Resistance and Resilience to Droughts: Hydropedological Controls on Catchment Storage and Runoff Response

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Abstract

Hydropedological units are of critical importance in modulating catchment response in terms of storage and flux dynamics under changing hydrological conditions. We examined the short-term impacts of an extreme drought on the storage dynamics and runoff response in hydropedological units in a headwater catchment in the Scottish Highlands. These included poorly drained histosols in riparian zones and freely draining podzols on steeper hillslopes. To characterise the storage and runoff dynamics prior to, during, and after the drought period, precipitation, soil moisture, shallow ground water levels, and consequent runoff were monitored and stable water isotopes samples collected. Storage changes in the histosols were remarkably small (<40 mm), compared to those in moorland (~100 mm) and forest (~200mm) covered podzols. Although storage in all soils recovered soon after the drought, this took longest (3-4 months) for the forested podzols. During events, there was consistent threshold behaviour in most hydropedological units and the integrated response at the catchment scale, which was not affected by drying or wetting. The results suggest that during dry periods, large parts of the catchment were disconnected from the river network and runoff was generated mainly from the wet histosols. However, during events, there was an intermittent connection of the hillslopes that recharged the wetland and stream. This contributed to strong recovery and resilience of the catchment in its runoff response. Nevertheless, as future climate projections for northern environments suggest that prolonged dry periods are likely to become more frequent, further work is needed on the potential cumulative or carry over effects of consecutive drier periods.

Keywords: hydropedology, droughts, water storage, runoff response, isotopes

1. Introduction

Northern upland catchments sustain rivers that provide vital sources of water and energy in many areas, as well as supporting important ecosystems, including peatlands (Acreman *et al.*, 2009; Tetzlaff *et al.*, 2013). Although relatively water resource rich in a global context (Gerten *et al.*, 2011), water scarcity can occur during exceptional dry periods. In these environments, the concept of a 'drought' thus refers to relative rather than absolute deficits (Wilhite and Glantz, 1987; Gosling *et al.*, 2012). In addition to reductions in water and energy supplies, such events can cause changes in the physical properties of catchment soils, which may have serious hydrological implications. Soil cracking may lead to increased infiltration and vertical water movements (Holden and Burt, 2002; Jarvis *et al.*, 2012). Alternatively, the development of a hydrophobic layer could reduce infiltration and enhance overland flows (Doerr *et al.*, 2006). Droughts and lower water tables in northern uplands have also been linked to changes in soil chemistry (Juckers and Watmough, 2014), increases in carbon fluxes (Worrall *et al.*, 2006) and solutes (Burt *et al.*, 2014), alterations in microbal activity (Mettrop *et al.*, 2014) and the mobilisation of sediment (Evans *et al.*, 2006), and (temporary) loss of habitat (Stubbington *et al.*, 2009). For many ecosystems, timing of water availability in particular is crucial. Droughts can be most detrimental, for example, during or at the onset of growing seasons (Michelot *et al.*, 2012; Matías *et al.*, 2014), or at times of fish migration for spawning (Tetzlaff *et al.*, 2005). Economically, replacing ecosystem services lost during drought conditions and adapting to new ecosystem equilibria may be extremely costly (Banerjee *et al.*, 2013).

The impacts of droughts (both in severity and duration) are known to depend on catchment characteristics, including soil type, land use, and geology (Peters *et al.*, 2003; Van Lanen *et al.*, 2013). In general, meteorological droughts tend to develop more often into hydrological droughts for catchments with relatively fast responding flowpaths, although they are of shorter duration than those for more slowly responding (e.g. groundwater dominated) catchments (Van Lanen *et al.*, 2004; 2013). Of importance in the context of drought tolerance are the systems' resistance, resilience and recovery to drought perturbations, concepts which are more commonly used in the field of ecology (e.g. Lloret *et al.*, 2011; Taeger *et al.*, 2013). Resistance relates to the strength of the system's state to remain unchanged under stress, while resilience expresses the system's ability to respond to stress by repelling damage and recovering quickly (Carey *et al*., 2010; Taeger *et al*., 2013). Recovery, in turn, refers to the system's restoration to pre-stress conditions. For example, if a system has low resistance and low resilience to change, it will show dramatic state changes under stress conditions, and prolonged (or indefinite) recovery times to pre-stress conditions.

The present work focuses on short-term (event-based and seasonal) impacts of drought on water storage and transmission dynamics in northern environments. We examined the impacts on these processes in different hydropedological units in Scotland, UK, as well as their integrated response at the catchment scale. Hydropedological characteristics are known to be of great importance in regulating water storage and flux dynamics in these humid upland catchments (Soulsby and Tetzlaff, 2008; Hrachowitz *et al*., 2009). Permanently wet, poorly draining histosols exhibit little dynamic storage and highly responsive near-surface hydrological pathways, while processes in more freely draining pozolic soils are mainly characterised by vertical movement to deeper flow paths (Tetzlaff *et al.,* 2014). Some studies have shown that the hydrological impacts of periods of drought in humid environments tend to be small and short-lived at the catchment scale (e.g. Evans *et al*., 1999; Worrall et al., 2007a; Burt *et al*., 2014). However, the sensitivity to droughts of the different characteristic hydropedological units in northern landscapes, and their integrated response at the catchment scale remain poorly understood.

A key limitation to understanding impacts of droughts on storage and transmission dynamics in northern environments is the lack of spatially distributed data. This is caused by the difficulty of measuring subsurface processes directly and the challenges associated with monitoring an uncommon hydroclimatological event. Through the integration of hydrometric data with stable water istotopes, new insights can be gained into the resistance, recovery and resilience of storage and transmission dynamics in hydropeodological units to droughts. Whereas soil moisture and groundwater level monitoring provide partial insights into total water storage dynamics (e.g. Haga *et al*., 2005; Salve *et al*., 2012), isotope tracers are crucial to further understand water transport, partitioning (e.g. evapotranspiration), and mixing processes (see reviews by Kendall and McDonnell, 1998; Vitvar *et al.*, 2005; Soderberg *et al*., 2012).

The main aim of this study was to investigate the short-term impacts of an exceptionally dry period on the storage dynamics in different hydropedological units and runoff response of a northern headwater catchment using a combination of hydrometric and stable isotope data. In particular, the following questions were addressed: (i) What are the hydroclimatological conditions prior to, during, and after the extremely dry period?, (ii) How do different hydropedological units respond to the dry period, in terms of dynamic storage as characteristed by soil moisture and shallow ground water level responses?, and (iii) How is the catchment behaviour as a whole affected by the exceptionally dry period?

2. Site Description

This study was conducted in the 3.2 km^2 Bruntland Burn northern headwater catchment, in the Cairngorms National Park, NorthEast Scotland, UK (Figure 1). The climate is generally characterised by high annual preciptiation (~1000 mm), mostly occuring in small and low intensity storms, relatively evenly distributed throughout the year. Annual potential evapotranspiration (~400 mm) is concentrated in the period between April and September (Birkel *et al*., 2011a). The Bruntland catchment is underlain by granite and metamorphic bedrock. Elevations range from 248 to 539 masl (mean 351 masl) and the mean slope is ~13°. The catchment is characterised by distinctly different hydropedological units typical for glaciated northern headwater catchments. Drift deposits in an over-widened glaciated valley are poorly draining, which has allowed the formation of peat bogs (histosols; approximately 9% of total catchment area) of up to 4 m deep in the riparian zone. Here, vegetation is dominated by *Sphagnum* and Bog Myrtle (*Myrica gale*). The histosols exhibit high water storage and are wet throughout the year, owing to high porosities and water retention capacities. Consequently these soils provide a very responsive hydrological regime with runoff generated mainly via surface and near-surface horizontal flow in the riparian zone (Tetzlaff *et al*., 2007; Birkel *et al*., 2011b). At the footslopes, the histosols thin to less than 0.5 m and gradually move to peaty gleys (gleysols; 12% of total catchment area) that mostly support *Molinia* and heather (*Calluna* and *Erica* species) vegetation. These soils exhibit similar poorly draining properties, although overall storage is generally lower. Humus-iron podzols (spodosols; 36% of total catchment area) with heather vegetation overlay the steeper hillslopes. In comparison to the histosols and gleysols, these soils are much more freely draining, with clear drying and wetting patterns in response to rainfall

(Geris *et al*., 2014). On the hillslopes, water flow is characterised by more 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). On the steeper slopes (> 25°), the podzols thin to ranker soils (leptosols, 14%) and bedrock outcrops (approximately 29% of total catchment area). As a result of high deer grazing densities, tree cover is limited to areas generally inaccessible to deer (i.e. on steeper scree slopes and behind deer fences). There are several patches (approximately 20% of catchment area in total) of Scots Pine (*Pinus sylvestris*) and other native (incl. Birch (*Betula*), Alder (*Alnus*)) and non-native (e.g. Sitka Spruce (*Picea sitchensis*)) tree species.

3. Data and Methods

3.1 Hydrometric Data and Analyses

The Burntland Burn is part of a long-term experimental monitoring programme with a dense hillslope monitoring network of hydrological variables. As part of this, precipitation, soil moisture, shallow ground water levels, and consequent runoff at the catchment outlet were monitored, and analysed here to characterise the storage and runoff dynamics prior to, during, and after the drying period in the 2013 summer. Soil moisture and ground water level responses in the main soil types (poorly draining histosols and gleysols, and freely draining podzols) were investigated. Five sites were selected that demonstrate the overall variability in hillslope responses (Table 1; Figure 1), equally representing poorly draining and freely draining soils. The first three sites were positioned along a hillslope transect, so that S1, S2, and S3 were located on a histosol-gleysol-podzol soil catena with typical vegetation, respectively. In addition, S4 (tree cover) and S5 (heather vegetation cover) were positioned on podzol soils. Site characteristics, vegetation, and soil physical properties for the five sites are provided in Table 1.

Volumetric soil moisture (VSM) content of the upper 0.6 m profile was measured at sites S1 – S4 with *Campbell Scientific* Time Domain Reflectometry (TDR) probes at 0.1, 0.3 and 0.5 m depth. These depths correspond roughly to the main soil horizons (Table 1). Assuming idealised soil profiles, these VSM data were converted to absolute soil moisture (SM) estimates of the upper 0.6 m soil profile, by multiplying the VSM data of each probe with the representative soil horizon thickness (0.2 m). Average values of two replicate probes for each soil layer were used. For S1, VSM was measured at -0.1 m only, assuming that the lower soil layers (-0.2 m and beyond) were permanently saturated (cf. Geris *et al*., 2014). Groundwater table levels (GWL) were measured at sites S1-S3 and S5 using *Odyssey* capacitance probes. The stony nature of the drift and podzol parent material prohibited installation of wells deeper than approximately 0.5 m (well depths are provided in Table 1). Precipitation and other climatological variables were obtained from an automatic weather station located 1 km west of the catchment. Potential evapotranspiration rates were estimated using a simplified version of the Penman-Monteith Equation (cf. Dunn and Mackay, 1995). All hydrometric variables were monitored at a 15 minute interval.

Three distinctly different, 4 month periods in hydroclimatological conditions were identified, involving a pre-drying, drying, and rewetting period. General statistics of precipitation, potential evapotranspiration, and discharge were derived to characterise the different nature of hydroclimatological conditions during these three periods. T-tests were performed to assess the statistical differences between these event characteristics of the three periods. Drought tolerance indices based on timeseries percentiles were computed for the soil water storage in the different hydropedological units and the runoff at the catchment scale. For each of the timeseries' statistics (X), the system's resistance, recovery, and resilience (all [-]) was calculated according to Equations 1, 2, and 3 respectively (following Lloret *et al*., 2011; Taeger *et al*., 2013):

$$Resistance = X_{i,drying}/X_{i,pre} \quad \text{(Equation 1)}$$

$$Recovery = X_{i,wetting}/X_{i,drying} \quad \text{(Equation 2)}$$

$$Resilience = X_{i,wetting}/X_{i,pre} \quad \text{(Equation 3)}$$

for which *i* is the timeseries (*X)* percentile (including the 0.1, 0.5, and 0.9 percentiles as well as minimum and maximum), during the 'pre' (X_{pre}), 'drying' (X_{drying}), and 'wetting' ($X_{wetting}$) periods. A resistance of 1, for example for the discharge 0.5 percentile, signifies no change in the mean flow, while values below one indicate decreases and increasingly lower resistance. Similarly, recovery and resilience values below 1 indicate incomplete recovery and relatively low resilience, while values above 1 show recovery to levels higher than before the drying period and a highly resilient system.

Subsequently, event-based analyses were performed to explore the spatio-temporal soil moisture, groundwater and runoff responses of the different hydropedological units and at the catchment scale under the different hydroclimatological conditions. In the context of this study, a precipitation event was defined by a 12 hour dry period before and after the occurrence of precipitation larger than the measurement error of 0.2 mm. Because of the low intensity and long duration nature of most precipitation in the Scottish Highlands, events last up to several days. The magnitude and timing of peak responses in SM and GWL for the hydropedological units and in discharge at the catchment outlet were extracted. The peak response (and its timing) were defined as the maximum level of each of the variables in the period between the start of the event under consideration and that of the next event. The lag times in responses were expressed as the difference between timing of the precipitation mass centroid and the peak timing. Antecedent precipitation was calculated according to Equation 4:

$$API_{(t)} = k * API_{(t-1)} + P_{(t)} \qquad \text{(Equation 4)}$$

where API (mm) is the antecedent precipitation index and time t (days), k (-) is an API time decay factor, and P (mm day^{-1}) precipitation. Parameter k inversely represents the rate at which the catchment wetness declines in the absence of precipitation and affects both the average magnitude of API and the weightings given to historical rainfall. Here it was set at 0.8 to reflect the relatively flashy nature of the catchment (the effect of rainfall falls to 10% over 10 days).

3.2 Stable Water Isotope Data and Analyses

Soil and stream water samples were collected for stable water isotope analyses to further explore mixing, storage and evapotranspiration effects. During the full duration of the study period, daily precipitation and stream flow samples were collected by automatic *ISCO* (3700) samplers. Isotopic fractionation between sampling and collection was prevented by a paraffin seal in the field. During the pre-drying and drying periods only, fortnightly soil water samples from the three VSM monitoring depths were collected for sites S1-S4 using

Rhizosphere Research Products MacroRhizon moisture samplers. Water samples were analysed for stable isotope composition with a *Los Gatos* DLT-100 laser liquid water isotope analyser. Lab procedures followed standard protocols and data are presented in the δ-notation (‰) relative to Vienna Standard Mean Ocean Water (VSMOW). Duplicates for each soil layer were collected and average results are given here.

To assess general mixing and storage processes, catchment isotope input-output relationships were investigated and compared with the isotope dynamics of soil water. Evaporative fractionation in the top soil of the different hydropedological units and its potential propagation throughout the soil profile were explored. Soil water isotope signatures for the three depths were compared against the global and local meteoric water lines for the different periods. Similarly, the integrated effects at the catchment scale in addition to direct evaporation from water in the stream were evaluated.

4. Results

4.1 General Hydroclimatological Conditions and Responses Prior to, During, and After the Drying Period

The climatological conditions of the study year (February 2013 – January 2014) included an unusually dry and warm summer which was followed by an extremely wet winter. Figure 2 shows the mean monthly temperature and monthly precipitation during the study year for the closest long-term monitoring station at Braemar, approximately 20km west of the catchment. Compared to the long-term (1981-2010) average, January to April 2013 was colder, while in particular July and December 2013 were generally warmer. Precipitation occurred predominantly as rain. Regular field visits confirmed occasional snow lying up to April 2013, while this was negligible for the 2013-2014 winter period. Monthly precipitation totals at Braemar were significantly less than the long-term average during the 2013 summer period (43% less for June-September; 67% less for August-September). In terms of total precipitation, these conditions had an estimated return period of 8-12 years (NHMP, September 2013). Moreover, a large part of this rain fell during late July, during a few large convective events, so that there were unusually prolonged periods without any precipitation. The winter that followed this dry period was extremely wet. For North-East Scotland, 179% of the average rainfall for December 2013 – January 2014 was recorded, with an estimated return period exceeding 100 years (NHMP, January 2014). Daily catchment hydrometric data (Figure 3, Table 2 top) revealed three markedly different periods: February – May 2013 (the period prior to the drying), June – September 2013 (a period with significant drying), and October 2013 – January 2014 (a period during with catchment rewetting occured), hereafter referred to as the 'pre', 'drying', and 'wetting' periods, respectively. Although it may be argued that the 'wetting' period started later for some of the sites (e.g. S4), overall Figure 3 shows that from the start of October 2013, there were regular precipitation inputs, potential evapotranspiration rates were low, and discharge at the catchment scale increased.

During the drying period, potential evapotranspiration greatly exceeded precipitation and discharge (Table 2). There were 3 extended periods without rain, with a maximum length of 18 days. The majority of preciptiation during the drying period occurred during a wave of convective events at the end of July. To some degree, decreases in SM were observed for all soil types, although this was most distinct for the podzol soils at S3 and S4, with the strongest drying effects under tree cover at S4 (Figure 3). The maximum difference in SM for the S1 histosol site was limited to approximately 20 mm (around 4% of its maximum observed total storage in the upper 60 cm of the soil profile). For GWL, similar patterns were observed in drawdown, with little drawdown at S1 and marked declines for the podzolic soils at S3 and S5, for which levels dropped beyond the measuring range for the majority of drying period. Subsequent deeper drilling at S3 has revealed a minimum water table depth of around 1.2m. Discharge declined substantially during the drying period, and runoff ratios were considerably lower than during the two other periods (Figure 3, Table 2). Median flow (Q50) was around a third of flows during the pre and wetting periods, while Q10 (i.e. the amount of flow exceeded for 10% of the time) of the drying period was still less than two thirds of Q50 at the two other periods (Table 2).

From the beginning of October 2013, the catchment started rewetting and discharge levels recovered (Figure 3). In terms of water storage recovery in the hydropedological units to pre-June levels, this appeared to take longer for the podzols. However for each particular unit, there was similarity in the rewetting patterns observed in the GWL and VSM data. The resistance, recovery, and resilience of the SM storage dynamics in the different hydropedological units and the consequent catchment runoff Q, as represented by SM and flow percentiles, respectively, are summarised in Figure 4. GWL data are not shown, as these data had large gaps during the drying period at S3. As the poorly draining histosols and gleysols are highly resistant (values close to 1), their recovery and resilience to the drying period is also high. The resistance of the freely draining podzols appeared relatively low, although recovery was good. As the rewetting of the podzols took considerable time, their resilience, especially as reflected for the lower percentiles, is relatively low. Note the log scale of the y axes and the high variety between the indices of the podzols, reflecting the more variable nature in their dynamics. A large proportion of the catchment (~80%) is represented by freely draining podzols, ranker soils and bedrock outcrops. At the catchment scale (as quantified by discharge at the catchment outlet), resistance to the drought over the whole time series is, as for the podzols, low, and recovery high.

4.2 Event Based Storage (Soil Moisture and Groundwater Level) and Runoff Responses

We analysed 40, 28, and 39 events for the 'pre', 'drying', and 'wetting' periods respectively. There was considerable natural variability in the precipitation events, which is evident in the large spread in the event characteristic boxplots during the three periods (Figure 5). In general, precipitation events during the entire study year were long in duration (up to a few days, and ~10 hr on average) and had relatively low intensities (Figure 5), typical for the climate in the Scottish Highlands. Although the large spread at first sight suggests that there are no clear differences between the precipitation event characteristics of the three periods, events during the drying period were, on average, shorter in duration and smaller in magnitude, in particular when compared with the wetting period (Figure 5;Table 3). Because of the general drier conditions, the antecedent precipitation index prior to the events was also smaller. Associated with these drier conditions, it appears that the peak discharge (Q_{peak}) for similar precipitation totals was generally lower for the drying events. Precipitation intensities were generally similar for events in the three different periods.

For the three periods, Figures 6 and 7 show the peak event magnitude and timing, respectively, for the responses of SM, GWL and discharge (Q) in relation to each other. As in Figure 3, there are large differences in the SM_{peak} ranges between the different hydropedological units (Figure 6). The freely draining podzolic soils show much larger ranges in peak responses than the poorly draining soils. As the SM ranges observed at S1 are small, apparent peak responses in the histosols cannot be clearly identified; hence, timings of peak responses at S1 are not shown in Figure 7.

At the catchment outlet, event peak discharges during the ‘pre’ and ‘rewetting’ period up to ~ 0.8 mm/hr were observed, while the maximum peak flow during the drying period was only 0.42 mm/hr (Figures 5c, 6). However, even though these ranges were quite different, all soil types exhibited clear threshold behaviour in the relationship between Q_{peak} and the SM_{peak} (top row Figure 6), so that highest discharges only occur when SM storage throughout the catchment is relatively high. Similar threshold behaviour was observed for GWL_{peak} in relation to Q_{peak} (middle row Figure 6), although again not for S1 which was always wet. Importantly, there was no clear difference in these relationships between the pre, drying and the rewetting periods. The exception was the podzolic soil with tree cover (S4), where high discharges occurred during periods with some of lowest SM observations, both during the drying and (start of) the rewetting period. This suggests that during those times, there was little or no connection of this hydropedological unit with the river network.

Maximum observed stream discharge lag times were in the order of two days during the ‘pre’ and ‘drying’ periods (Figure 7). They were generally less than a day during the ‘rewetting’ period, when conditions were generally wetter, and total precipitation larger. In terms of relative peak timing, Figure 7 showed large scatter for the SM and GWL responses in relation to Q (upper two rows) and each other (bottom row) in all hydropedological units. However, it is noted that, as for peak magnitude, there are no clear differences in the event peak timings between the three periods, even though soil water storages were much lower during the drying period.

4.3 Stable Water Isotope Dynamics in the Hydropedological Units and in Stream water

Isotopes in precipitation input showed high variability throughout the study year, though in general more enriched values were evident during the drying period (δD weighted average = -49.6 ‰) than during the pre-drying (-50.8 ‰) and the rewetting (-66.6 ‰) periods. Albeit significantly damped, this pattern was reflected in the temporal isotope signatures of the stream water outputs (Figure 8, δD weighted averages of -53.6 ‰, compared to -56.3 ‰ and ‰ -58.0 respectively).

For each of the individual sites, the soil water isotopes, in particular at the top of the profiles, were also more enriched during the drying period (Figure 9). The large variability of the precipitation inputs is most clearly reflected in the soil water of the freely draining podzols at S3 and S4. The damping of isotope variability, especially for the poorly draining sites (S1 and S2), increases with depth. There was a slight indication of evaporative fractionation in the upper soil profiles during the drying period, but transmission of this signal to greater depths was not apparent. This suggests that the proportion of stored soil water that was affected by evaporation was relatively small, as it would be subsequently mixed with any new precipitation inputs that would have penetrated further down the soil profile.

Apart from the more generally enriched stream water isotopes during the drying period, there were no clear differences between the three periods in the stream water signatures in terms of evaporative fractionation influence (Figure 10). The more enriched soil water in the upper profiles (top row Figure 9) was not reflected to the same extent in the stream water (Figure 10). Throughout the entire observation period, it appeared the stream water signatures remained similar to those observed at S1 at 0.3 m, consistent with the riparian wetland being the main source of runoff. Open water evaporation effects, or inputs from fractionated soil water, were small or absent, as stream water plotted close or on the local meteoric water line (LMWL). Even during periods with no rain, there was no relation between deviations from the LMWL that indicate fractionation effects of evaporation (inset Figure 10). It is noted, however, that during periods with little new precipitation inputs and decreasing discharge, the stream water signatures were increasingly depleted, which suggests relatively more groundwater inputs that are mainly recharged with depleted winter precipitation. These effects appeared more dominant than any potential fractionation impacts as a result of evapotranspiration during the lowest flows during the drying period.

5. Discussion

5.1 Hydroclimatological conditions

The Scottish climate is generally characterised by high preciptiation inputs that are relatively evenly distributed throughout the year. The study year, however, showed a distinctly dry period with precipitation inputs below - and mean temperatures above - average. In addition to the impacts of this dry period on general storage and flow conditions, the dynamics during individual events were analysed. The definition of an event we used here (i.e. 12 hr pre- and post-event windows with no precipitation), may initially seem arbitrary. It is, however, most suitable for the prevailing climate, where events are generally characterised by long and low intensity inputs of precipitation, which can last for days. Initial analyses (not shown here) indicated that different time windows for the characterisation of events would not have affected the relative differences in conditions between the pre, drying, and wetting periods, nor the interpretation of the drought impacts on storage and transmission processes. However, the local climate has natural variability and individual drought events can provide only a limited insight into potential future system responses. For the Girnock catchment (30 km^2), into which the study catchment drains, Birkel *et al*. (2015) showed that catchment scale storage deficits for a dry period in 2003 persisted well into 2004. The winter of 2013-2014 received almost twice as much precipitation than average, with an estimated return period exceeding 100 years (NHMP, January 2014), so it is likely that rewetting processes occurred more quickly during this study year.

5.2 How do the hydropedological units respond to the dry period, in terms of dynamic storage as characteristed by soil moisture and shallow ground water level responses?

Storage dynamics in all soil types were affected by the dry period, but the results demonstrated markedly different responses in the resistance, resilience and recovery to drought. This can be explained by their relative differences in hydrophysical properties. Despite relatively limited drying effects (<40 mm), water storage in the histosols showed a high resistence to drought. The high moisture retention capacity in particular is known as a key regulator of peatland ecohydrological resilience to perturbations. This is characterised by a set of hydrological negative feedback mechanisms that regulate changes in preciptiation and temperature (Waddington *et al*., 2014). For example, water loss in peatlands under drought conditions is regulated by increases in near-surface tensions as the peat dries, and thereby reductions in the availability of water for evaporation (Kettridge and Waddington, 2014). This may perhaps also explain the absence of strong evaporative isotopic enrichment effects in the upper histosol profiles, which in northern wetlands has only been observed in permanently shallow water surfaces (e.g. Levy *et al*., 2013).

Storage deficits in the podzols were up to 5 times higher than in the histosols and recovery in general appeared to take longer. Distinct wetting and drying cycles in winter, the marked drying in summer, and reduced damping of isotope variability with depth for the podzols all indicated that transmission processes through these soils are faster and less mixing occurs (see also Tetzlaff *et al*., 2014; Geris *et al*., 2014). Water retention capacities of mineral soils in general are lower than those for histosols (Letts *et al*., 2000). In addition, macropores or cracks in the podzol could have caused preferential water flow through the upper soil layer to deeper soil horizons. Such quick flow paths could also explain the fast responses observed in the the GWL data.

Nevertheless, although lower than the histosols, the podzols still demonstrated relatively high resilience. As storage and transmission dynamics of all hydropedological units recovered within a relatively short timeframe (max 3-4 months), it is suggested that no significant changes in the soil hydrophysical properties that might affect storage and transmission dynamics (e.g. hydrophobicity, soil cracking) occured, such as observed for more severe and repeated (laboratory) drought periods in histosols by Holden and Burt (2002) and in podzols by Sowerby *et al*. (2008). This would also be consistent with the lack of impacts in the relationship of the storage dynamics in the different units and their integrated runoff response at the catchment scale suggesting that runoff generation flow pathways remained unchanged (Worrall *et al.,* 2007a).

However, the results did suggest that land use may have further exacerbated the high spatial variability in the resistance and resilience in terms of storage dynamics to drought impacts. Dynamic storage changes in the podzols were twice as high under forest cover compared to heather vegetation cover. Although it is difficult to fully separate soil, vegetation and topography effects on soil water storage dynamics (Lin *et al*., 2006; Geris *et al*., 2014), evidence from other studies in Scotland suggests that evapotranspiration under Scots pine may be larger than under moorland cover (Haria and Price, 2000). Similar findings were consistently observed elsewhere (e.g. Green *et al*., 2006). In addition, it has been shown that different water use strategies by vegetation communities can affect the downstream water resources impacts of droughts (Leitinger *et al*., 2015). Although overall small, there was a relatively higher fractionation of isotopes resulting from evaporative effects in soil water under tree cover at S4. As previously argued by Geris *et al.* (2014), this could be associated with higher surface roughness and throughfall of fractionated interception under forest cover. However, the evaporative enrichment was relatively small compared to the additional storage deficits at this site, and did not extend to the deeper soil horizons. It is likely that additional water use of trees, which does not alter isotope signatures of soil water (Ehrlinger and Dawson, 1992), was the dominant mechanism. Based on data from several catchments in central and western Europe, Teuling *et al*. (2013) demonstrated that the effects of low precipitation inputs during droughts are typically amplified by additional evapotranspiration. It could further be argued that any intercepted water might have fully evaporated, and therefore throughfall of fractionated water was limited or non-existing.

5.3 Is the catchment response behaviour as a whole affected by the exceptionally dry period?

Using daily data, Tetzlaff *et al*. (2014) previously demonstrated that the storage dynamics in different hydropedological units control hydrological connectivity between hillslopes and stream network, runoff generation and the evolution of catchment transit time distributions. In addition, Geris *et al*. (2014) argued that the pedological role on water storage and transmission dynamics in northern headwater catchments is stronger than that of vegetation. Furthermore, the analyses here have shown that the catchment resistance, resilience and recovery to drought are also affected by the impact of drying on the different hydropedological units.

High water storage in the poorly draining histosols and underlying drift of the riparian zone sustained flows throughout the dry period, and there were catchment runoff responses to even small precipitation events. The strong damping of isotope inputs in the riparian zone and connected stream network has been linked previously to considerable mixing of new precipitation inputs with a large volume of stored water with relatively long residence times (Tetzlaff *et al*., 2014; Geris *et al*., 2014). The isotope data further indicated that although the riparian wetland was the main continuous source, the relative contribution from deeper groundwater increased during the lowest flows (Birkel *et al*., 2014). This was evidenced by increasingly more depleted stream water isotopes during these periods with no additional precipitation inputs. Mean ground water isotopes are generally more depleted (approximately δD -61, and δ18O -9, Tetzlaff *et al*., 2014). For the majority of time, disconnectedness of large parts of the catchment from the river network caused a significant decrease in flows during the dry period. A strong correlation existed between the drought tolerance, i.e. high resistance, resilience, and recovery, of the podzols and the catchment as a whole (Figure 4).

Nevertheless, the analyses have shown that during events, the catchment behaviour as a whole shows high resistance as well as high resilience to drier periods. For all hydropedological units that showed significant storage changes during the study period, there was consistent threshold behaviour in the relationship between the storage in the hydropedological units and the catchment response. This suggests that the dynamic storage capacity is a dominant factor in controlling initiation of increased runoff and connectivity, as also observed elsewhere (e.g. Evans *et al*., 1999; Detty and McGuire, 2010; Carrer *et al*., 2014). These integrated responses at the catchment scale, apart from those of the tree covered podzol, appeared not to be affected by relative drying or wetting conditions. Clear differences in the relative timings of storage and peak flows were also absent, although it is noted that, in our analyses, lag times were not compared directly e.g. with antecedent conditions or rainfall intensity (e.g. Haga *et al*., 2005), which may potentially affect variations in lag time responses. We demonstrated that rainfall intensity was not significantly different between the three study periods. In addition, antecedent conditations were also unlikely to have a considerable effect on the event response lag times, since if such significant impacts of the drought period on event response lag times would have occured, these would have emerged out of the natural scatter data plots of Figure 7.

The consistent threshold behaviour demonstrated that through quick preferential flow pathways there was an intermittent connection of the upper hillslopes recharging the wetland and stream during events, even during dry periods. Although relatively small compared to the precipitation input signatures, this was in extreme cases also evidenced by a characteristic response in stream isotope signatures, for example during the event at the end of July (Figure 8). Similar findings in resilience to droughts in catchment response in northern environments have been reported elsewhere. For a peat-covered upland catchment in northwest England, Worrall *et al*. (2007a) found no permanent effects on runoff initiation beyond a 1 in 33 year drought period, also suggesting that flowpaths were resistent against changes in droughts. Likewise, Burt *et al*. (2014) reported a quick recovery in runoff production and solute transport in a headwater catchment in southwest England, after the most severe drought ever recorded throughout the UK. However, land management practices in these environments such as drainage, vegetation burning, and high grazing levels are known to affect water table depths and runoff generation processes (e.g. Worrall *et al*., 2007b; Ramchunder *et al*., 2009). They may therefore indirectly also affect the local susceptibility of such affected areas to droughts.

The drought sensitivity indices (resistence, recovery, and resilience) which were used here are relatively simple, yet they have provided effective tools to compare the responses of the different hydropedological units and their integrated response at the catchment scale. However, their absolute values are depending on local site conditions including the climate regime (overall precipitation totals) and the mean values of flow and storage. To be able to use the indices in a wider context (e.g. comparisons between study sites), equations 1-3 should consider normalising the data through the use of for example, a rainfall index or average soil moisture regimes. Another limitation of the approach taken here relates to the clustering of the data. Both the total length as well as the timing of the three periods are likely to affect the absolute drought sensitivity indices. If the time periods were much shorter than the duration of a season, for example in the order of a few days or a week, the absolute values and the relative differences between the sites would most likely be more extreme. However, the definition of the exact periods would become even more complex owing to the difficulties related to precipitation events with long duration and the timescales of the storage responses. The three seasons analysed here were clearly defined based on differences in overall hydroclimatological conditions.

We recognise that the five monitoring sites alone will not represent the full spatial heterogeneity of drought impacts on storage and transmission processes within the catchment. However, their respective locations were carefully chosen so that the main functional landscape and hydropedological units could be characterised, and indeed have broad relevance for many northern upland catchments. Furthermore, the combination of the hydrometric and isotope datasets has assisted interpreting the integrated catchment scale effects of the processes observed at the plot scale. Such integration of processes across scales has provided additional insights into the patterns of storage processes in more general terms, for example on the identification and connectedness of stream water sources under contrasting hydroclimatological conditions, and the relative effects of evaporative processes.

Although permanent changes in hydrological processes were not observed, the disruption of hydrological connection during large parts of the dry period could have had other direct or indirect effects on, for example, the biogeochemistry, habitat quality for aquatic organisms, food resources, and the strength and structure of terrestrial and aquatic interlinkages (see reviews by Humphries and Baldwin, 2003; Lake, 2003; Bond *et al*., 2008). Furthermore, the current work has focussed on short-term (event-based and seasonal) impacts of one occurrence of unusually dry conditions only. Climate projections for northern environments suggest that prolonged warm and dry periods are likely to become more frequent (Murphy *et al*., 2009; IPCC, 2013). Indeed, decreasing trends in summer low flows have already been observed (Stahl *et al.*, 2010) and across Scotland, increases in the frequency of summer water resource scarcity have serious management implications (Capell *et al*., 2013; Gosling, 2014). As these periods are likely to become more common, and water demand is ever increasing (Kowalski *et al*., 2011) due to other pressures (such as increased energy demands and agricultural expansion/intensification), further work is needed on the potential cumulative or carry over effects of consecutive dry periods and the role of the spatial organisation of hydropedological and vegetation characteristics therein. This is of critical importance for ecosystems, where communities can show resilience to low-frequency disturbance, but high frequency disturbance may exceed the capacity for recovery (e.g. Lake 2003; Ledger *et al.*, 2012).

6. Conclusions

With water scarcity across the world ever more increasing, catchments, ecosystems and communities are becoming progressively more vulnerable to drought conditions (Hoekstra and Mekonnen, 2011; Falkenmark, 2013). For a humid, temperate,northern climate, we opportunistically assessed the impacts of an exceptionally dry period on the storage and transmission dynamics in different hydropedological units (poorly draining histosols in riparian zones and freely draining podzols on hillslopes), and their integrated catchment scale response. For this, we used an integrated approach of hydrometric data and stable water isotopes in precipitation, stream, soil, and groundwater. Our key findings were as follows:

1. There was large spatial heterogeneity in the resistance, resilience and recovery to drought impacts, associated with differences in dynamic storage changes of the hydropedological units. While resistant histosols remained wet thoughout the dry period, the podzols showed significant drying. This caused hydrological disconnectedness of large parts of the catchment during dry periods.
2. The spatial heterogeneity in drought tolerance was exacerbated by land use, where dynamic storage differences in podzols under tree cover were almost double than under heather moorland and recovery took relatively longer.
3. During events, consistent threshold behaviour in most hydropedological units was not affected by relative drying or wetting conditions, suggesting that there was an intermittent connection of the upper hillslopes that recharged the wetland and stream during events. This caused a strong recovery and resilience of the catchment in its overall runoff response.
4. Overall storage in all hydropedological units and stream flow recovered within a short time scale, which may be attributed to the extremely wet conditions that followed the dry period.
5. Our findings provide novel contributions to the understanding of catchment drought tolerance heterogeneities, and the important role of hydropedological units in northern environments.

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Table 1: Site Characteristics for the 5 monitoring locations. X indicates these data are available.

Site	Elevation	Main Vegetation	Soil Properties					Monitoring			
			Soil Type	Horizon (depth [m])	Bulk Density	Porosity	Organic Matter	GWL max monitoring depth [m]	Monitoring Depth	VSM	Stable Isotopes
S1	254	Sphagnum; Myrtle	Histosol (Peat)	O (0-0.6)	0.09	0.92	0.57	-1.25	0.1	X	X
					0.08	0.93	0.61		0.3	-	X
					0.06	0.95	0.72		0.5	-	-
S2	259	Heather; Sphagnum	Histosol (Gley)	O/Ap (0-0.2)	0.16	0.98	0.88	-0.61	0.1	X	X
				A/E (0.2-0.4)	1.50	0.46	0.03		0.3	X	X
				Bs (0.4-0.6)	-	-	-		0.5	X	X
S3	277	Heather	Podzol	O/Ap (0-0.2)	0.78	0.73	0.17	-0.495	0.1	X	X
				A/E (0.2-0.4)	1.25	0.47	0.03		0.3	X	X
				Bs (0.4-0.6)	1.47	0.42	0.02		0.5	X	X
S4	261	Scots Pine	Podzol	O/Ap (0-0.2)	0.74	0.68	0.80	-	0.1	X	X
				A/E (0.2-0.4)	1.04	0.60	0.08		0.3	X	X
				Bs (0.4-0.6)	1.35	0.45	0.02		0.5	X	X
S5	273	Heather	Podzol	O/Ap (0-0.2)	-	-	-	-0.48	0.1	-	-
				A/E (0.2-0.4)	-	-	-		0.3	-	-
				Bs (0.4-0.6)	-	-	-		0.5	-	-

Table 2: Hydroclimatological Characteristics for the pre, drying, and re-wetting periods

		February – May 2013 (Pre)*	June – September 2013 (Drying)	October 2013- January 14 (Wetting)
4 Monthly Statistics				
Temperature (°C)	Range	-6.8 – 12.7	5.7 – 20.2	-4.2 – 15.5
	Mean	3.0	12.6	4.6
Potential	Total	157	310	49
Precipitation (mm)	Total	325	193	588
Longest period witout P		5	18	4
No P (days)	Total	28	59	25
Discharge (mm)	Total	269	82	355
Q90 (mm/hr)		0.043	0.014	0.027
Q50 (mm/hr)		0.073	0.022	0.065
Q10 (mm/hr)		0.160	0.043	0.258
Runoff Ratio (P/Q)		0.72	0.43	0.60

Table 3: Statistical T-test results (p values) related to event characteristics for the different periods

Periods	Event Precipitation	Event Duration	Event Intensity	Maximum Event Intensity	Antecedent Precipitation Index	Maximum Peak Flow
Pre and Drying	0.368	0.302	0.261	0.270	0.028	0.016
Drying and Wetting	0.004	0.001	0.641	0.992	0.001	<0.001
Pre and Wetting	0.089	0.024	0.385	0.116	0.576	0.067

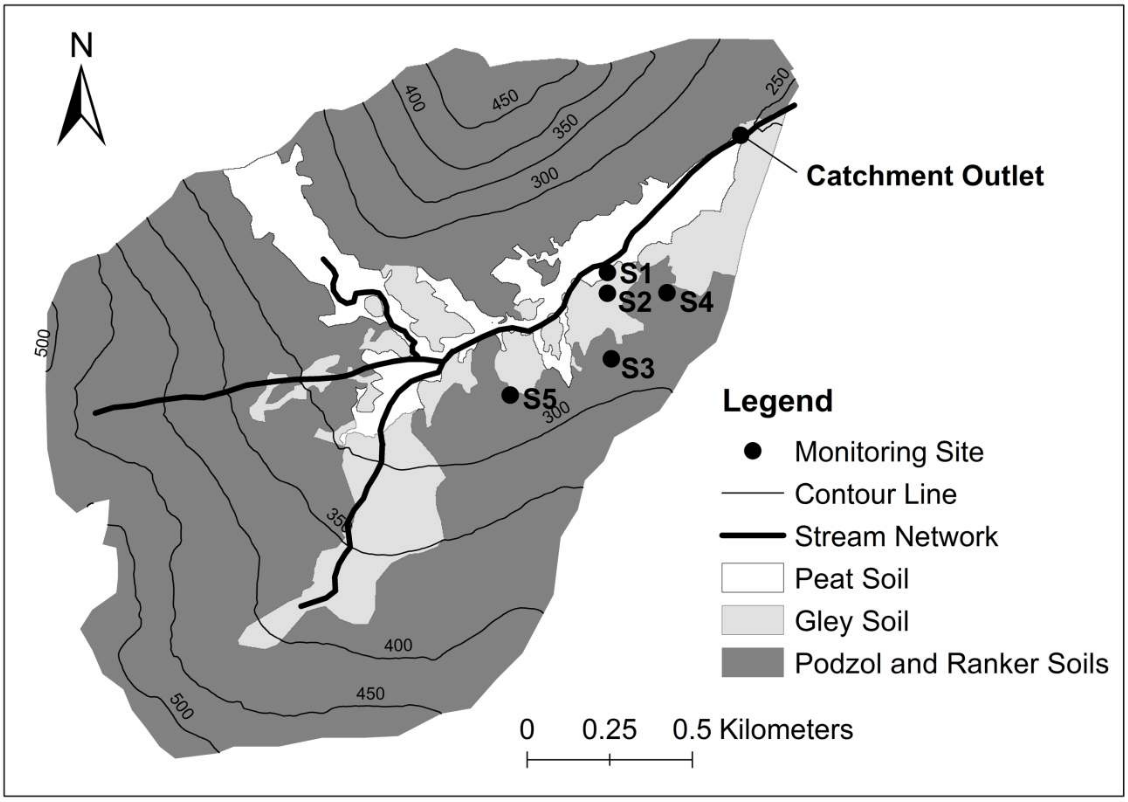

Figure 1. Bruntland Burn catchment: topography, soil distribution, and monitoring sites.

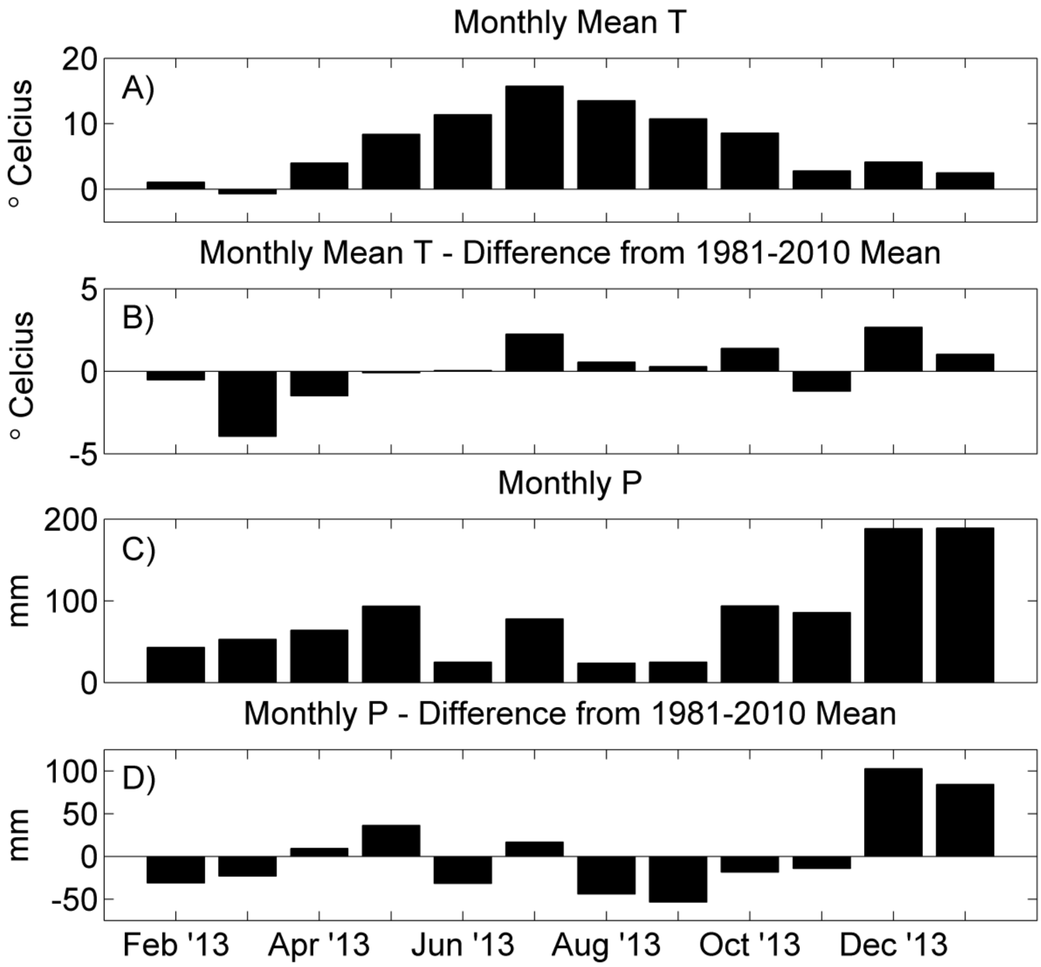

Figure 2: Monthly climatic conditions (Temperature (T) and Precipitation (P)) for the long term Braemar monitoring station (339 m AMSL), showing the observed values for the study period (A and C for T and P respectively) and the difference with the long term mean (B and D).

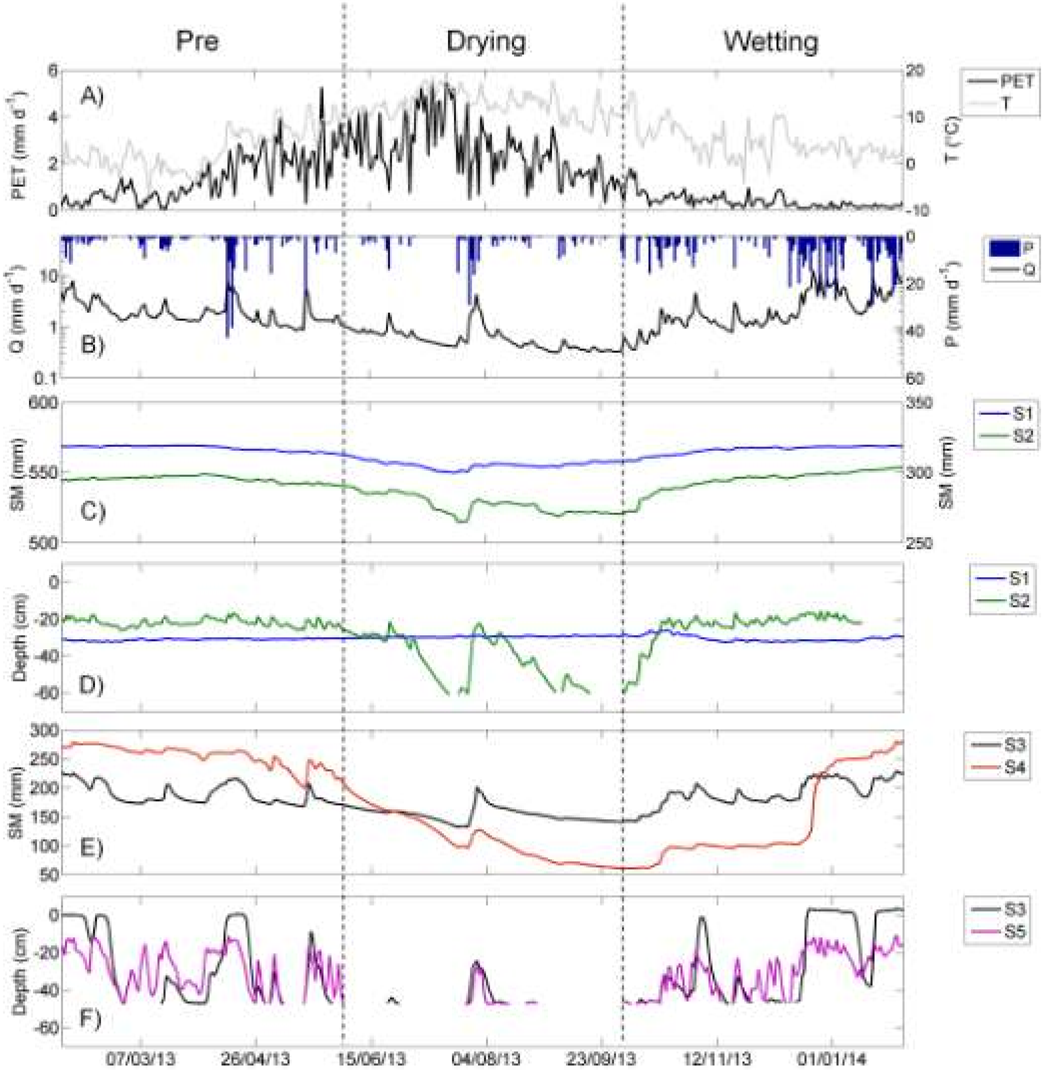

Figure 3: Temporal dynamics (01/02/2013 – 31/01/2014) in daily (a) Air Temperature and Potential Evapotranspiration, (b) Precipitation and Discharge for the Bruntlan Burn and (c) Soil Moisture, and (d) Shallow Groundwater Levels for Histosols (S1 and S2) and (e and f) Podzols (S3 and S4,S5), respectively. Distinct catchment drying and re-wetting occurred in the periods 01/06 – 30/09 and 01/10 – 31/01 respectively, as indicated by the dotted lines.

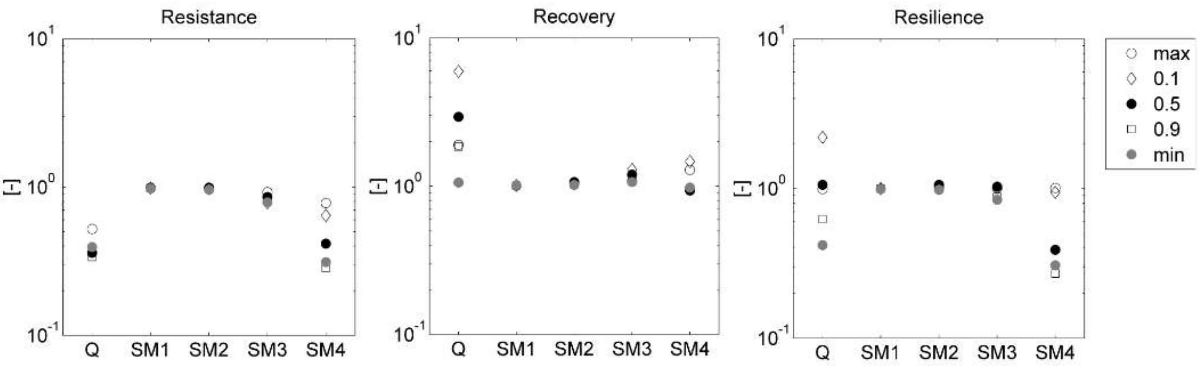

Figure 4: Drought tolerance indices (resistance, recovery, and resilience) for percentiles of discharge at the catchment outlet and absolute soil moisture estimates at four monitoring sites (soil moisture not measured at S5)

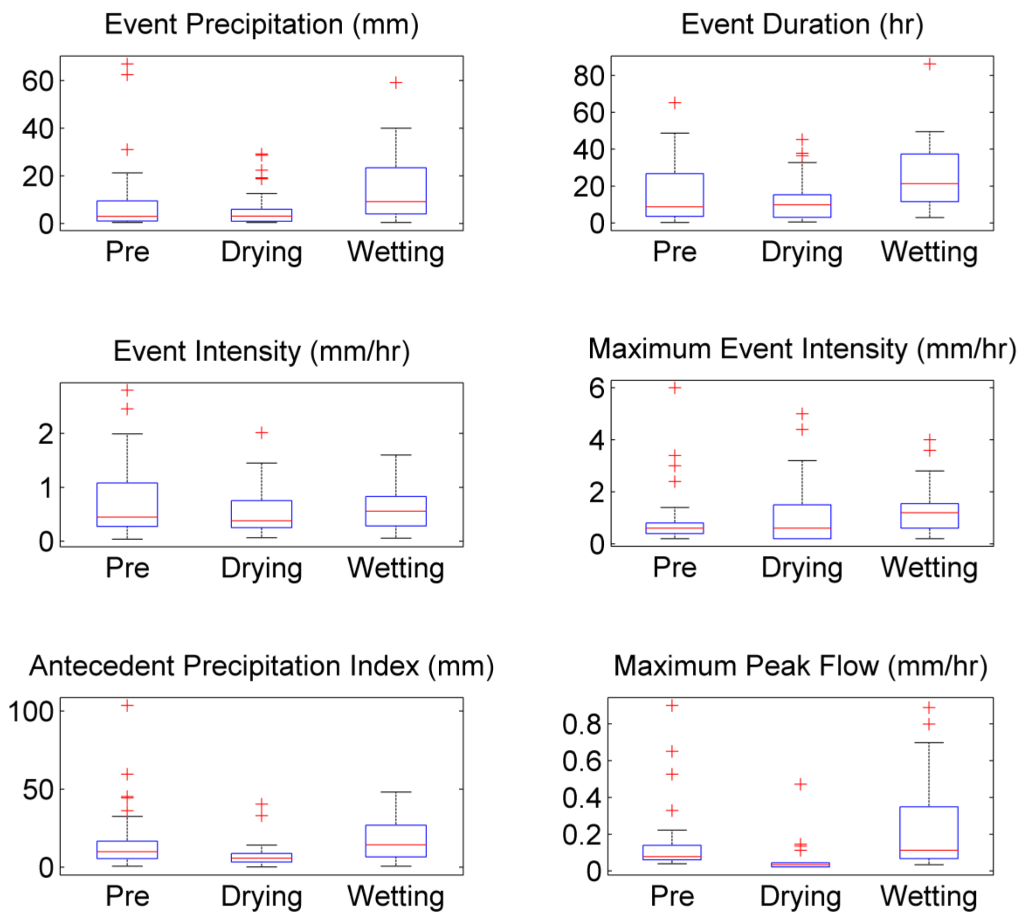

Figure 5: Precipitation event characteristic boxplots for the 'pre', 'drying' and 'wetting' periods, including event total precipitation, event duration, event precipitation intensity, maximum precipitation intensity, and maximum Bruntland event peak flow. For each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points, and outliers are plotted individually.

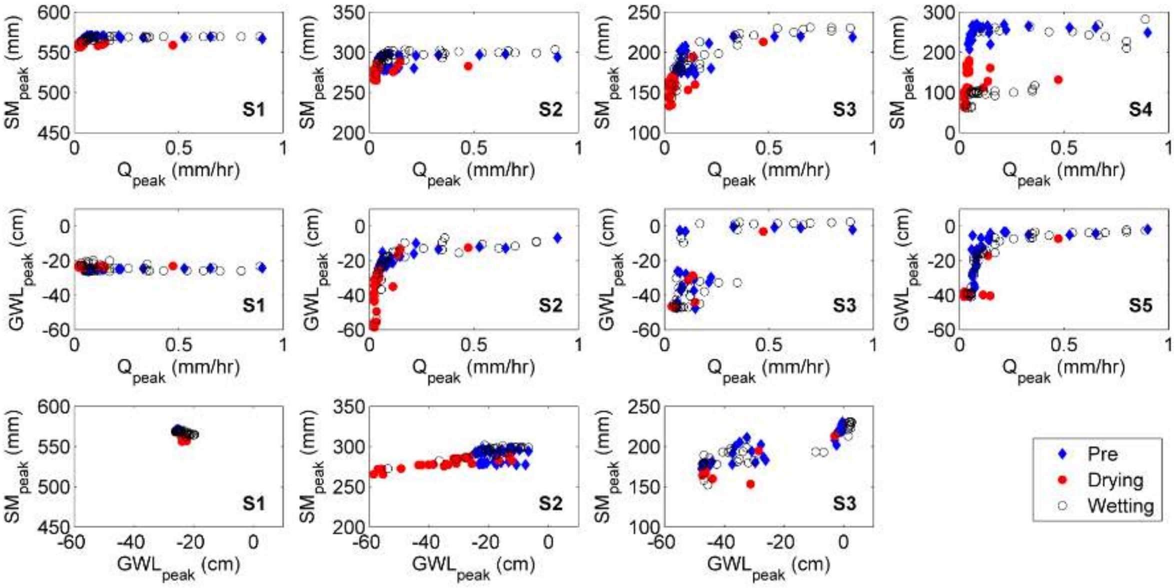

Figure 6: Event Magnitude Characteristics for the 'pre-drying', 'drying' and 'wetting' periods, respectively. The top and middle rows show the peak response in soil moisture and groundwater, respectively, versus the peak in discharge and the bottom row the peak response in soil moisture versus peak response in ground water level. Note the difference in scale for soil moisture at S4, compared to S1-S3, and the different absolute range for S1. The last plots of the top and middle row are from different sites (S4 and S5 respectively), due to lack of data availability.

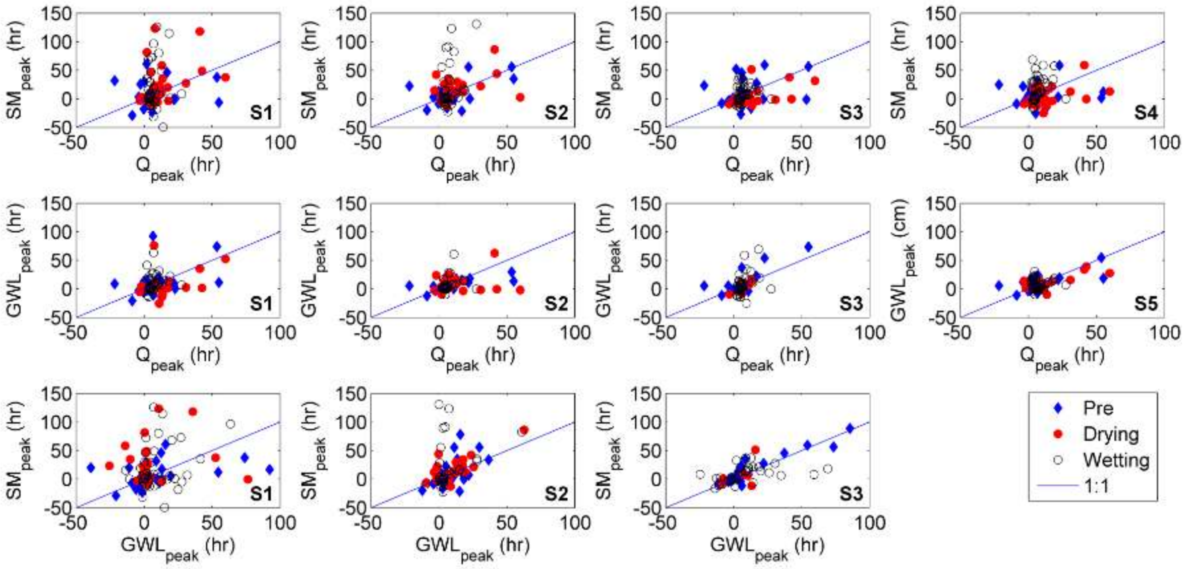

Figure 7: Event Lag Time Characteristics for the 'pre-drying', 'drying' and 'wetting' periods, respectively. The top and middle rows show the event peak timing in soil moisture and groundwater, respectively, versus the peak timing in discharge and the bottom row the peak timing in soil moisture versus peak timing in ground water level. The last plots of the top and middle row are from different sites (S4 and S5 respectively), due to lack of data availability.

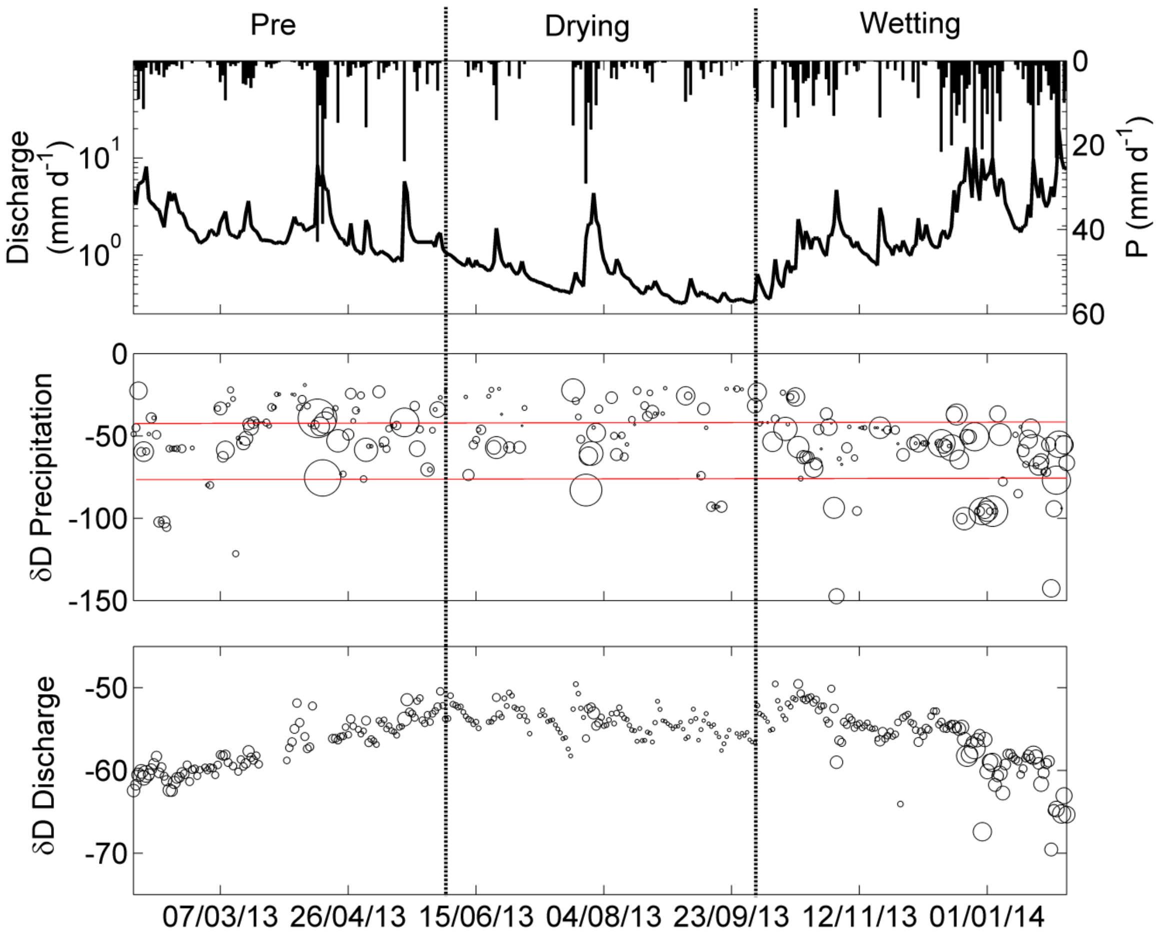

Figure 8: Daily precipitation and streamwater rates (top) deuterium isotopes (middle and bottom respectively). The size of the circles in the lower two plots indicates the magnitude of precipitation and discharge respectively. The red lines in the middle plot indicate the deuterium range of the discharge deuterium range (shown in the bottom plot).

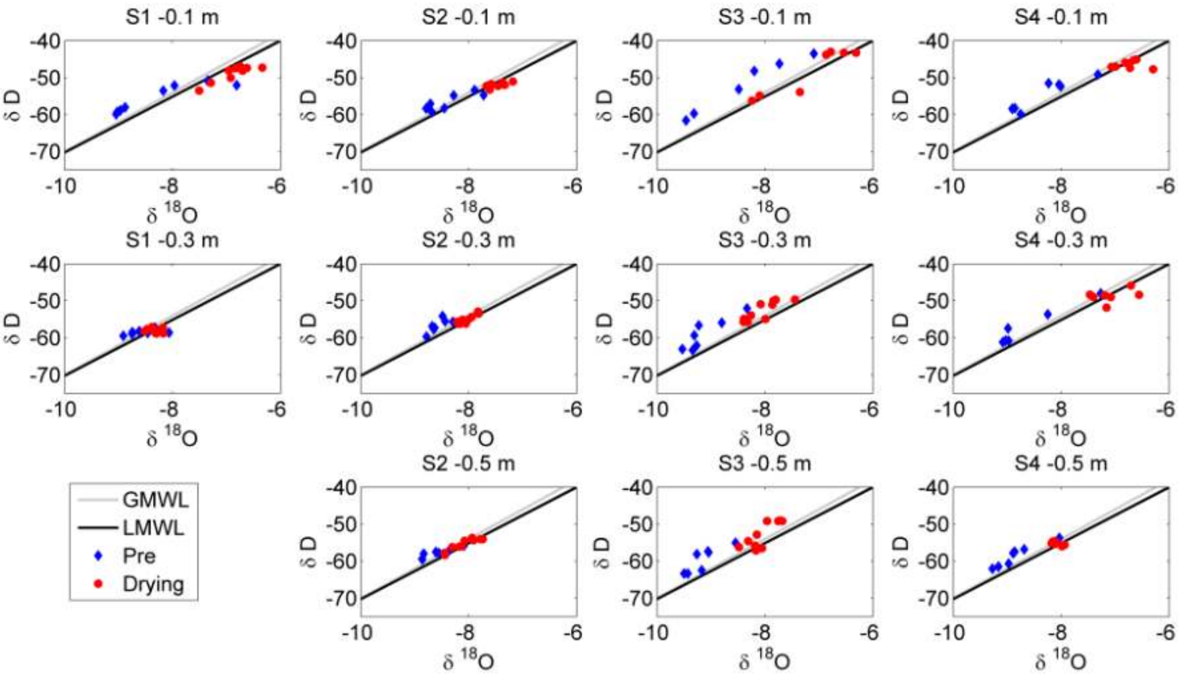

Figure 9: Soil Isotopes on the global and local meteoric water line for Sites 1-4, at depths of 0.1 , 0.3, and 0.5 m, for the period prior to and during drying.

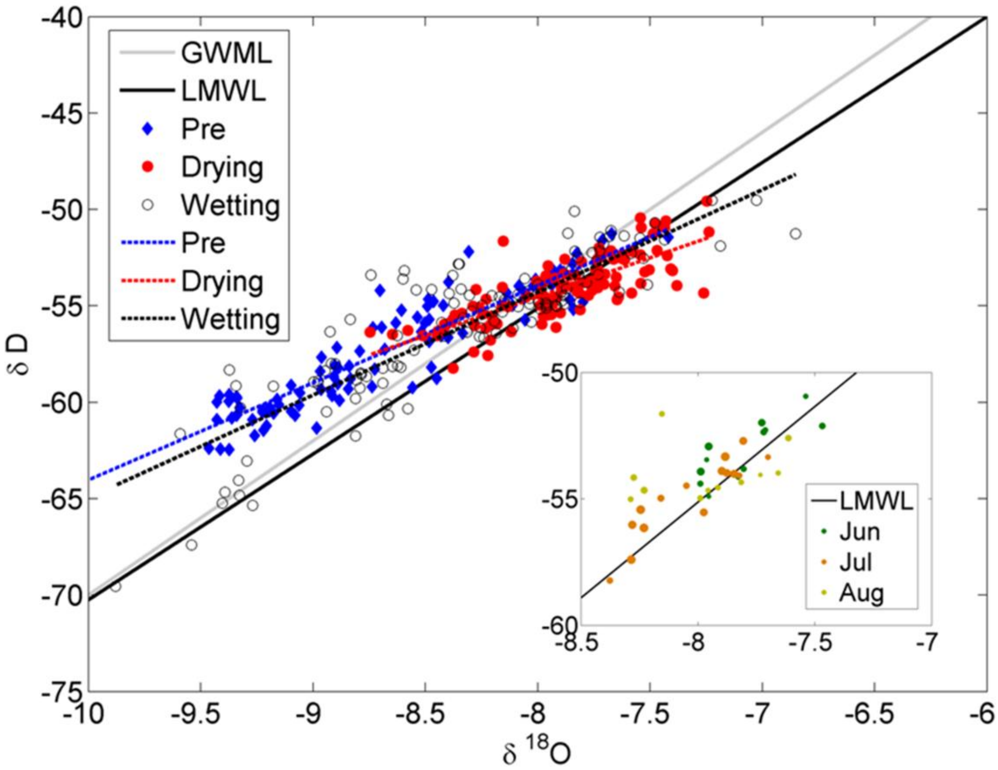

Figure 10: Stream water stable isotopes on the global and local meteoric water line, for the three different hydroclimatic periods (main figure) and for three months in summer, during which no precipitation was observed with symbol size reflecting the relative potential evapotranspiration of that day (lower right inset).