careful approaches to moorland burning. The study underlines the value of long-term data in experimental catchments, both to contextualize and more fully understand hydrological function and provide data from extreme events to challenge modelling.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Chris Soulsby https://orcid.org/0000-0001-6910-2118
Doerthe Tetzlaff https://orcid.org/0000-0002-7183-8674

REFERENCES

Ala-Aho, P., Soulsby, C., Wang, H., & Tetzlaff, D. (2017). Integrated surface-subsurface model to investigate the role of groundwater in headwater catchment runoff generation: A minimalist approach to parameterisation. *Journal of Hydrology*, *547*, 664–677. https://doi.org/10.1016/j.jhydrol.2017.02.023

Bales, R. C., Goulden, M. L., Hunsaker, C. T., Conklin, M. H., Hartsough, P. C., O'Geen, A. T., Hopmans, J. W., & Safeeq, M. (2018). Mechanisms controlling the impact of multi-year drought on mountain hydrology. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-017-19007-0

Barbeta, A., Mejía-Chang, M., Ogaya, R., Voltas, J., Dawson, T. E., & Peñuelas, J. (2015). The combined effects of a long-term experimental drought and an extreme drought on the use of plant-water sources in a Mediterranean forest. *Global Change Biology*, *21*, 1213–1225. https://doi.org/10.1111/gcb.12785

Birkel, C., Correa-Barahona, A., Martinez-Martinez, M., Granados-Bolaños, S., Venegas-Cordero, N., Gutiérrez-García, K., Blanco-Ramírez, S., Quesada-Mora, R., Solano-Rivera, V., Mussio-Mora, J., Chavarría-Palma, A., Vargas-Arias, K., Moore, G. W., Durán-Quesada, A. M., Vasquez-Morera, J., Soulsby, C., Tetzlaff, D., Espinoza-Cisneros, E., & Sánchez-Murillo, C. (2020). Headwaters drive streamflow and lowlands tracer export in a meso-scale humid tropical catchment. *Hydrological Processes*, *34*, 3824–3841. https://doi.org/10.1002/hyp.13841

Birkel, C., Soulsby, C., & Tetzlaff, D. (2011). Modelling catchment-scale water storage dynamics: Reconciling dynamic storage with tracer-inferred passive storage. *Hydrological Processes*, *25*, 3924–3936.

Birkel, C., Tetzlaff, D., Dunn, S. M., & Soulsby, C. (2011). Using time domain and geographic source tracers to conceptualise streamflow generation processes in lumped rainfall-runoff models. *Water Resources Research*, *47*, W02515. https://doi.org/10.1029/2010WR009547

Blumstock, M., Tetzlaff, D., Dick, J. J., Nuetzmann, G., & Soulsby, C. (2016). Spatial organisation of groundwater dynamics and streamflow response from different hydropedological units in a montane catchment. *Hydrological Processes*, *30*, 3735–3753. https://doi.org/10.1002/hyp.10848

Brown, L. E., & Holden, J. (2020). Contextualizing UKmoorland burning studies with geographical variables and sponsor identity. *Journal of Applied Ecology*, *57*, 2121–2131. https://doi.org/10.1111/1365-2664.13708

Brown, L. E., Holden, J., Palmer, S. M., Johnston, K., Ramchunder, S. J., & Grayson, R. (2015). Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems. *Freshwater Science*, *34*(4), 1406–1425. https://doi.org/10.1086/683426

Burt, T. P., & Howden, N. J. K. (2013). North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain. *Water Resources Research*, *49*(6), 3504–3515. https://doi.org/10.1002/wrcr.20297

Capell, R., Tetzlaff, D., Essery, R., & Soulsby, C. (2014). Projecting climate change impacts on stream flow regimes with tracer-aided runoff models—Preliminary assessment of heterogeneity at the mesoscale. *Hydrological Processes*, *28*, 545–558.

Capell, R., Tetzlaff, D., & Soulsby, C. (2013). Will catchment characteristics moderate the projected effects of climate change on flow regimes in the Scottish Highlands? *Hydrological Processes*, *27*, 687–699.

Chiogna, G., Skrobanek, P., Narany, T., Ludwig, R., & Stumpp, C. (2018). Effects of the 2017 drought on isotopic and geochemical gradients in the Adige catchment, Italy. *Science of The Total Environment*, *645*, 924–936.

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus*, *16*, 436–468. https://doi.org/10.3402/tellusa.v16i4.8993

Davies, G. M., Kettridge, N., Stoof, C. R., Gray, A., Ascoli, D., Fernandes, P. M., Marrs, R., Allen, K. A., Doerr, S. H., Clay, G. D., McMorrow, J., & Vandvik, V. (2016). The role of fire in UKpeatland and moorland management: The need for informed, unbiased debate. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *371*(1696), 20150342. https://doi.org/10.1098/rstb.2015.0342

Dick, J. D., Tetzlaff, D., Bradford, J., & Soulsby, C. (2018). Using repeat electrical resistivity surveys to assess heterogeneity in soil moisture dynamics under contrasting vegetation types. *Journal of Hydrology*, *559*, 684–697. https://doi.org/10.1016/j.jhydrol.2018.02.062

Dimitrova-Petrova, K., Geris, J., Wilkinson, M., Rosolem, R., Verrot, L., Lilly, A., & Soulsby, C. (2020). Opportunities and challenges in using catchment-scale storage estimates from cosmic ray sensors in rainfall-runoff modelling in mixed/managed landscapes. *Journal of Hydrology*, *586*, 124878. https://doi.org/10.1016/j.jhydrol.2020.124878

Douinot, A., Tetzlaff, D., Maneta, M., Kuppel, S., & Soulsby, C. (2019). Eco-hydrological modelling with EcH$_2$O-iso to quantify forest and grassland effects on water partitioning and flux ages. *Hydrological Processes*, *33*, 2174–2191. https://doi.org/10.1002/hyp.13480

Fabris, L., Malcolm, I. A., Buddendorf, W. B., & Soulsby, C. (2018). Integrating process-based flow and temperature models to assess riparian forests and temperature amelioration in salmon streams. *Hydrological Processes*, *32*(6), 776–791.

Fennell, J., Geris, J., Wilkinson, M. E., Daalmans, R., & Soulsby, C. (2020). Lessons from the 2018 drought for management of local water supplies in upland areas: A tracer-based assessment. *Hydrological Processes*, *34*(22), 4190–4210.

Garner, G., Malcolm, I. A., Sadler, J. P., & Hannah, D. M. (2014). What causes cooling water temperature gradients in a forested stream reach? *Hydrology and Earth System Sciences*, *18*, 5361–5376. https://doi.org/10.5194/hess-18-5361-2014

Geris, J., Tetzlaff, D., & Soulsby, C. (2015). Resistance and resilience to droughts: Hydropedological controls on catchment storage and runoff response. *Hydrological Processes*, *29*, 4579–4593. https://doi.org/10.1002/hyp.10480

Glover, R., Soulsby, C., Fryer, R., Birkel, C., & Malcolm, I. A. (2020). Quantifying the relative importance of stock level, river temperature and discharge on the abundance of juvenile Atlantic salmon (*Salmo salar*). *Ecohydrology*, *13*, e2231. https://doi.org/10.1002/eco.2231

Hrachowitz, M., Soulsby, C., Imholt, C., Malcolm, I. A., & Tetzlaff, D. (2010). Thermal regimes in a large upland salmon river: A simple model to identify the influence of landscape controls and climate change on maximum temperatures. *Hydrological Processes*, *24*(23), 3374–3391. https://doi.org/10.1002/hyp.7756

Haria, A. H., & Price, D. J. (2000). Evaproation from scots pine (*Pinus sylvestris*) following natural re-colonisation of the cairngorm mountains, Scotland. *Hydrology and Earth System Sciences*, *4*(3), 451–461.

Hayes, M., Wilhite, D. A., Svoboda, M., & Vanyarkho, O. (1999). Monitoring the 1996 drought using the standardized precipitation index. *Bulletin of the American Meteorological Society*, *80*(3), 429–438.

Huang, S., Li, P., Huang, Q., Leng, G., Hou, B., & Ma, L. (2017). The propagation from meteorological to hydrological drought and its potential influence factors. *Journal of Hydrology*, *547*, 184–195.

Imbery, F., Friedrich, K., Fleckenstein, R., Kaspar, F., Ziese, M., Fildebrandt, J., & Schube, C. (2018). Mai 2018: Zweiter monatlicher Temperaturrekord in Folge, regional mit Dürren und Starkniederschlägen, Tech. rep., DWD, Retrieved from https://www.dwd.de/DE/leistungen/besondereereignisse/temperatur/20180604_bericht_mai2018.pdf

Kennedy, J., Ferré, T. P. A., Güntner, A., AbeKenn, M., & Creutzfeldt, B. (2014). Direct measurement of subsurface mass change using the variable baseline gravity gradient method. *Geophysical Research Letters*, *41*(8), 2827–2834.

Kleine, L., Tetzlaff, D., Smith, A., Wang, H., & Soulsby, C. (2020). Using water stable isotopes to understand evaporation, moisture stress, and re-wetting in catchment forest and grassland soils of the summer drought of 2018. *Hydrology and Earth System Sciences (HESS)*, *24*, 3737–3752. https://doi.org/10.5194/hess-2020-81

Kuppel, S., Tetzlaff, D., Maneta, M. P., & Soulsby, C. (2018). EcH 2 O-iso 1.0: Water isotopes and age tracking in a process-based, distributed ecohydrological model. *Geoscientific Model Development*, *11*, 3045–3069. https://doi.org/10.5194/gmd-2018-25

Kuppel, S., Tetzlaff, D., Maneta, M. P., & Soulsby, C. (2020). Critical zone storage controls on the water ages of ecohydrological outputs. *Geophysical Research Letters*, *47*, e2020GL088897. https://doi.org/10.1029/2020GL088897

Landwehr, J. M., & Coplen, T. B. (2006). Line-conditioned excess: A new method for characterizing stable hydrogen and oxygen isotope rations in hydrologic systems. In *Isotopes in environmental studies* (pp. 132–135). Vienna: IAEA.

Maneta, M. P., Soulsby, C., Kuppel, S., & Tetzlaff, D. (2018). Conceptualizing catchment storage dynamics and nonlinearities. *Hydrological Processes*, *32*(21), 3299–3303. https://doi.org/10.1002/hyp.13262

Neal, C. (2001). Alkalinity measurements within natural waters: Towards a standardised approach. *Science of the Total Environment*, *265*(1–3), 99–113.

Neal, C., Hill, T., Hill, S., & Reynolds, B. (1997). Acid neutralization capacity measurements in surface and ground waters in the Upper River Severn, Plynlimon: From hydrograph splitting to water flow pathways. *Hydrology and Earth System Sciences*, *1*(3), 687–696.

Noble, J., & Arzoo Ansari, M. (2019). Isotope hydrology and geophysical techniques for reviving a part of the drought prone areas of Vidarbha, Maharashtra, India. *Journal of Hydrology*, *570*, 495–507.

Orth, R., & Destouni, G. (2018). Drought reduces blue-water fluxes more strongly than green-water fluxes in Europe. *Nature Communications*, *9*, 3602. https://doi.org/10.1038/s41467-018-06013-7

Scheliga, B., Tetzlaff, D., Nuetzmann, G., & Soulsby, C. (2017). Groundwater isoscapes in a montane headwater catchment show dominance of well-mixed storage. *Hydrological Processes*, *31*, 3504–3519. https://doi.org/10.1002/hyp.11271

Scheliga, B., Tetzlaff, D., Nuetzmann, G., & Soulsby, C. (2018). Groundwater dynamics at the hillslope—Riparian interface in a year with extreme winter rainfall. *Journal of Hydrology*, *564*, 509–528. https://doi.org/10.1016/j.jhydrol.2018.06.082

Scottish Government. (2019). *Scotland's forestry strategy 2019–2029*. Scottish Government 60pp.

Smith, A., Tetzlaff, D., Kleine, L., Maneta, M. P., & Soulsby, C. (2021). Quantifying the effects of land-use and model scale on water partitioning and water ages using tracer-aided ecohydrological models. *Hydrology and Earth System Science*, *25*(4), 2239–2259. https://doi.org/10.5194/hess-2020-539

Smith, A. A., Tetzlaff, D., Kleine, L., Maneta, M., & Soulsby, C. (2020). Isotope-aided modelling of ecohydrologic fluxes and water ages under mixed land use in Central Europe: The 2018 drought and its recovery. *Hydrological Processes*, *34*, 3406–3425. https://doi.org/10.1002/hyp.13838

Soulsby, C., Birkel, C., Geris, J., Dick, J., Tunaley, C., & Tetzlaff, D. (2015). Stream water age distributions controlled by storage dynamics and non-linear hydrologic connectivity: Modelling with high resolution isotope data. *Water Resources Research*, *51*, 7759–7776. https://doi.org/10.1002/2015WR017888

Soulsby, C., Birkel, C., & Tetzlaff, D. (2016). Modelling storage-driven connectivity between landscapes and riverscapes: Towards a simple framework for long-term ecohydrological assessment. *Hydrological Processes*, *30*, 2482–2497. https://doi.org/10.1002/hyp.10862

Soulsby, C., Bradford, J., Blumstock, M., Dick, J., Geris, J., Lessels, J., McNamara, J. P., & Tetzlaff, D. (2016). Using electrical resistivity surveys to test tracer-based storage estimates in headwater catchments. *Hydrological Processes*, *30*(23), 4434–4445. https://doi.org/10.1002/hyp.10889

Soulsby, C., Braun, H., Sprenger, M., Weiler, M., & Tetzlaff, D. (2017). Influence of forest and shrub canopies on precipitation partitioning and isotopic signatures. *Hydrological Processes*, *31*, 4282–4296. https://doi.org/10.1002/hyp.11351

Soulsby, C., Dick, J., Scheliga, B., & Tetzlaff, D. (2017). Taming the flood—How far can we go with trees? *Hydrological Processes*, *31*, 3122–3126. https://doi.org/10.1002/hyp.11226

Soulsby, C., Tetzlaff, D., van den Bedem, N., Malcolm, I. A., Bacon, P. J., & Youngson, A. F. (2007). Inferring groundwater influences on streamwater in montane catchments from hydrochemical surveys of springs and streamwaters. *Journal of Hydrology*, *333*, 199–213.

Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., & Dosio, A. (2018). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, *38*, 1718–1736. https://doi.org/10.1002/joc.5291

Sprenger, M., Leistert, H., Gimbel, K., & Weiler, M. (2016). Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes. *Reviews of Geophysics*, *54*(3), 674–704.

Tetzlaff, D., Birkel, C., Dick, J., Geris, J., & Soulsby, C. (2014). Storage dynamics in hydropedological units control hillslope connectivity, runoff generation and the evolution of catchment transit time distributions. *Water Resources Research*, *50*, 969–985. https://doi.org/10.1002/2013WR014147

Tetzlaff, D., Carey, S., McNamara, J., Laudon, H., & Soulsby, C. (2017). The essential value of long-term experimental data for hydrology and water management. *Water Resources Research*, *53*, 2598–2604. https://doi.org/10.1002/2017WR020838

Tetzlaff, D., Gibbins, C. N., Bacon, P. J., Youngson, A. F., & Soulsby, C. (2008). Influences of hydrological regimes on the pre-spawning entry of Atlantic salmon (*Salmo salar L.*) into an upland river. *Rivers Research and Application*, *24*(5), 528–542. https://doi.org/10.1002/rrra.1144

Tigkas, D., Vangelis, H., & Tsakiris, G. (2015). DrinC: A software for drought analysis based on drought indices. *Earth Science Informatics*, *8*, 697–709. https://doi.org/10.1007/s12145-014-0178-y

Turetsky, M., Benscoter, B., Page, S., Rein, G., van der Werf, G. R., & Watts, A. (2015). Global vulnerability of peatlands to fire and carbon loss. *Nature Geoscience*, *8*, 11–14. https://doi.org/10.1038/ngeo2325

Wanders, N., Wada, Y., & van Lanen, H. A. J. (2015). Global hydrological droughts in the 21st century under a changing hydrological regime. *Earth System Dynamics*, *6*, 1–15.

Wang, H., Tetzlaff, D., Dick, J., & Soulsby, C. (2017). Assessing the environmental controls on scots pine transpiration and the implications for water partitioning in a boreal headwater catchment. *Agricultural and Forest Meteorology*, *240-241*, 58–66. https://doi.org/10.1016/j.agrformet.2017.04.002

Werritty, A. (2019). 'How can we learn to live with floods? Challenges for science and management: Guest editorial introduction. *Scottish Geographical Journal*, *135*, 1–2. https://doi.org/10.1080/14702541.2019.1667625

Werritty, A., & Sugden, D. (2012). Climate change and Scotland: Recent trends and impacts. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, *103*(2), 133–147.

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