Landscape influence on small scale water temperature variations in a moorland catchment

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Landscape influence on small scale water temperature variations in a moorland catchment

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Abstract

We monitored temperatures in stream water, groundwater and riparian wetland surface water over 18 months in a 3.2 km^2 moorland catchment in the Scottish Highlands. The stream occupies a glaciated valley, aligned west-east and has three main headwater tributaries with northerly, southerly and westerly aspects. Much of the stream network is fringed by riparian peatlands. Stream temperatures are mainly regulated by energy exchanges at the air-water interface. However, they are also influenced by inflows from the saturated riparian zone, where surface water source areas are strongly connected with the stream network. Consequently, the spatial distribution of stream temperatures exhibits limited variability. However, there are significant summer differences between the headwaters, despite their close proximity to each other. This is consistent with aspect (and incident radiation), with the south and west facing headwaters having higher temperatures. The largest, north-facing sub-catchment shows lower summer diurnal temperature variability, suggesting that lower radiation inputs dampen temperature extremes. Whilst stream water temperature regimes in the lower catchment exhibit little change along a 1km reach, they are similar to those in the largest headwater; probably reflecting size and comparable catchment aspect and hydrological flow paths. Our results suggest that

different parts of the channel network and its connected wetlands have contrasting sensitivity to higher summer temperatures. This may be important in land management strategies designed to mitigate the impacts of projected climatic warming.

Keywords: stream temperature, riparian zones, thermal regime, connectivity, moorland hydrology, runoff processes.

1. Introduction

Stream water temperature is a critical physical parameter in riverine ecosystems (Caissie 2006); it governs many biogeochemical and ecological processes which influence water quality dynamics (Isaak and Hubert 2001) and stream metabolism (Izagirre et al. 2008; Kaushal et al. 2010; Birkel et al. 2013). It has the capacity to influence life cycles of aquatic organisms, such as determining the timing of fish spawning and the ability of organisms to resist disease (Malcolm et al. 2008). Temperature is also known to be a fundamental control on the distribution of organisms, as different species have contrasting tolerance to different temperature ranges (Malcolm et al. 2004; Caissie 2006). Climate change projections imply that even for low emission scenarios, both the winter and summer mean air temperatures in Northern Britain will increase by >1^{o}C over the next 30 years; worse case scenarios suggest 4^{o}C increase (UKCP09 2009). Given that temperatures are largely controlled by hydroclimatic drivers (e.g. net radiation fluxes), and modulated by the terrestrial environment, these projections suggest that stream temperatures will increase, with concomitant impacts on stream ecology and biogeochemistry likely (Hrachowitz et al. 2010).

Controlling terrestrial environmental factors include shading, provided by riparian vegetation and topography, elevation, groundwater contributions and stream channel morphology (Imholt et al. 2013). Some of these factors can be manipulated to mitigate the effects of climatic warming; this is a current area of policy development. Changes in stream thermal regimes occur as a result of both the aforementioned natural influences, but also of anthropogenic activity, for example, environmental change, reductions in flow, deforestation/afforestation and direct thermal pollution (e.g. effluent discharges). These may occur at all scales, from local, to regional, to global (Isaak et al. 2010; Ficklin et al. 2013).

In the UK, the headwaters of most large river systems drain upland areas of mountain and moorland environments. In such streams, short term (hours to days) temperature dynamics are driven by a combination of incoming solar radiation, stream flows, humidity and evaporation (Sinokrot and Stefan 1994; Caissie 2006; Hannah et al. 2008; Brown et al. 2010). Longer term variations (months, years etc.) are further influenced by reach characteristics (Malcolm et al. 2004), e.g. seasonal changes to riparian shading (Isaak and Hubert 2001; Hannah et al. 2008) and decadal to centurial lasting land management practices. The open moorland settings of many UK headwater streams have resulted from historical tree clearance and land management, which promote grazing of mammals (i.e. sheep (*Ovis aries*) and red deer (*Cervus elaphus*) or shooting of game birds such as red grouse (*Lagopus lagopus scotica*). These channels have limited shading as they often only have dwarf shrubs and grasses bordering them (Brown et al. 2010). Here, surface energy exchanges such as radiation inputs, air temperature, relative humidity and wind speed are the most important factors influencing stream temperatures. These factors determine the heat exchanges at the air-water interface (e.g. evaporation, sensible, and latent heat). Heat exchange also occurs at the water-channel bed interface as bed heat flux or loss and gain of net radiative energy. The balance of these components is dynamic, varying both sub-daily and seasonally, with many alternating between both heat sources and sinks (Hannah et al. 2008; Brown et al. 2010). Importantly, in such moorland locations, the daily means are often similar (Malcolm et al. 2004), though the temperature extremes are greater (i.e. the maximum and minimum water temperatures) (Hrachowitz et al. 2010) than in higher order watercourses, where riparian tree cover increases (Hannah et al. 2008, Brown et al. 2010). This contrasts with many studies in other regions which have shown that the daily minimum, maximum and mean temperatures in headwater streams tend to be generally lower than larger rivers, as the temperatures more closely reflect groundwater (Poole and Berman 2001; Caissie 2006). Others have also found that water temperatures generally increase downstream reflecting wider stream channels and less shading by vegetation than in forested headwaters (e.g. Lewis et al. 2000; MacDonald et al. 2013a; Moore, Nelitz, and Parkinson 2013).

To date, there have been relatively few investigations into the thermal regimes of open moorland streams. Previous work has largely focused on forest streams (e.g. Malcolm et al. 2004; Hannah et al. 2008; Brown et al. 2010) or alpine systems (Brown et al. 2006a; Brown and Hannah 2008; Blaen et al. 2012). The small scale spatial and temporal variations of thermal regimes in moorland channels and their associated hydrological source areas (e.g. soil water and groundwater) and landscape controls have rarely been investigated. Given the importance of such headwaters in providing ecosystem services to downstream river systems (Bishop et al. 2008) and the likely impacts of climate change, it is imperative that we have a good understanding of the thermal regimes of such streams and their associated controls.

In the Scottish Highlands, climate change projections indicate a likely warming of streams in summer, which will be exacerbated by reduced low flows (Capell et al., 2013, 2014). Such streams sustain aquatic ecosystems that have high conservation and economic value, with internationally important populations of Atlantic salmon (*Salmo salar*) (Malcolm et al. 2008) which may be threatened by warming. Consequently, there are proposals to mitigate the effects in such streams by riparian planting, though the implications of afforestation on ecosystem function are poorly understood (Birkel et al. 2013). Moreover, there is little guidance as to where such planting could be most effective (Wilkerson et al. 2006; Gomi et al. 2006).

Here, we examine small scale variability in stream temperatures and associated source waters in the 3.2km^2 Bruntland Burn catchment in the Scottish Highlands. This is a tributary of the 31km^2 Girnock catchment, a mainly moorland catchment that is a long-term monitoring site for Atlantic salmon and has a history of stream temperature studies (Hannah et al. 2008; Malcolm et al., 2008a). Previous work has shown a remarkable spatial consistency of thermal regimes in the moorland part of the river network, with any differences mainly due to the effect of riparian shading by trees in the lower 2km reach of the Girnock stream (Malcom et al., 2004). However, the thermal regime of the Bruntland Burn exhibited more highly moderated temperatures than other sites in the catchment; in addition to reduced diurnal variations, there are higher winter temperatures and lower summer temperatures than the other sites (Malcolm et al., 2004). It was also shown that there are subtle differences between the dominant runoff processes in the Bruntland and larger Girnock catchment; with proportionally higher groundwater contributions in the former (Birkel et al. 2011), but also a strong influence of a large riparian wetland that generates around 80% of the annual runoff (Tetzlaff et al., 2014). The current study aimed to characterise and explain the spatial and temporal variability of stream water temperatures within the Bruntland Burn catchment; the specific objectives were to:

1. Characterise any small scale spatial differences in water temperatures in the channel network of the Bruntland Burn and the source areas draining into it.
2. Investigate the temporal variability and the catchment wide spatial differences at both seasonal and 24 hour scales.
3. Examine the dominant controls on spatial and temporal variations in stream water temperatures, particularly with respect to landscape structure and linked water sources.

2. Study Site

The Bruntland Burn is located in the Cairngorms National Park, Scotland, UK (Tetzlaff et al. 2007; Tetzlaff et al. 2014). In brief, the area has been glaciated and has over-widened, gently sloping valley floors, receiving drainage from steeper hillslopes. The geology is mainly granite in the most elevated areas, with associated metamorphic rocks fringing. The bedrock is covered by various drift deposits (mainly poorly sorted till), which can be up to 40m deep in the valley bottoms. Land cover in the Bruntland Burn is mostly heather (*Calluna* vulgaris) dominated moorland, with limited forest cover (Figure 1a). The only significant riparian tree shading is located at the catchment outlet, where a plantation fringes the southern side of the stream. Thereafter the channel becomes tree-lined up to its confluence with the Girnock Burn. Upstream of this, dominant vegetation in the riparian zone includes *Sphagnum spp*. mosses, dwarf shrubs (*Myrica gale*) and grasses (*Molina caerulea*). The channel is relatively narrow (typically <1m) and deep (up to 2m in places) with overhanging vegetation, so in summer, when the *Myrica* is in leaf and water levels are lower, the radiation flux to the water surface is lower than might be expected.

A dominant feature of the catchment hydrology is that the riparian areas are mainly comprised of organic soils (histosols), which are quasi-permanent saturation zones that can be highly dynamic in their expansion and contraction (Figure 1b). The extent of the saturated area ranges between 2-40% of the catchment, depending upon the antecedent hydroclimatic conditions (Birkel et al. 2010). Around 80% of annual streamflow is generated from overland flow and seepage from these areas, the remainder comes from deeper groundwater discharge into the stream channel (Tetzlaff et al. 2014). Mean annual precipitation (P) is approximately 1000 mm and mean annual evapotranspiration (ET) is relatively low (~ 400 mm). Snow usually comprises < 10% of the annual P. Precipitation is evenly distributed with limited seasonality and most falls in low intensity frontal events (50% falls in events of <10 mm). Most events instigate a streamflow response, as water is displaced via saturation-excess overland flow from the saturated riparian zones, which are most of the time hydrologically connected to the channel network (Birkel et al. 2010). Runoff coefficients are typically <10%, but these increase non-linearly in wetter periods to around >40%, as the saturated zone in the valley bottom expands and connects lateral flow in the podzolic soils on the steeper hillslope to the channel network (Tetzlaff et al. 2014).

Mean annual air temperatures are about 6^{o}C, ranging between 12^{o}C and 1^{o}C in summer and winter respectively.

The Bruntland Burn has three main headwaters with contrasting characteristics (Figure 1c): Headwater One (HW1, 0.65 km^2) is south-facing and distinguished by a large mire in the valley bottom; the edges of the mire receive groundwater seepage from the surrounding hillslopes. Histosols cover 17% of this sub-catchment. The small stream draining HW1 has a shallow gradient and predominantly pool-riffle morphology. In contrast, Headwater Two (HW2, 0.43 km^2) is a steep east-facing valley (average slope 15^{o}) drained by a channel dominated by a cascade morphology. Soils on the steep slopes are mainly podsols and rankers, though histosols in the valley bottom cover 8% of the sub-catchment. Headwater Three (HW3, 0.81 km^2), is the largest and drains a wetland-dominated cirque, where deep peats (histosols) and shallow peats constitute 22% of the sub-catchment. The corrie base is wide; the average slope of the catchment is 14^{o}. Channel morphology is predominantly step-pool, with pool-riffle becoming more common in the lower area close to the confluence with main channel.

The confluence of these three headwaters is located in an over-widened glaciated valley, orientated west-east with a large area of histosols fringing the main Bruntland Burn. In this lower catchment, histosols cover 21.5% of the area. The dominant channel morphology here is pool-riffle. As noted above, the lower stream channel is narrow with a low width-depth ratio. This, together with a lack of riparian trees, means that most shading is due to channel dimensions, aspect (West-East) and riparian shrub cover (Table 1). Throughout the stream network there are point source influxes of surface water draining adjacent mires

(Figure 1). These are active most of the year, and stop flowing only in the driest conditions (Birkel et al. 2010).

3. Data and methods

The monitoring period ran between 21st June 2012 and 21st September 2013, though in order to not produce a summer bias, all annual analysis was based on the period 1st July 2012 to 30th June 2013. The monitoring period was chosen to allow seasonal comparison. Seasons were defined astronomically (i.e. between solstice and equinox) based on the orbit of the Earth.

Hydroclimatic data (precipitation, air temperatures, radiation, humidity and wind speed) were measured at an automatic weather station (AWS) in the Girnock catchment, operated by Marine Scotland Science (c.f. Hannah et al. 2004). Both discharge, calculated using an established rating equation (with stage height derived from a capacitance water level recorder in a rated natural section) and precipitation (using a Davis tipping bucket rain gauge) were measured within the Bruntland Burn catchment, using Odyssey data recording loggers at 15 minute intervals and averaged to hourly records.

Water temperature was measured using TinyTag TGP-4017 loggers (Gemini data loggers) with internal thermistors of 0.5°C precision. They have a response time of 25 minutes ("Temperature Loggers and Outdoor Data Loggers for Environmental Monitoring" 2013). Due to logistical and physical constraints, a 1 hour recording interval was used to reduce the download frequency, account for the response time and to control the quantity of data produced. Data was also used from two CTD Divers (Schlumberger Water Services), precise to 0.1°C. These were originally installed in the catchment in 2011, as part of a separate hydrology study. These also recorded every 15 minutes (and were averaged to one hour). All loggers were calibrated across a range larger than field temperatures, before and after the study period and were shown to be within 0.5°C accuracy.

The monitoring network represented a compromise between extensive spatial coverage, and being logistically manageable. Eleven stream loggers were installed to measure temperature; one in each of the headwater tributaries (HW1-HW3) and then at regular distances along the main stem of the Burn (SW4-11) (Figure 1). Logistics and access problems precluded installation at upstream sites in the tributaries, but data collected at their lower points captured their thermal characteristics. Previous work showed that the main deep groundwater influxes to the stream channel occurred along the wide, flat valley bottom, downstream of the headwater confluence. The intense monitoring along the main stem was therefore designed to detect effects of any major groundwater discharges as winter "hot spots" or summer "cold spots". To measure deeper (>2m) groundwater temperatures, one logger was located in an emerging spring (GW1) at the foot of the northern slopes in the lower catchment. Three further loggers were situated in wells along a hillslope transect (GW2-4) measuring shallower (<2m) groundwater levels. This hillslope transect has been the focus of detailed process studies on water flows paths and residence times, particularly in the hydrologically dominant riparian saturation zone (Tetzlaff et al. 2014; Geris et al. 2014). To measure surface water temperatures in this critical riparian zone, four loggers were positioned within connected perennial water tracks on the hillslope (SFW1) and riparian zone (SFW2-4) (Figure 1). The stream water loggers were attached to rocks and tethered to the bank, due to the lack of other available substrates and mainly peat bed and banks. The thermistors were shielded from radiation (Long and Jackson, 2013) and positioned on the streambed. Stream loggers were placed in sections of deeper water to reduce the chance of dewatering (Table 1). Given the small channel dimensions, relative water velocities, lack of a hyporheic influence and earlier work by Imholt et al., (2013) the effects of locational biasing was deemed unlikely to have a major effect.

Prior to statistical analysis, the data was manually checked and all spurious outliers (e.g. dewatering during data download) were removed (Sowder and Steel 2012) to produce a set of data free of errors. To investigate spatial differences in water temperatures mean, maximum, minimum and standard deviation were calculated for each of the stream water (HW1-3 and SW4-11) and groundwater (GW1-4) loggers for the whole study period and then for each of the seasons (including summer 2012). Degree days were calculated for each of the stream water locations as another way of visualising the differences, as they represent the sum of temperatures above the base level of 0^{o}C. In addition, we also carried out Kruskall-Wallis tests (Hollander, Wolfe, and Chicken 2013) and Wilcoxon signed-rank tests (Hollander, Wolfe, and Chicken 2013). These were selected as they are non-parametric tests, to compare the medians of non-normally distributed data sets. Because of the nature of stream water and its down-stream interdependence, we used the maximum instantaneous temperature recorded per day as well as the median. The reason for this was that previous work on spatially distributed temperature sensors in the Girnock had shown that differences were most apparent in the upper ranges, whilst lower temperatures were constrained by freezing, and medians were similar between sites.

The Kruskall-Wallis test was run using the full data set from July 2012 – July 2013 for all sites, as well as just the daily maximum temperatures. In addition, we ran the Wilcoxon test on paired loggers moving downstream as a post-hoc test for the variability between them, using a Bonferroni correction (Holm 1979) to adjust the p values. These tests assume that the data are independent, which is not strictly true in stream temperature studies, thus the results must be interpreted cautiously. The analysis then focussed on selected loggers (loggers HW1, HW2, HW3, SW5, SW9 and SW11) that summarized the thermal regime of the stream network and produced reasonable spatial distribution (see Figure 1), which then allowed more analysis at sub-seasonal scales.

To further assess differences between locations, seasonal temperature-duration curves (Brown et al. 2006b) were derived showing the percentage of time a particular temperature was equalled or exceeded. Based on the hydrometric data, we also calculated time-series of the extent of catchment saturation, using the algorithm (based on precipitation, antecedent wetness and a soil moisture parameter over the previous seven days) developed by Birkel et al., (2010). This was coupled with the available precipitation data and discharge data as a measure of antecedent wetness, and as a proxy for the source areas of water within the stream, on which incoming radiation can act. This characterisation of the catchment's wetness allowed the selection of contrasting 24 hour periods throughout the year. These were categorised as warm/wet, warm/dry, cold/wet and cold/dry. Temperatures for HW1-3, SW11, SFW3 & 4, GW1 and air temperature were investigated for each of the periods: cold/dry on 9th November 2012 (mean air T 6.8^{o}C, mean daily Q 0.03 $m^3 s^{-1}$, daily P 0mm and saturation extent 7%); cold/wet on 1st February 2013 (mean air T 1.6^{o}C, mean daily Q 0.17 $m^3 s^{-1}$, daily P 1mm and saturation extent 33%); warm/dry on 8th September 2012 (mean air T 15.6^{o}C, mean daily Q 0.024 $m^3 s^{-1}$, daily P 0mm and saturation extent 2%); warm/wet on

27th August 2012 (mean air T 12.6^{o}C, mean daily Q 0.04 m^3 s^{-1}, daily P 12.6mm and saturation extent 7%).

4. Results

4.1 Hydroclimatological context

Air temperatures followed expected seasonal patterns, reflecting incoming radiation (Figure 2a and b). However, a cool, wet summer in 2012 was followed by an unusually cold winter and spring in 2013 (Figure 2b), with below-average temperatures persisting until April (Met Office 2013a; 2013b). This also corresponded with long periods of snow cover and ground frost which coincided with intermittent partial freezing of the upper soils (<5cm) and the stream surface. Warmer spells in mid-December 2012 and late February 2013 led to snow melt and substantial increases in discharge of up to 16 mm per day, which was the highest discharge observed (Figure 2d). Whilst the summer of 2012 was the wettest for 100 years, summer 2013 was the driest and warmest for 10 years (Met Office 2012; Met Office 2013c). The extent of the saturated riparian zone (as a percentage of catchment area) was calculated using an algorithm that expressed antecedent conditions as a function of evapotranspiration (ET) and precipitation (Birkel et al. 2010). During the wetter periods (e.g. winter 2012-2013) the saturation extent was >40% (Figure 2e). In summer with higher temperatures, saturation extent remained <20% and was <5% for sub-monthly periods.

4.2 Spatial variations in water temperature

Spatially, the average, range and dynamics of stream water temperatures are very similar throughout the catchment (Table 2 and Figure 3). Differences between the three headwaters become apparent only during the summer periods, when temperatures are highest. HW1 had the largest variations in temperature and a slightly higher mean. HW2 had the highest maximum temperature but a slightly smaller standard deviation than HW1. In contrast, HW3 showed the most damped dynamics (low standard deviations) and lowest mean temperature. Degree day analysis correspondingly showed similar patterns between the headwaters; HW3 had the lowest and HW1 the highest. The minimum temperatures for all sites were similar and within the precision of the instrumentation, they remained in liquid water throughout the period.

Mean stream water temperatures, downstream of the headwater confluence, (locations SW4-11) remained relatively constant, though they were closest in range to HW3 and did not exhibit the extreme high temperatures of HW2 and HW3. Only SW10 deviated substantially with a lower mean and maximum temperature. This site is downstream of the inflow of the groundwater spring monitored at GW1. The annual degree days for the post confluence sites also showed relative homogeneity, though they were lowest of all sites at SW10 (Table 2).

Of the groundwater sites, GW1 exhibited remarkable thermal constancy and had the highest median. Shallower subsurface water at the upslope sites (GW2 and 3) had greater variability (Figures 3 and 4, Table 2). These dynamics differed from stream waters, in terms of a reduced range, though the medians of GW2 and 3 were close to the stream sites. GW4 (situated in the riparian peats where the water table remains within 20cm of the soil surface) had lower variation, showed higher mean and minimum, but lower maximum temperature than sites further up the hillslope (where the water table depth varies between 20cm to >1m below the surface).

The riparian surface water loggers (SFW3 & SFW4) had similar median temperatures to stream water. The variation of these surface waters was higher than the stream water temperatures along the main stem. SFW3 showed similar temperatures to the main channel, and SFW4, situated in the riparian zone further upstream from SFW3, showed the greatest temperature variability of all surface water loggers, largely as a result of occasional winter freezing (Figure 3 and Figure 4).

Results of the statistical tests showed that there were no statistically significant differences between the medians of stream water sites ($p>0.05$). However, for the maximum daily temperatures showed a significant difference ($p=<0.05$) with HW3 being different to HWs1 and 2. The tests also confirmed the difference of the four GW sites from the stream water sites ($p<0.5$), whilst there was no pairwise difference between the stream water site at SW11 and the four SFW loggers.

4.3 Seasonal variability in water temperatures

The seasonality of weekly stream temperatures showed similar temporal variations at the headwater sites and the sites along the main stem (Figure 5, Table 3). The main stem (SW4-11) showed no significant inter-site seasonal variation (Table 3) and exhibited similar variability during all seasons. HW3, which had the lowest variability in all seasons, was most similar to the main stem sites. The most apparent differences were the higher summer temperatures in HW1 and HW2.

Temperature exceedance curves show the integrated effect of these seasonal changes; differences are most clear during summer (Figure 6). HW3's lower summer temperatures and variability is apparent, as is the intermediate distribution of main stem summer stream temperatures plotting between HW1&2 and HW3. During autumn 2012, the upper portion of the curves for all sites was similar, with the tail of the distribution showing separation, and HW3 being warmer than HW2 and HW1 as temperatures dropped (Figure 6a). During winter and spring (Figure 6b and c), the duration curves converged with little difference, though in spring the warmer temperatures in HW1 began to become apparent. The warm, dry summer of 2013 (Figure 6d) had higher temperature extremes than the cooler, wetter summer of 2012 (Figure 6e), with inter-site differences becoming more evident as temperatures increased, particularly in 2013. In this latter year (Figure 6d), HW2 had the steepest and HW3 the shallowest curve. During such warm conditions, temperatures in the riparian surface water sites (SFW) tend to be higher than HW3, but cooler than HW1 & 2.

4.4. Diurnal variability in water temperature

Temperatures during four 24 hour periods (Figures 7-10) give examples of the typical diurnal variations of the stream waters and representative source waters. These show fairly consistent differences in the diurnal cycles of the 3 headwaters, in relation to the main stem sites. The 24 hour periods exemplify contrasting antecedent and hydroclimatic conditions: cold and wet (1st February 2013), cold and dry (9th November 2012), warm and wet (28th August 2012) and warm and dry (8th September 2012). Stream temperatures in the lower catchment (SW sites) usually fall between HW1&2 and HW3, but are also similar to the SFW sites. The deep groundwater (GW 1) remains constant throughout each 24 hour period considered.

The cold/wet period (Figure 7a) exhibited the least spatial variability between sites. Water at all sites was super-cooled and close to 0^{o}C. Over the 24 hours, air temperature dropped steadily (Figure 7b). Of the headwater sites, HW3 exhibited the highest maximum temperature and HW1, the lowest. In the main stem, SW11 showed the highest peak (~1.5 ^{o}C) of all, with the peak around 3pm approximately 2 hours after the headwaters. SFW3 remained more constant, at around 1.5^{o}C, and showed similar levels and patterns as the streams and remained above air temperature during the afternoon. SFW4 showed greatest variability.

The cold, dry 24 hour period occurred at the end of a dry autumn. Air temperature (Figure 8) showed modest variability, but a decrease in the evening of ~4 ^{o}C. Stream temperatures varied between 4.5 and 6.5^{o}C (Figure 8a). HW3 showed the least variability and HW2 the greatest. SW11's diel curve was most similar to the shape and magnitude of HW3. Both HW1 and HW3 reached thermal maxima around 14:00, several hours after HW2. This was also about 2 hours before the peak of SW11, at the catchment outlet, and several hours after the peak at surface water site SFW3. This site showed the least variability in surface water temperatures, with temperatures being slightly cooler than stream water, though the variability in SFW4 was similar to the stream.

The wet, warm period in August 2012 had stream water temperatures ranging from around 10^{o}C to 12^{o}C (Figure 9a); air temperatures varied between 9^{o}C and 14^{o}C. HW3 had the lowest variation (~1^{o}C). The highest maximum (>12^{o}C) was at HW2. HW1 was intermediate but had the lowest minimum value. Thermal maxima at all sites occurred at 16:00. Both

HW3 and SW11 had very similar magnitude diel variations, with HW3 generally having a slightly lower maximum and higher minimum values. Surface water temperatures exhibited slightly higher values and variability was higher at SFW4, but lower at SFW3. Day-time peaks occurred slightly before stream water temperature at SW11 peaked.

Warm, dry conditions in September 2012 saw air temperature ranges from 7^{o}C to >20^{o}C (Figure 10). Again, HW3 showed least variability (range <2.0^{o}C) and HW1 the greatest (range ~5^{o}C). The daily maxima for the three headwaters occurred simultaneously (15:00) with SW11 being about 2 hours later. As with other periods, SFW3 showed lower variability with a lower magnitude curve, more similar to stream waters than SFW4, which was more pronounced like the diurnal air temperature curve.

5. Discussion and wider implications

Many studies have examined interactions between landscape structures and stream temperatures (Malcolm et al. 2004; Hannah et al. 2008; Malcolm et al. 2008; Brown et al. 2010), though some have been based in very different geographical settings to the one in this study (Brown et al. 2006a; Brown and Hannah 2008; Isaak et al. 2010; Mayer 2012; Blaen et al. 2012; Leach and Moore 2013). However, all have highlighted heterogeneities that can occur in stream thermal regimes, with differences in controls at contrasting temporal and spatial scales (Webb and Walling 1985).

The first obvious finding of the study was the general similarities in stream water temperatures, throughout the catchment, for most of the period. Only during the summer months did differences between any stream water sites become apparent and statistically significant. This was largely restricted to the south-facing HW1 and east facing HW2 sub-catchments and showed higher maximum temperatures. Correspondingly, it seems that HW3 has a disproportionate influence on the thermal regime of the lower catchment downstream of the confluence of the three tributaries, as its annual range seasonal variations and diurnal dynamics were most similar to the main stem sites. On the one hand, this probably simply reflects the larger size and, therefore, likely higher discharge and higher thermal capacity (Constantz et al. 1994). Additionally, the characteristics of HW3 and the lower catchment have many similarities, including large north-facing areas, similar distributions of soils and drift and similar landscape structure in terms of riparian saturated zones. This is likely to result in a similar relative importance of runoff generation processes (Tetzlaff et al. 2007). Such influence of different runoff sources on stream thermal regimes has been previously shown (R. D. (Dan) Moore 2006; Mayer 2012; MacDonald et al. 2013b; Imholt et al. 2013). Runoff generation in the Bruntland Burn is dominated by near surface flow paths – particularly overland flow from peaty soils – which maintain strong hydrological connectivity with the channel network. These extensive areas of saturation act, not only as hydrological source areas, but as a water-air interface for energy exchange additional to the actual channel network (Janisch et al. 2012). This is consistent with the finding that the surface water sites have similar thermal regimes to stream water sites.

Groundwater inflows have been shown to have a moderating effect on steam water temperatures in many locations (e.g. Webb and Walling 1985; MacDonald et al. 2013). The groundwater temperatures at GW1 are clearly very stable throughout the year, due to the insulation effects of surface sediments (soil, glacial drift etc; (Figura et al. 2011). However, in the Bruntland Burn up to 40% of annual runoff is generated by hillslope groundwater discharging into the riparian wetlands (Tetzlaff et al. 2014), thus facilitating an opportunity for atmospheric energy exchanges to occur, before water reaches the stream channel. Indeed, the groundwater wells in the riparian zone showed that temperatures in shallower groundwater had more variable thermal regimes, reflecting the greater influence of atmospheric energy exchanges (Kurylyk et al. 2013). The contribution of deeper groundwater discharge directly into the stream channel network is low (around 19% of annual runoff) (Birkel et al. 2011). Its influence is most apparent during winter when heat transfer into streams can account for up to 30% of inputs – as atmospheric energy inputs are low – and probably prevent the stream from freezing (Hannah et al., 2004). Nevertheless, the effects of the spring, monitored at GW1, on stream temperatures is evident at SW10, which has the lowest degree days of all stream water sites.

Aside from SW10, the thermal regimes of the monitoring sites in the lower part of the catchment, along the main stem of the stream channel, are consistent and lacking in variability. In addition to the similar catchment characteristics and runoff sources as HW3, in summer, this may also, to some extent, reflect the low width:depth ratio of the channel (Sinokrot and Stefan 1993; Hawkins et al. 1997; Arscott et al. 2001; Long and Jackson 2013) and the riparian cover of shrubs. This would mitigate further warming by limiting incident short wave radiation and moderate night time cooling by back scatter of long wave (Hannah et al. 2008; Malcolm et al. 2008).

The thermal regimes monitored in stream water in the Bruntland Burn largely reflect the dominance of hydroclimatic controls at inter-annual, seasonal and diurnal scales, which give overall similarity between sites. The most obvious difference is that the spatial variability in stream water primarily reflects aspect (and the resulting influence on energy inputs), with the three headwater streams having the most marked differences in thermal regimes in summer. The importance of aspect as a landscape factor in the moderation of atmospheric exposure is well documented (e.g Cadbury et al., 2008; Quinton and Carey, 2008; Janisch et al., 2012) among others. The south-facing HW1 is generally the most variable, whilst the east facing HW2 exhibits the highest summer maxima, particularly in 2013. This may also affect hydrological influences, as flows (although unmeasured) were observed to be very low from this sub-catchment, during the 2013 drought period, and this will have affected the thermal capacity of this stream (Sinokrot and Gulliver 2000; Caissie 2006; Orr et al. 2014). HW3 has the most moderated thermal regime, with attenuated maxima and minima and the lowest range through autumn, spring, and summer.

Projections indicate that there is likely to be large scale warming of streams, due to the effects of climate change, on un-forested headwater streams in the northern UK, by the middle of the 21st Century (Hrachowitz et al. 2010). Our results suggest that an understanding, of small scale, subtle spatial differences in summer stream water temperature, is likely to be important in impact assessment for small moorland catchments, like the Bruntland Burn. Such understanding enables the evaluation of the implications of changing meteorological conditions on small headwater catchments, in which the thermal heterogeneity can be substantial (e.g. in sub-catchment comparisons) at higher temperatures. Here lethal or sub-lethal effects may occur on organisms adapted to colder water upland streams. As upland streams are often important nursery streams for Atlantic salmon (*Salmo salar*), concerns over projected temperature increases have resulted in the promotion of riparian tree planting as an ameliorative measure (Rutherford et al. 1997; Broadmeadow et al. 2011). Given the likely importance of the water-air interface on saturated peaty soils, more extensive buffer strips that result in natural tree cover in such a saturated area may need to be considered, to achieve temperature amelioration goals.

These preliminary results provide a basis for using more quantitative methods focusing on analyses of temporal and spatial distributions of land/water-energy exchanges, for example, using LIDAR in conjunction with daily assessment of solar position to account for effects of aspect, hillslope and channel shading. Additionally, groundwater models are being used to simultaneously track water and heat fluxes, to assess the overall effect of direct and indirect groundwater fluxes (Kurylyk, Bourque, and MacQuarrie 2013b). Finally, whilst increasing riparian shading to improve the thermal habitat for juvenile salmonids is a current target of some land management strategies, there are wider ecosystem effects on other components of aquatic function that need to be assessed.

6. Conclusions

This study investigated the spatial and temporal variations in stream water temperatures in a small headwater catchment. We conclude that:

- Stream waters within the catchment have very similar thermal regimes; the main differences are restricted to differing summer high temperatures in three headwater sub-catchments with contrasting aspect.
- The largest headwater catchment (HW3) appears to have a dominant influence on the lower catchment which reflects both the size of HW3 but also the similarities in water sources, mitigation effects of the saturated riparian zones.

- The temperature profile of the stream in the lower catchment appears to be strongly influenced by the energy balance of the source areas (e.g. riparian saturation zones with overland flow) and not just the stream channel.

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Catchment	Area (km2)	% wetland soils	Mean Slope (^{o})	Aspect (^{o})	Mean elevation (m)	W:D ratio at point of sample
HW1	0.65	17.2	15	146 (NW)	339	1.50
HW2	0.43	8.4	15	103 (E)	397	2.00
HW3	0.81	22	14	122 (NW)	409	0.75
SW4	2.03	10.3	14	126 (NW)	379	1.00
SW5	2.04	17.9	14	126 (NW)	378	1.75
SW6	2.29	18.2	13	138 (NW)	371	3.00
SW7	2.39	18.3	13	141 (NW)	368	1.00
SW8	2.44	18.6	13	143 (NW)	367	1.17
SW9	2.54	19.1	13	145 (NW)	364	1.17
SW10	2.82	20.8	13	150 (NW)	358	0.88
SW11	3.16	21.5	13	151 (NW)	352	3.50
Bruntland Burn	3.29	21.5	13	151 (NW)	349	1.30

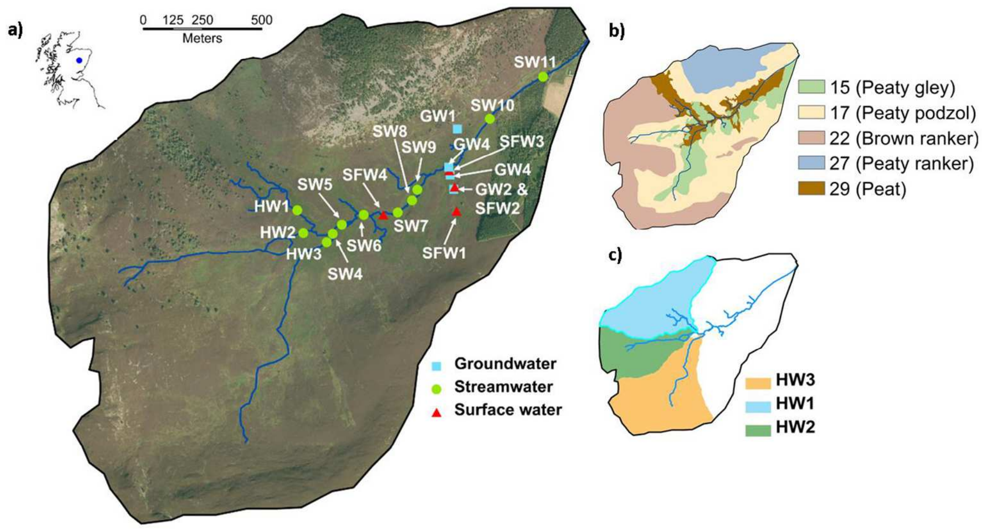
Table 1: Characteristics of the catchment areas above each of the stream water temperature loggers, including the three headwaters (HW1-HW3).

	Mean (°C)	Minimum (°C)	Maximum (°C)	Max-Min Difference (°C)	Std. Deviation (°C)	Degree Days
HW1	6.55	-0.03	21.07	21.1	5.45	2392
HW2	6.45	0.06	23.70	23.64	5.33	2355
HW3	6.31	0.04	17.53	17.49	4.71	2303
SW4	6.41	0.06	18.19	18.13	4.90	2340
SW5	6.41	0.03	18.30	18.27	4.92	2341
SW6	6.44	0.07	18.24	18.17	4.89	2350
SW7	6.40	0.05	18.15	18.1	4.85	2338
SW8	6.42	0.06	18.09	18.03	4.81	2343
SW9	6.41	0.04	17.99	17.95	4.75	2340
SW10	6.02	-0.55	17.73	18.28	4.90	2198
SW11	6.32	-0.31	18.23	18.54	4.87	2305
Deep groundwater (GW1)	6.98	5.49	8.67	3.18	1.02	2666
Shallow groundwater (GW2)	5.50	1.36	13.32	11.97	3.39	2207
Shallow groundwater (GW3)	5.82	1.81	12.96	11.15	3.25	2308
Shallow groundwater (GW4)	6.69	3.29	11.02	7.73	2.31	2440
Surface water (SFW1)	6.31	0.28	19.53	19.25	4.90	2301
Surface water (SFW2)	6.44	-0.89	19.53	20.42	5.14	2352
Surface water (SFW3)	6.17	0.15	17.43	17.28	5.05	2132
Surface water (SFW4)	6.43	-9.11	23.78	32.89	5.69	2362
Air temperature	5.74	-13.59	22.11	35.7	6.00	1865

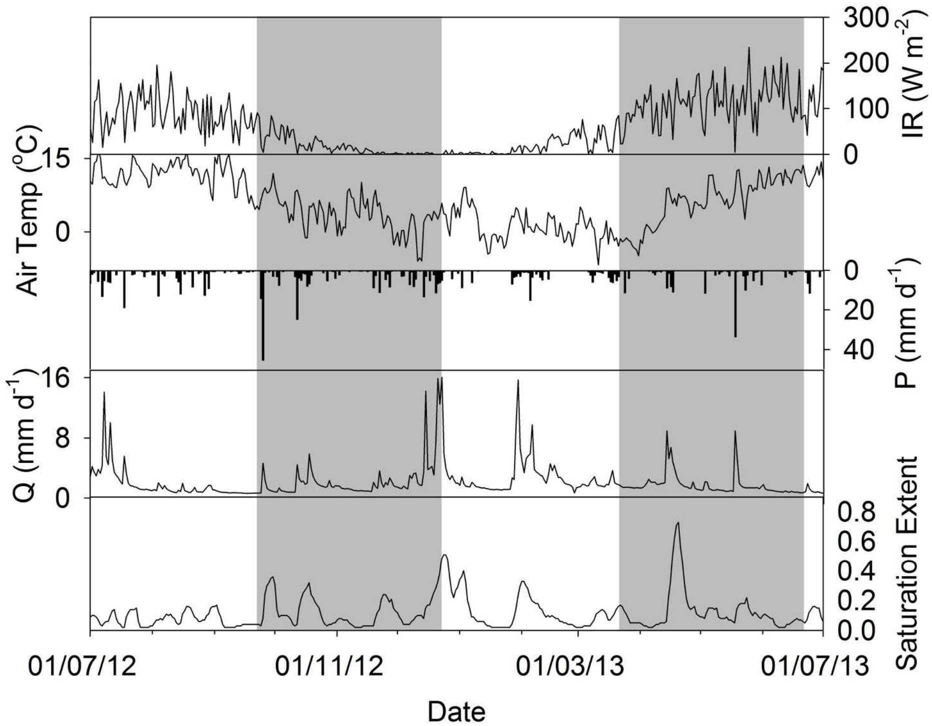
Table 2: Descriptive statistics for all stream water (HW1-3 and SW4-11), groundwater (GW1-4) during the period July 2012 to July 2013 (based on hourly data). The period was chosen to avoid biasing the data by including two summer periods.

		HW1	HW2	HW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	SW11	AT
Summer 2012	**Mean**	12.90	12.55	12.05	12.29	12.31	12.33	12.27	12.23	12.16	11.88	12.14	11.77
	Minimum	5.53	5.66	7.10	6.74	6.70	6.76	6.81	6.73	6.59	5.79	5.65	-3.31
	Maximum	21.47	21.49	17.53	18.35	18.61	18.62	18.54	18.41	18.14	17.73	18.11	22.11
	Std. Deviation	2.62	2.51	1.71	1.93	1.95	1.94	1.92	1.91	1.91	2.04	1.99	3.70
Autumn 2012	**Mean**	3.76	3.89	4.34	4.19	4.17	4.21	4.19	4.23	4.25	3.75	4.08	3.62
	Minimum	-0.02	0.10	0.08	0.09	0.06	0.09	0.07	0.08	0.07	-0.55	-0.26	-12.10
	Maximum	11.67	12.03	9.91	10.29	10.25	10.25	10.11	10.13	10.19	10.24	10.59	15.05
	Std. Deviation	2.84	2.77	2.47	2.57	2.58	2.57	2.56	2.54	2.51	2.55	2.57	4.42
Winter 2012/13	**Mean**	1.30	1.33	1.51	1.49	1.48	1.53	1.53	1.59	1.65	1.14	1.46	1.24
	Minimum	-0.03	0.06	0.04	0.06	0.03	0.07	0.05	0.06	0.04	-0.55	-0.31	-13.60
	Maximum	5.96	5.67	5.37	5.52	5.53	5.57	5.56	5.59	5.64	5.41	5.58	11.82
	Std. Deviation	1.37	1.27	1.24	1.27	1.28	1.27	1.27	1.27	1.27	1.33	1.33	3.85
Spring 2013	**Mean**	8.00	7.76	7.13	7.44	7.47	7.47	7.43	7.44	7.39	7.10	7.36	6.09
	Minimum	-0.03	0.06	0.07	0.08	0.04	0.07	0.05	0.07	0.04	-0.55	-0.30	-12.72
	Maximum	20.80	23.70	15.97	17.30	17.58	17.04	16.54	16.67	16.95	17.73	18.23	19.39
	Std. Deviation	4.91	5.01	4.15	4.37	4.38	4.34	4.27	4.22	4.17	4.34	4.29	5.78
Summer 2013	**Mean**	13.82	13.78	12.53	12.91	12.88	11.57	12.57	12.58	12.58	13.60	13.13	13.06
	Minimum	6.15	5.36	7.64	7.38	7.21	7.09	6.67	5.72	5.75	8.04	5.23	0.26
	Maximum	23.19	25.97	17.87	19.21	19.41	19.30	19.19	19.56	19.43	20.91	21.67	26.93
	Std. Deviation	2.79	3.55	1.73	1.98	2.00	2.49	2.00	2.30	2.32	2.42	2.75	4.53

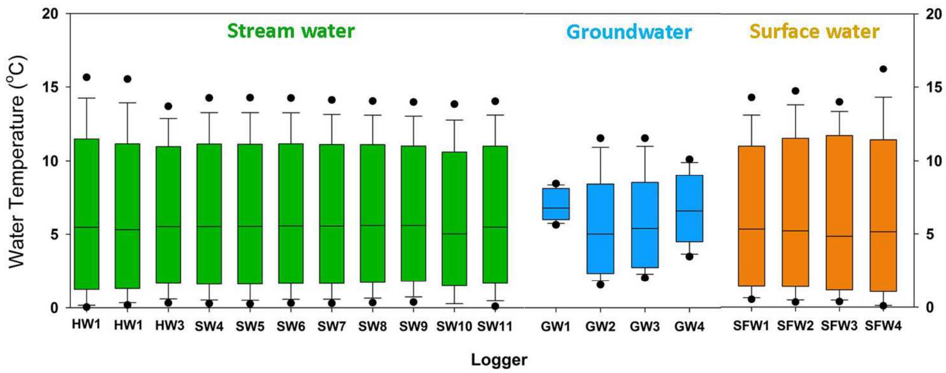
Table 3: Descriptive statistics for stream water loggers (HW1-3 and SW4-11) and air temperature (AT) during 5 different seasons (^{o}C, based on hourly data). Seasons defined astronomically.



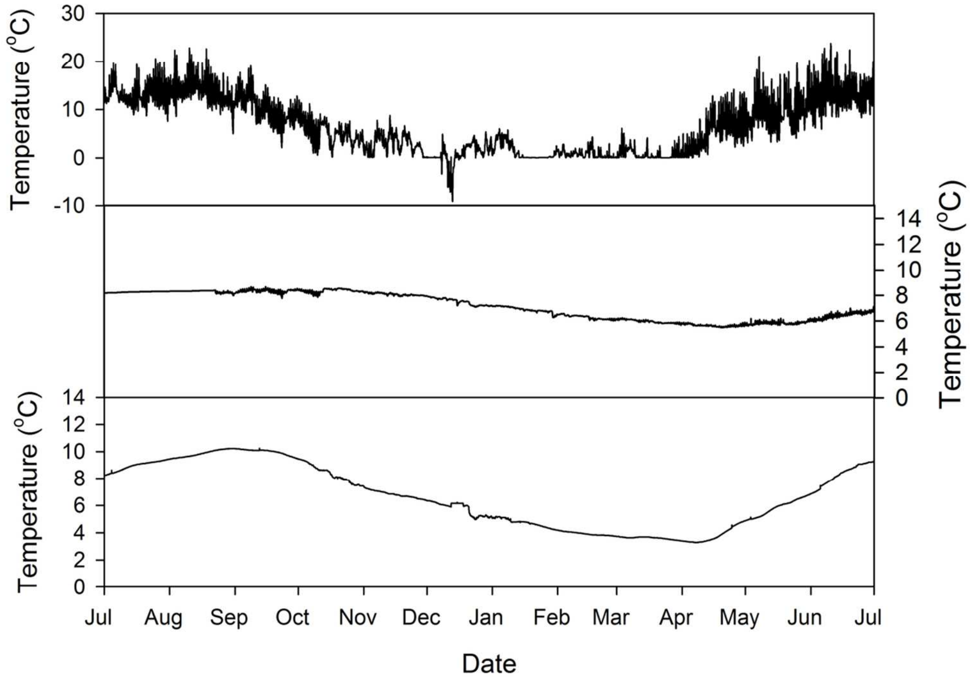
Aerial map of Bruntland Burn valley bottom showing locations of temperature loggers and logger IDs. (HW: Headwater streams; SW: Stream water; GW: Groundwater; SFW: Surface water). The precipitation and dicscharge was measured in the same location as SW11. Map inserts show: a) location of study site within Scotland, b) the location of the headwaters, and c) the soil cover.
244x141mm (150 x 150 DPI)



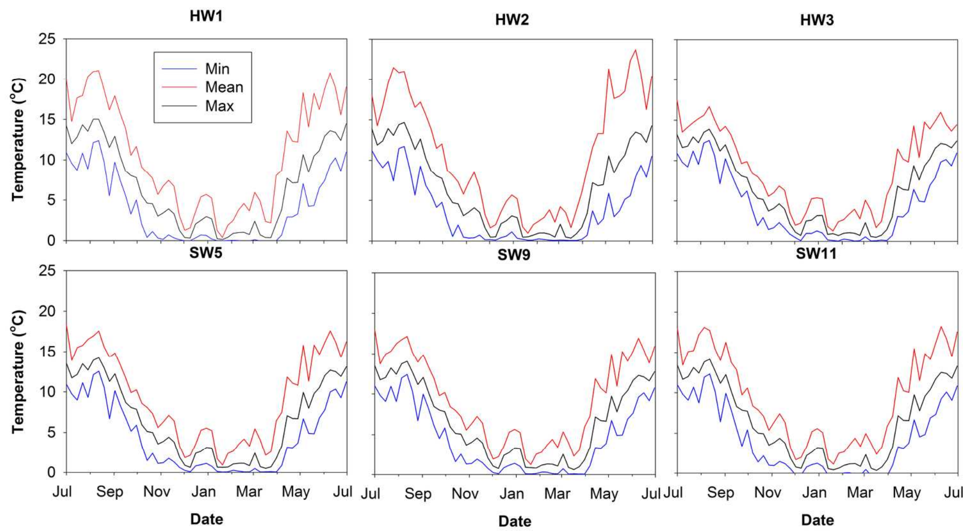
a) Mean daily incoming radiation b) Mean daily air temperature, c) precipitation d) discharge and e) daily saturation extent (calculated as percentage of total catchment area) for study period (1st July 12 – 30th June 13) Spring and autumn are shaded in grey. Data from automatic weather station located in the Girnock Burn catchment.
187x148mm (300 x 300 DPI)



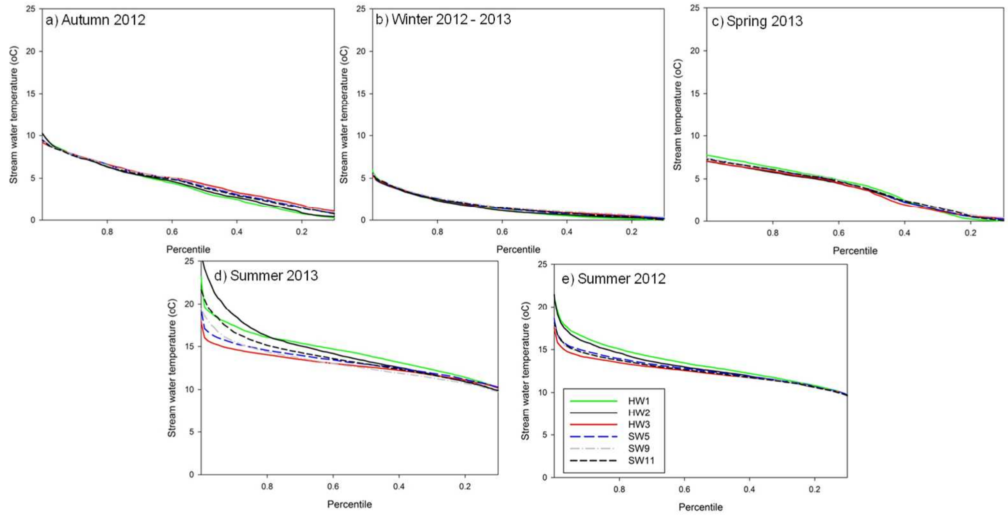
Hourly temperature box plots for each water temperature logger for the period July 2012 to July 2013. The plot shows: 5th and 95th percentiles (dots); 10th and 90th percentiles (whiskers); 25th and 75th percentiles (box); median (centre line)
281x119mm (150 x 150 DPI)



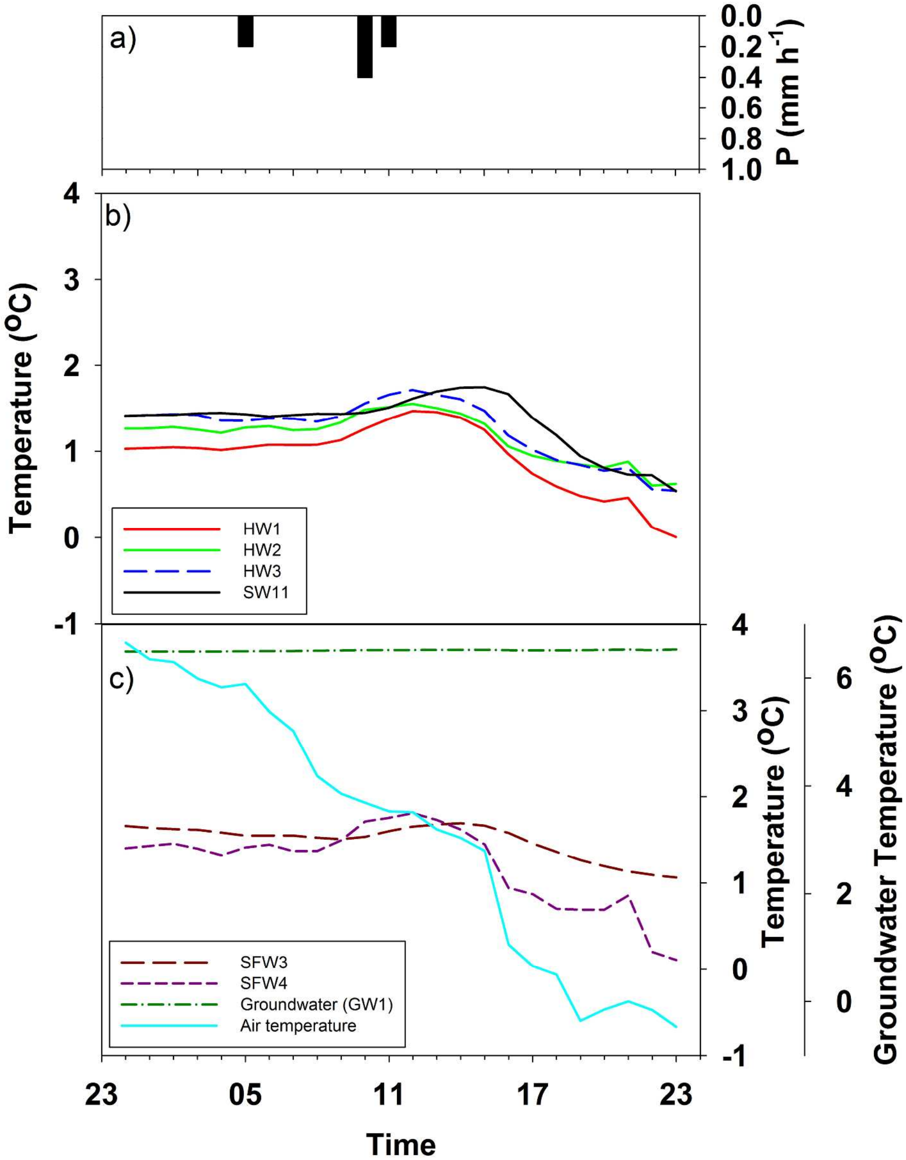
Water temperatures for 1st July 12 – 1st July 13. a) Logger SFW4 as an example for an atmospheric driven site; b) GW1 deeper groundwater; c) GW4 Shallow groundwater within riparian zone peats. Loggers were selected to provide examples of deep groundwater with little seasonality, shallow groundwater with more seasonality and greater influence from atmospheric drivers, and the purely atmospherically driven surface water.
118x87mm (300 x 300 DPI)



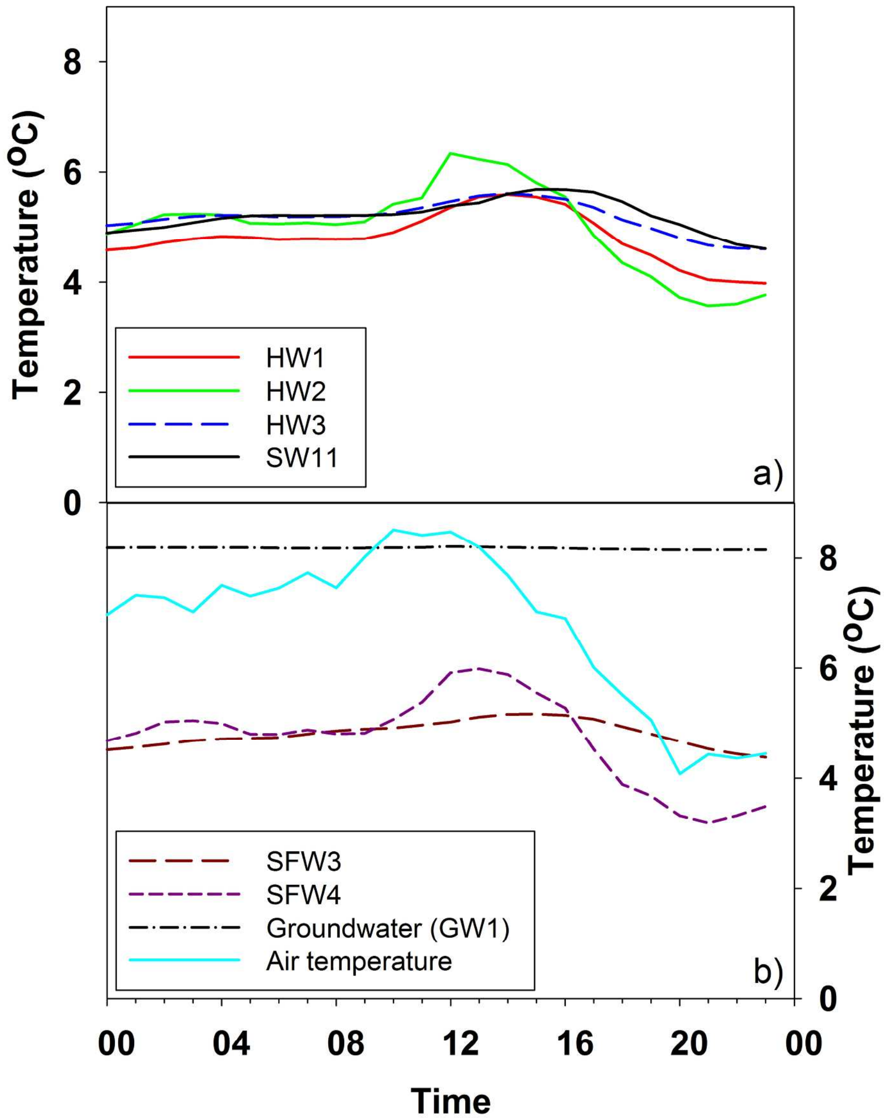
Selected stream water loggers: HW1, HW2, HW3, SW5, SW9 and SW11 clockwise (based on weekly data). Showing Min (blue), max (red) and mean weekly water temperatures (black) for period 1st July 2012 to 30th June 2013
177x98mm (300 x 300 DPI)



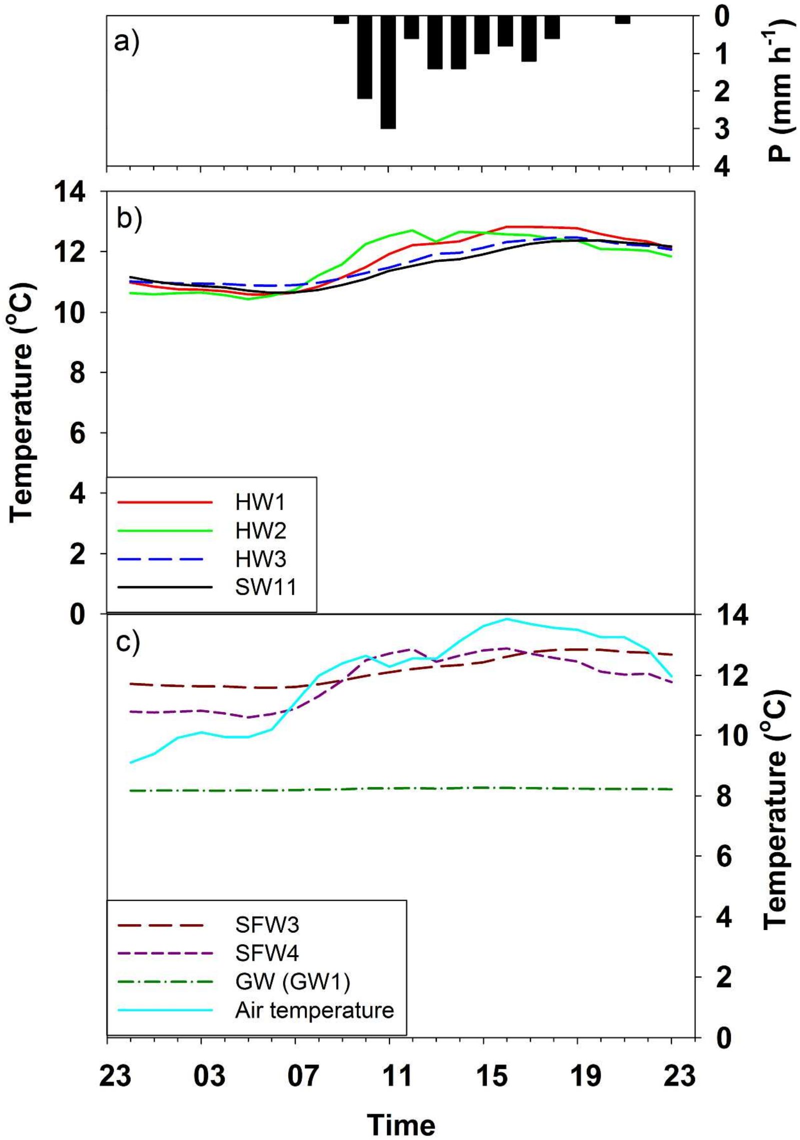
Stream water temperature exceedance curves (based on hourly data) for a) Winter; b) Spring; c) Summer; d) Autumn. Seasons are delineated using astronomical definitions, with each season separated by the two equinoxes and solstices of March 20th, June 21st, September 22nd, December 21st.
276x141mm (150 x 150 DPI)



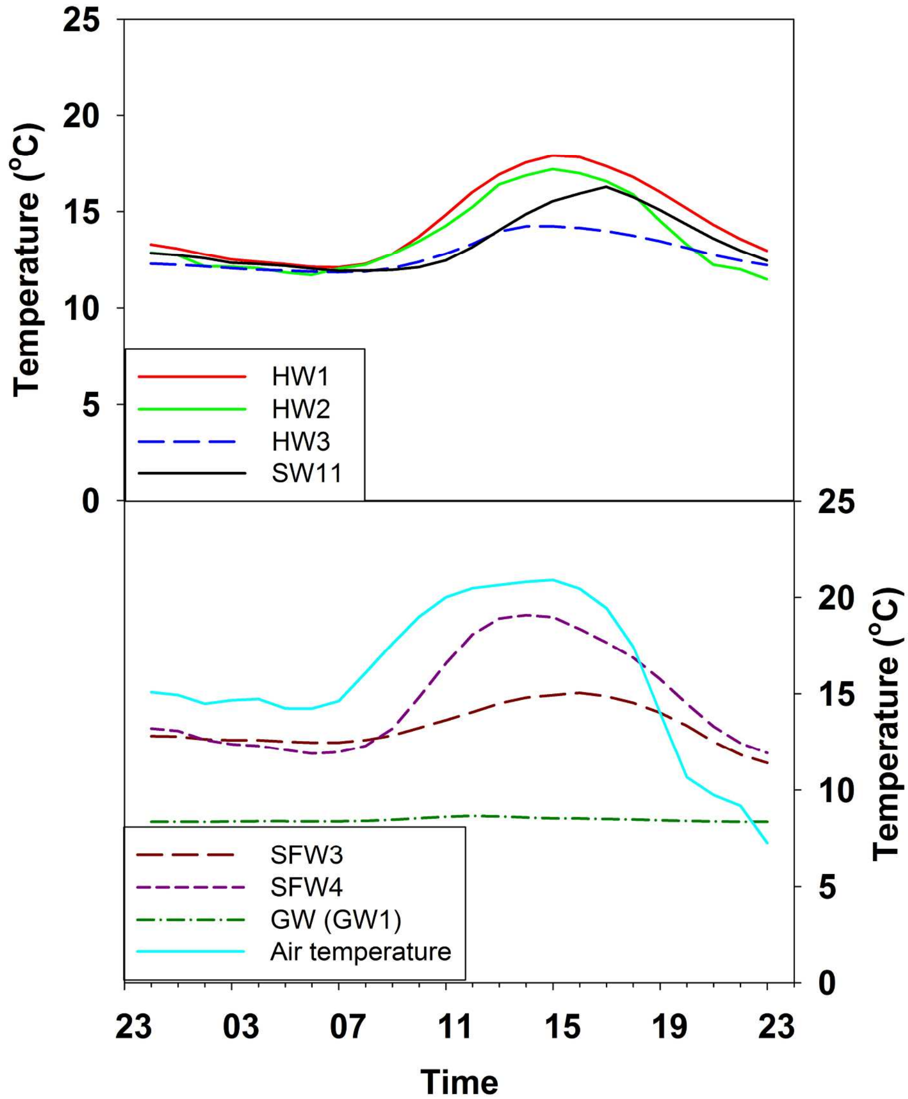
Water temperatures for a 24 hr, cold / wet period (1st February 2013); a) precipitation b) Stream water temperatures for each headwater catchment (HW1, HW2, HW3) and the outlet (SW11) and c) Surface water temperatures in riparian zone (SFW1, SFW2 and SFW3) (shown as hourly data).
250x329mm (300 x 300 DPI)



Water temperatures for a 24 hr, cold/dry period (9th November 2012) a) Stream water temperatures for each headwater catchment (HW1, HW2, HW3) and the outlet (SW11) and b) Surface water temperatures in riparian zone (SFW1, SFW2 and SFW3) (shown as hourly data).
217x264mm (300 x 300 DPI)



Water temperatures for a 24 hr, warm / wet period (27th August 2012): a) precipitation b) Stream water temperatures for each headwater catchment (HW1, HW2, HW3) and the outlet (SW11) and c) Surface water temperatures in riparian zone (SFW3, SFW4, GW1 and air temperature) (shown as hourly data).
255x346mm (300 x 300 DPI)



Water temperatures for a 24 hr, warm / dry period (8th September 2012) a) Stream water temperatures for each headwater catchment (HW1, HW2, HW3) and the outlet (SW11) and b) Surface water temperatures in riparian zone (SFW3, SFW4, GW1 and air temperature) (shown as hourly data).
221x261mm (300 x 300 DPI)