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Flow regulation alters alpine river thermal regimes

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SUMMARY

Impacts of anthropogenic flow regulation on the thermal regimes of alpine river systems are poorly understood. This is surprising given the importance of water temperature for river ecosystems and the widespread regulation of mountain rivers across the world. This study examined water temperature dynamics year-round between July 2008 and September 2009 in the Eisboden river system, central Austrian Alps. Water temperature data were examined alongside hydroclimatological data to infer the key processes driving thermal variability from diurnal to inter-annual scales. As expected, interactions between meteorology and water source controlled year-round thermal heterogeneity. However, water entering the proglacial river from a hydropower storage reservoir caused significant increases in water temperature during both late summer and early winter, resulting in a marked longitudinal thermal discontinuity. The timing and duration of flows discharged from reservoirs, and thus effects on river thermal regimes, differed considerably from previous studies of subalpine hydropeaking. Furthermore, thermal responses to flow regulation extended laterally to some groundwater tributaries even where there was no upstream surface connectivity, suggesting significant hyporheic flow or conduction of heat through coarse alluvium. River water temperature continued to be altered even after reservoir releases had ceased due to the removal of winter snow cover and recharged groundwater sources. Together, these insights into the thermal variability have broad implications for conservation and management of alpine river systems because water temperature is a key variable influencing aquatic ecosystems, and because anthropogenic pressures on alpine environments are expected to grow in the future.

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1. Introduction

Water temperature has a direct influence on the metabolism of many aquatic organisms and additionally affects freshwater ecosystems by moderating biogeochemical cycles and dissolved oxygen concentrations (e.g. Woodward et al., 2010). Temporal water temperature fluctuations have major effects on biotic distributions and stimulate behavioural responses in many organisms, altering life cycle duration (Céréghino et al., 1997; Füreder, 1999), insect emergence timing (Hogg and Williams, 1996), invertebrate drift (Brittain and Eikeland, 1988) and mortality (Cox and Rutherford, 2000). Understanding the processes influencing the thermal characteristics of river systems is therefore a key requirement for freshwater resource managers worldwide (Poole and Berman, 2001; Webb et al., 2008).

In alpine rivers, water temperature is one of the main physicochemical properties influencing the spatial distribution and diversity of aquatic organisms (Brown et al., 2007; Brown and Milner, 2012; Füreder et al., 2002; Milner et al., 2009), whole stream metabolism (Acuña et al., 2008; Robinson et al., 2008) and biogeochemical cycles (Tockner et al., 2002). An understanding and quantification of the processes driving water temperature fluctuations is therefore fundamental for the assessment and prediction of ecological patterns and processes in alpine rivers. Key drivers of water temperature in these systems are considered to be climatological conditions, water source (meltwater, groundwater, precipitation), channel geomorphology and basin characteristics such as aspect and altitude (Brown and Hannah, 2007, 2008; Brown et al., 2006b; Carrivick et al., 2012; Uehlinger et al., 2003).

Despite many high alpine river systems being impacted by anthropogenic modification, particularly from hydropower infrastructure (Füreder et al., 2002; Wehren et al., 2010), there remains minimal understanding of the extent to which alpine river temperature dynamics are affected (but see Anselmetti et al., 2007; Dickson et al., 2010). This is surprising, because it is well-known that river thermal regimes in non-alpine areas can be influenced heavily by flow regulation (Ward and Stanford, 1995; Webb et al., 2008; Webb and Walling, 1997; Zolezzi et al., 2010). For example, thermopeaking occurs daily in many regulated rivers as hypolimnetic reservoir waters are discharged periodically to meet daily surges in electricity demand (e.g. Céréghino et al., 2002; Zolezzi et al., 2010). Hypolimnetic water pulses are typically ~4 °C year-round and often contrast greatly with background river temperatures leading to 'summer cool' and 'winter warm' thermopeaking. Several studies have focused on peaking and abstraction from

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controlled, predictable turbine runs in sub-alpine river reaches (see Carolli et al., 2008; Céréghino et al., 2002; Zolezzi et al., 2010) but it remains unclear if the conclusions from such studies can be applied reliably to high alpine systems.

The spatial heterogeneity of water temperature in unmodified glacier-fed river systems, influenced in part by relative contributions of melt and ground water, has been observed in several recent studies (Arscott et al., 2001; Brown and Hannah, 2008; Carrivick et al., 2012; Uehlinger et al., 2003) and is considered to be an important feature influencing aquatic biodiversity (Malard et al., 2006). However, research into regulation-induced thermal modification of rivers has been undertaken largely along the longitudinal (upstream–downstream) dimension, and typically at low spatial and temporal resolution (e.g. Bruno et al., 2009; Toffolon et al., 2010). More research is necessary to assess the spatial impacts of flow regulation in high alpine systems, at time-scales from days to years, if impacts on biodiversity and ecosystem functioning are to be understood better. Furthermore, due to difficulties of access and conducting field work in high altitude catchments, especially during winter, few studies have collected detailed water temperature records year-round from alpine rivers (Brown et al., 2006b; Robinson and Matthaei, 2007; Uehlinger et al., 2003).

This paper reports the results of an intensive study of water temperature undertaken across eight sites in the glacierized Eisboden basin (>2000 m altitude), central Austrian Alps, which is subject to partial flow regulation. The study tested the following linked hypotheses: (H_1) water temperature in predominantly meltwater-fed river channels would show a longitudinal pattern of warming (Carrivick et al., 2012; Uehlinger et al., 2003) but temperatures would be lower and less variable than nearby groundwater tributaries during unregulated parts of summer melt (Brown and Hannah, 2008; Brown et al., 2006a). In contrast, during regulated periods of flow we hypothesised that (H_2) discharges of hydropower reservoir water would decrease water temperature in stream reaches downstream of the water entry point (cf. Carolli et al., 2008; Céréghino et al., 2002), whereas streams lacking a direct upstream connection to these reaches would maintain an unimpacted thermal regime. However, (H_3) during winter, we expected water temperature would be elevated by discharge from the reservoir but show minimal variability reflecting the lentic water source. In contrast, (H_4) at all times during winter the thermal regimes of streams with no direct surface connection to the reservoir outlet stream were expected to be unaffected by regulated flows. The findings of this study are considered in the context of more general observations and theories related to the drivers of alpine river thermal dynamics, and the effects of river regulation on water temperature dynamics.

2. Methods

2.1. Study site

The Ödenwinkelkees catchment (9.2 km^2, 19.5% glaciated) is partially within the Hohe Tauern National Park, central Austria (see Carrivick et al. (in press) for full details). Water temperature was monitored at eight river sites located within the Eisboden river between the Ödenwinkelkees terminus (2197 m.a.s.l.) and the outlet of a braidplain, 1.8 km downstream (2099 m.a.s.l.; Fig. 1; Table 1). The catchment occasionally receives additional runoff from basins to the west via the Weiβsee hydropower storage lake (surface area 0.5 km^2; maximum depth 51 m; volume 15.7 Mm^3; Berger, 1963). The Weiβsee collects runoff directly from the Sonnblick Glacier river, plus water routed underground in culverts from Amartaler See (4.3 km WSW; 2276 m) and Salzplatenzee (5.3 km W; 2294 m). The Weiβsee is not used as a direct feed for hydropower generation, instead serving as secondary storage with water routed to the Tauernmoossee predominantly via the Eisboden and occasionally via the Weiβbach.

Water temperature was measured continuously (15 min resolution) using a combination of Gemini Tinytag data loggers, Trafag DL/N 70 integrated pressure transducer/temperature probes and a Campbell Scientific CS547A conductivity/ temperature sensor linked to a CR1000 datalogger. Dataloggers were installed on, or prior to, day 182, 2008 (31st June) and removed on day 247, 2009 (4th September). Prior to installation in the field, sensors were cross-calibrated to ensure comparable temperatures (Brown et al., 2006a) and dataloggers were synchronised. Manufacturer's reported error ranges for all water temperature sensors were ±0.2 °C. Altitude, latitude/longitude and distance from the main source of each site were recorded using a dual phase Leica GPS500 differential GPS (±5 cm horizontal, ±10 cm vertical accuracy). Air temperature, incoming shortwave radiation and liquid precipitation were monitored at a nearby automatic weather station (AWS; Fig. 1) to provide a meteorological context for understanding river thermal dynamics. Discharge from the catchment was measured at a monitoring station at M3. Stage was measured at 15 min resolution using a Trafag DL/N 70 pressure transducer and a stage-discharge rating curve generated from salt-dilution gauging across the range of flows. Herein, all reported datalogger times are given in GMT, with dates provided as calendar days.

Dataloggers were installed along the main river of the Eisboden (Sites M1–4) to monitor longitudinal river water column thermal trends over 1.8 km. Unfortunately, the river bank at M1 suffered recurring major erosion during the monitoring period and attempts to maintain a monitoring site here were abandoned. However, spot river water temperature readings were taken regularly at M1 using a Hach HQ40d meter, and these were considered representative of most time periods as there were only minimal water temperature fluctuations owing to the close proximity of this site to the glacier. Sites G1–4 were selected to encompass a range of groundwater-fed tributaries. Temporal changes in channel structure, flow connectivity and discharge meant that some of the eight sites had intermittent flow. Dataloggers were not moved to another location when a site was observed without flow. Data were not recorded at M3 on days 179–183, 2009 because power was lost to the datalogger.

2.2. Data analysis

Where there was no winter snow cover over sites, and when rivers had very low or no discharge, water temperature records became very similar to air temperature (cf. Brown et al., 2006b). Where this occurred, data were omitted from further analysis for all sites to ensure comparable records. To permit the analysis of equivalent 'summer' periods in 2008 and 2009, days 183–247, 2008 and days 182–246, 2009 (nb. 2008 was a leap year) were used. Diurnal synchrony of air temperature, short wave radiation and water temperature were assessed by calculating cross correlation coefficients and lags/leads (Brown et al., 2006a). Longitudinal change in the proglacial river thermal regime was examined by considering changes from M1 to M4.

To assess the significance of late-summer reservoir overspill on the thermal regime of sites across the braidplain, the summer time-series for each year were split into two periods: (1) an unregulated period, when the Weiβsee overspill channel was inactive; the link between the adjacent Weiβsee basin and the Eisboden would not occur naturally, so flow regulation is a transient feature of the system, and (2) an overspill period (Fig. 2).

We assessed whether Weiβsee overspill acted as a significant modifier of stream water temperature by comparing regression model predictions between the two time periods for each individual site/year combination. The approach taken was similar to that

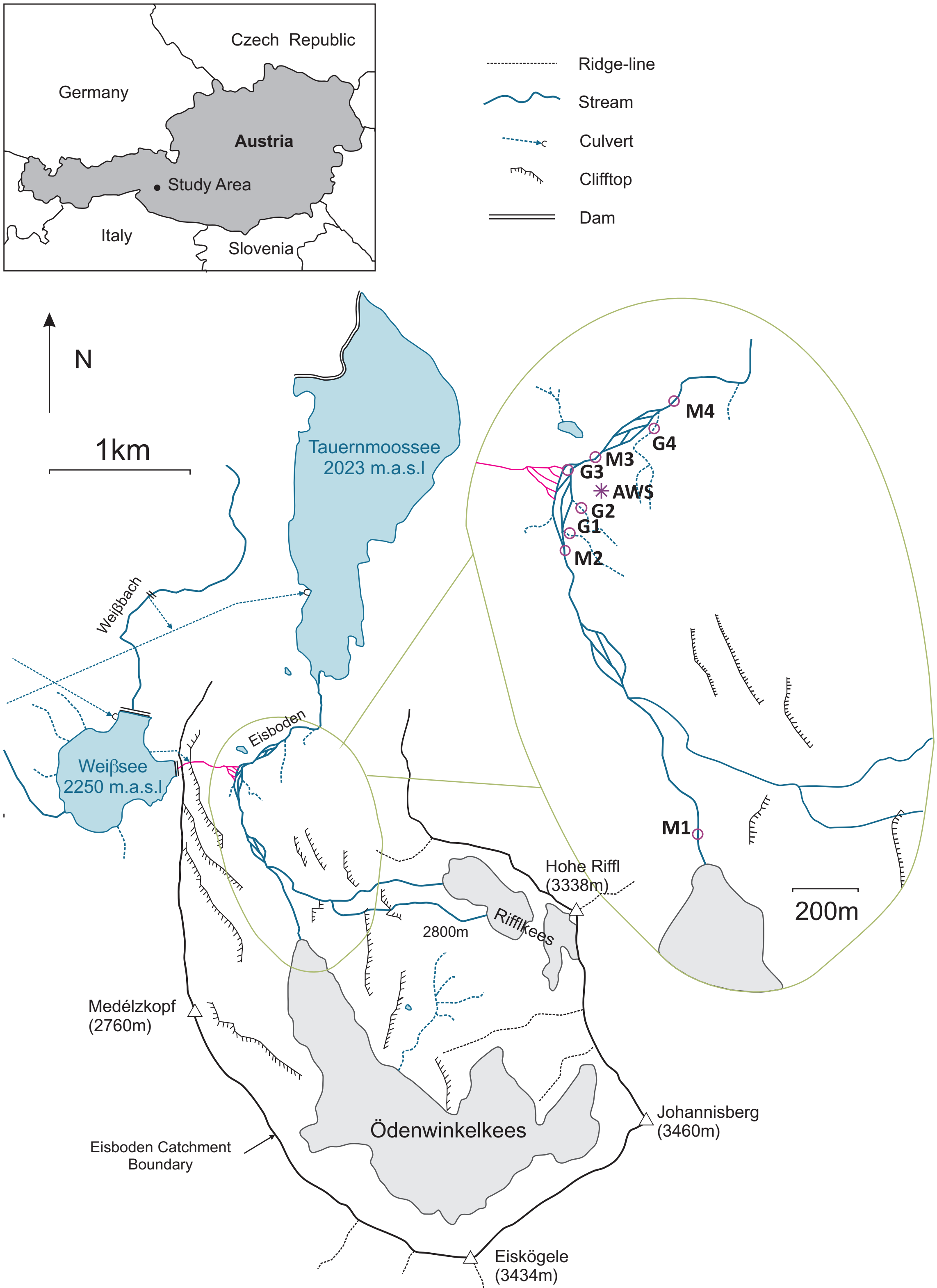

Fig. 1. Map of the Eisboden river catchment showing locations of the eight water temperature monitoring sites and the AWS.

described by Gomi et al. (2006) and first involved the establishment of air–water regressions based on daily mean temperature for unregulated periods. Initial exploratory ordinary least squares (OLS) regression, autocorrelation analyses and Durbin–Watson statistics highlighted significant residual autocorrelation for some data series (M2, 2008; M4 and G1–4, 2009), therefore we used generalised least squares (GLS) regression (Pinheiro et al., 2006). Models took the form $T_w = \alpha + \beta T_a + \varepsilon$ where T_w = water temperature, α = regression intercept, β = regression coefficient, T_a = air temperature and ε = error term. Error terms were modelled as first order autoregressive processes based on *a priori* examination of autocorrelation and partial autocorrelation functions.

Table 1
Monitoring site characteristics.

Code	Name	Dominant water source	Distance from source (m)	Altitude (m.a.s.l.)
M1	Ödenwinkelkees snout	Melt	25	2194
M2	Eisboden upper	Melt	1030	2135
M3	Eisboden lower	Melt	1500	2110
M4	Lower braidplain	Melt	1820	2099
G1	Groundwater tributary 1	Hillslope groundwater	80[a]	2127
G2	Groundwater tributary 2	Hillslope groundwater	70	2120
G3	Groundwater tributary 3	Alluvial groundwater	50 [a]	2117
G4	Groundwater tributary 4	Hillslope groundwater	90	2100

[a] Denotes approximate mean as stream was sourced from multiple springs.

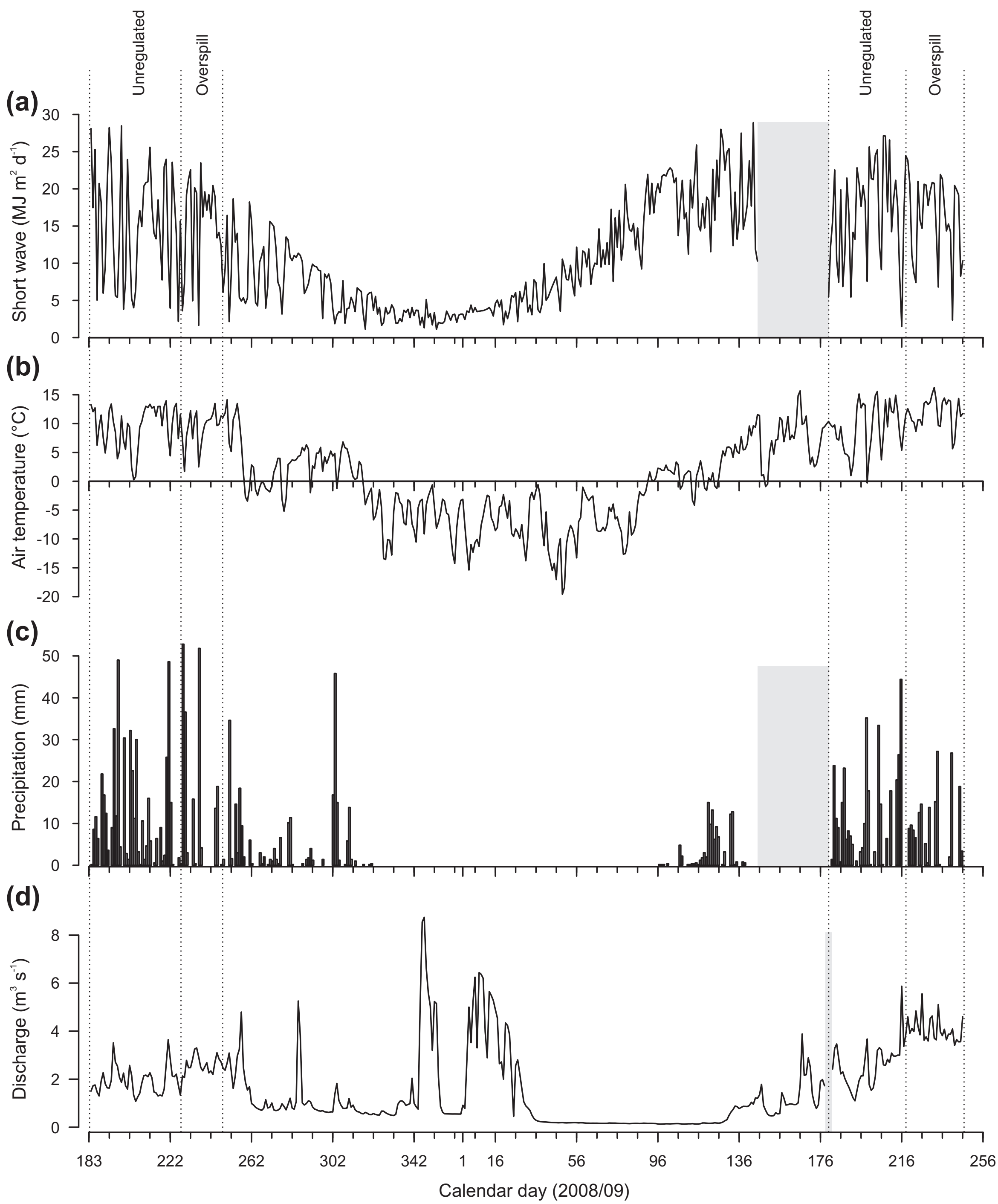

Fig. 2. Time series of (a) daily incoming shortwave radiation, (b) mean daily air temperature, (c) total daily precipitation (liquid phase only), and (d) mean daily discharge (Nb. Shaded areas represent missing data).

Regression models were used subsequently to predict water temperature during overspill periods. The approximate statistical significance of overspill effects was assessed by calculating a measure of random disturbance ($\hat{u}_t$) (Gomi et al., 2006; Watson et al., 2001):

$$\hat{u}_t = (y_t - \hat{y}_t) - \rho_1(y_{t-1} - \hat{y}_{t-1})$$

where y is the observed water temperature and $\hat{y}$ is the predicted water temperature on day t, and ρ_1 is the lag1 autocorrelation coefficient from the GLS regression. 95% confidence intervals of disturbance estimates were calculated as $1.96(\sigma\hat{u}_t)$. If there was no effect of overspill on water temperature, $\hat{u}_t$ would be similar to unregulated periods; two sample Kolmogorov–Smirnov tests were used to assess this hypothesis (Gomi et al., 2006). All statistical analyses were implemented in *R* 2.14 (R-Development-Core-Team, 2008).

3. Results

3.1. Hydroclimatological conditions

Incoming shortwave radiation, air temperature, and precipitation followed distinct seasonal cycles through the monitoring period (Fig. 2; Table 2). Both summers were characterised by large daily incoming shortwave radiation fluctuations (max = 28.5 MJ m^{-2} d^{-1} [day 198, 2008]; min = 1.5 MJ m^{-2} d^{-1} [day 216, 2009]; Fig. 2a). During the two summer melt seasons, periods with high day-time and positive night-time temperatures were interspersed with shorter colder periods where night-time temperatures dipped below freezing (Fig. 2b). The 2008 summer was wetter than 2009 (daily mean 10.3 vs. 8.1 mm, respectively). Precipitation fell more uniformly through summer 2009 than 2008 although drier periods were generally longer (e.g. days 217–219, 235–239; Fig. 2c). The summer of 2008 experienced three snowfall events (days 204, 229 and 236) compared with four in 2009 (days 188, 189, 191 and 199). From day 316, 2008 to 93, 2009, mean daily air temperature remained below freezing.

Mean daily discharge from the catchment was greater during the unregulated period of 2009 than 2008 (2.55 vs. 1.93 m^3 s^{-1}; Fig. 2d). Overspill from the Weiβsee reservoir started on day 230 in 2008 and day 218 in 2009. Discharge was markedly higher during the overspill period of 2009 cf. 2008 (mean daily 3.21 vs. 2.66 m^3 s^{-1}). A series of much larger drawdown releases occurred from day 332, 2008 through to day 44, 2009, leading to dramatic step fluctuations in discharge (Fig. 2d) and inundating the northwest part of the braidplain. From day 44, 2009, discharge at M3 remained low (0.2 m^3 s^{-1}) until day 128 when a gradual increase marked the start of the melt season.

3.2. Water temperature dynamics (summer unregulated periods)

Mean water temperature increased over the 0.8 km distance from M2 to M4 during unregulated summer periods by 1.2 °C (2008) and 1.9 °C (2009), or 1.5–2.4 °C km^{-1} (Fig. 3a; Table 3). Although water temperature was not recorded continuously at

Table 2
Summary statistics for hydroclimatological data based on 15 min data.

	T_{air} (°C)	Ppn[a] (mm)	Incoming shortwave (MJ m^2 d^{-1})	Q (m^3 s^{-1})
Summer season 2008 (day 183–247)				
Mean (sum[a])	9.4	10.3	15.4	2.13
Max	20.7	54.2	28.5	8.21
Min	−0.6	0.0	1.6	0.98
Range	21.3	54.2	26.8	7.23
St. dev.	4.6	14.2	7.3	0.82
Summer season 2009 (day 182–246)				
Mean (sum[a])	10.3	8.1	16.7	3.21
Max	25.4	44.4	27.1	9.07
Min	−2.6	0.0	1.5	1.03
Range	28.0	44.4	25.6	8.04
St. dev.	5.2	1.5	6.3	1.21
Unregulated period 2008 (day 183–217)				
Mean (sum[a])	9.5	10.5	14.9	1.93
Max	20.7	49.2	28.5	8.21
Min	−0.6	0.0	2.2	0.98
Range	21.3	49.2	26.3	7.23
St. dev.	4.7	12.8	7.7	0.76
Overspill period 2008 (219–247)				
Mean (sum[a])	9.8	6.2	16.5	2.66
Max	20.0	51.8	23.5	6.35
Min	−0.3	0.0	1.6	1.42
Range	20.3	51.8	21.9	4.94
St. dev.	4.4	13.3	5.9	0.69
Unregulated period 2009 (182–217)				
Mean (sum[a])	9.1	9.7	17.1	2.55
Max	25.4	44.4	27.1	8.77
Min	−2.6	0	1.5	1.03
Range	28.0	44.4	25.6	7.74
St. dev.	5.6	11.7	6.8	1.07
Overspill period 2009 (219–246)				
Mean (sum[a])	11.9	6.3	16.0	4.04
Max	22.8	27.2	21.9	9.07
Min	0.2	0	2.3	2.80
Range	22.6	27.2	19.6	6.28
St. dev.	4.1	8.4	5.5	0.81

[a] Precipitation statistics are based on daily totals.

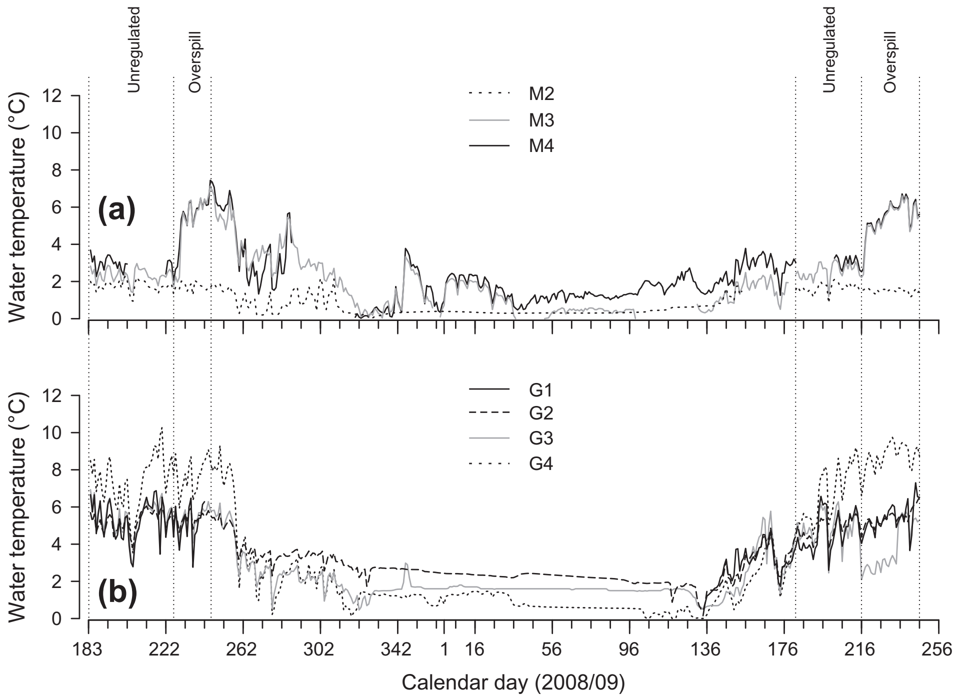

Fig. 3. Daily mean water temperature for (a) main river sites and (b) groundwater sites.

Table 3
Descriptive statistics, derived from 15 min temperature, for the seven continuously monitored sites (Values are for identical length time periods to account for missing data in some records).

	M2	M3	M4	G1	G2	G3	G4
Summer season 2008 (days 183–247)							
Mean	1.8	3.4	3.8	5.2	5.2	4.8	7.5
Max	3.6	7.7	8.0	13.5	7.9	8.1	12.8
Min	0.8	1.1	1.3	0.9	3.4	2.5	4.8
Range	2.8	6.6	6.7	12.6	4.5	5.6	7.9
Summer season 2009 (days 182–246)							
Mean	1.6	3.9	4.4	5.0	5.1	3.6	7.7
Max	3.7	8.0	8.3	15.5	8.0	14.7	13.2
Min	0.1	0.0	0.0	0.3	2.3	0.0	3.5
Range	3.6	8.0	8.3	15.2	5.6	14.7	9.8
Unregulated period 2008 (days 183–217)							
Mean	1.8	2.3	3.0	5.3	5.1	4.8	7.4
Max	3.6	5.1	6.0	12.2	7.9	8.1	12.7
Min	0.8	1.1	1.3	2.8	3.8	2.9	4.8
Range	2.8	4.0	4.7	9.4	4.2	5.2	7.8
Overspill period 2008 (days 219–247)							
Mean	1.8	5.8	5.8	5.2	5.5	4.9	7.6
Max	3.4	7.7	8.0	13.5	7.6	7.8	12.8
Min	0.8	4.2	4.2	0.9	3.4	2.5	5.1
Range	2.6	3.5	3.8	12.6	4.1	5.2	7.7
Unregulated period 2009 (days 182–217)							
Mean	1.7	2.6	3.6	4.6	4.8	3.7	6.8
Max	3.7	5.6	8.0	10.9	7.4	8.3	12.8
Min	0.1	0.0	0.0	0.3	2.3	0.0	3.5
Range	3.6	5.6	8.0	10.6	5.1	8.3	9.3
Overspill period 2009 (days 219–246)							
Mean	1.5	5.6	5.5	5.5	5.5	3.6	8.9
Max	2.8	8.0	8.3	15.5	8.0	14.7	13.2
Min	0.7	3.8	0.0	0.7	4.2	0.9	6.0
Range	2.2	4.2	8.3	14.8	3.7	13.8	7.2

Table 4
Air–water temperature, and incoming shortwave radiation-water temperature cross correlation coefficients and lag (h) in parentheses for 15 min data. All correlations significant ($P < 0.01$).

Site	Unregulated period		Overspill period	
	Air	Short wave	Air	Short wave
2008				
M2	0.618 (−0.50)	0.821 (0.25)	0.659 (−0.75)	0.863 (0.25)
M3	0.655 (−0.50)	0.891 (0.25)	0.510 (−1.00)	0.443 (0.00)
M4	0.548 (−0.75)	0.849 (0.00)	0.552 (−0.50)	0.539 (0.25)
G1	0.815 (0.00)	0.832 (0.25)	0.862 (−0.25)	0.887 (0.50)
G2	0.825 (−0.25)	0.807 (0.00)	0.843 (−0.50)	0.912 (0.25)
G3	0.842 (−0.50)	0.841 (−0.25)	0.831 (−0.50)	0.914 (0.00)
G4	0.842 (0.00)	0.707 (1.25)	0.862 (0.25)	0.841 (1.25)
2009				
M2	0.783 (1.25)	0.845 (0.25)	0.774 (0.00)	0.879 (0.5)
M3	0.775 (1.25)	0.885 (0.25)	0.596 (−1.00)	0.474 (−0.25)
M4	0.383 (1.50)	0.613 (0.75)	0.422 (−1.00)	0.384 (−0.25)
G1	0.820 (1.25)	0.797 (0.75)	0.794 (0.00)	0.859 (1.00)
G2	0.831 (0.00)	0.769 (−0.75)	0.395 (0.00)	0.512 (0.25)
G3	0.744 (0.75)	0.754 (0.00)	0.507 (−1.00)	0.603 (−0.25)
G4	0.820 (1.50)	0.664 (1.00)	0.840 (0.50)	0.848 (1.25)

the Ödenwinkelkees snout (M1), spot measurements were in the range of 0.8–1.1 °C. Assuming a mean water temperature of 1 °C, temperature increase from M1 to M4 (~1.8 km) averaged 1.2–1.6 °C km^{-1}. Mean, maximum and minimum water temperatures were typically higher in the groundwater streams than the main river during the period of unregulated flow (Fig. 3b; Table 3). With the exception of G4, which was slightly warmer than other groundwater sites, temperatures of groundwater sites were similar for much of the time (Fig. 3b). During the unregulated flow periods of summer 2008 and 2009, mean air temperature and incoming shortwave radiation correlated strongly with water temperature at all sites (Table 4). R values for air–water exceeded 0.6 for main river sites (with the exception of M4 in both years) and were typically >0.7 for groundwater sites. Correlations between shortwave-water were generally >0.7 with the exception of M4 (2009) and G4 (both summers). There were no obvious differences in air–water temperature lag times longitudinally or between meltwater and groundwater streams.

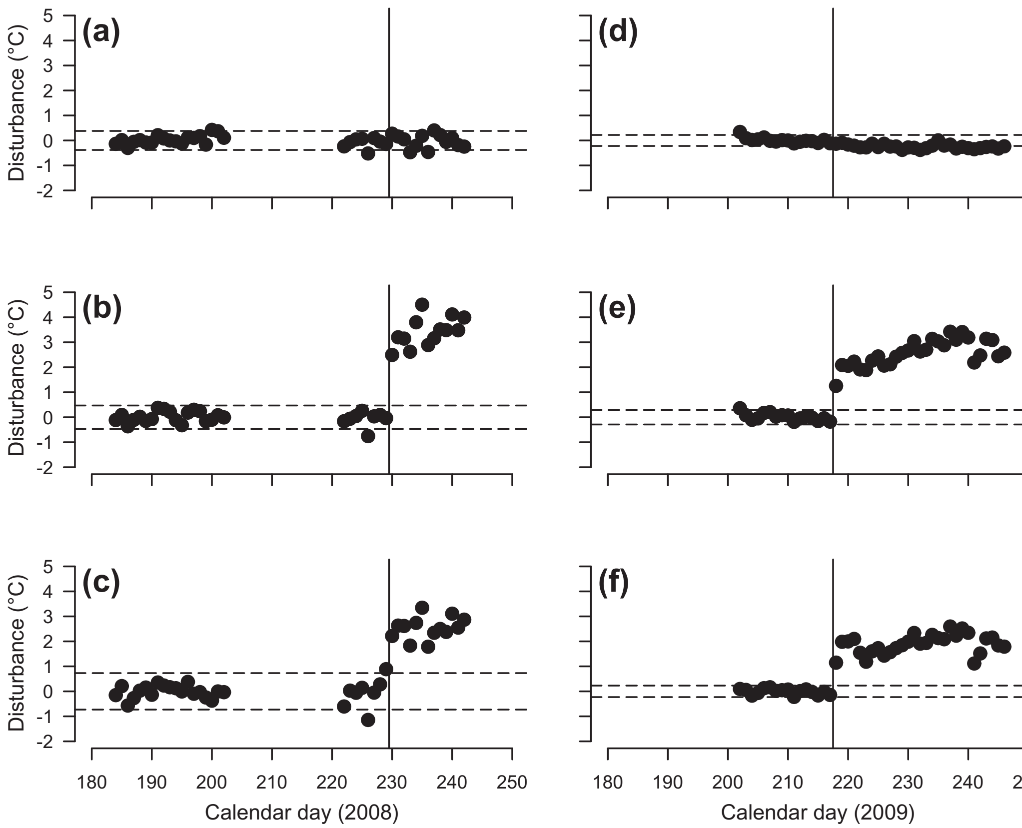

Fig. 4. Random disturbances to daily mean water temperature during unregulated and overspill periods (transition denoted by solid vertical lines) for: (a) M2, (b) M3, (c) M4 during 2008, and (d) M2, (e) M3, (f) M4 during 2009. Broken horizontal lines denote 95% confidence intervals (based on unregulated period data).

3.3. Water temperature dynamics (summer overspill periods)

During the summer overspill periods, mean water temperature increases of up to 3.5 °C were observed at M3 and M4 in both years (Fig. 3a), leading to temperature increases of up to 4.0 °C over the 0.8 km (5.0 °C per km) from M2 to M4. The GLS regression analysis revealed significant disturbances at Sites M3 and M4 in both years (Fig. 4; Table 5). During the 2009 overspill event mean air temperature was 2.8 °C higher than the unregulated period. M2 upstream of the reservoir outlet displayed a significant difference between unregulated and overspill periods but water temperatures during overspill were only marginally *lower* than unregulated periods (Fig. 4b; Table 5). During regulated flows in both years there were no clear effects on air–water temperature or shortwave radiation-water temperature correlations or lag times (Table 4).

Table 5
Mean (±1 SD) disturbances for unregulated and overspill periods, and significance values from two-sample Kolmogorov–Smirnov tests.

Site/year	Unregulated	Overspill	Sig.
2008			
M2	−0.006 (0.19)	−0.002 (0.28)	0.45
M3	−0.009 (0.24)	3.42 (0.59)	<0.0001
M4	−0.03 (0.37)	2.533 (0.44)	<0.0001
G1	−0.02 (0.61)	−0.13 (1.02)	0.30
G2	−0.009 (0.30)	0.30 (0.36)	0.018
G3	−0.02 (0.38)	0.05 (0.52)	0.80
G4	−0.02 (0.71)	0.12 (0.92)	0.79
2009			
M2	0.01 (0.11)	−0.24 (0.09)	<0.0001
M3	0.02 (0.15)	2.57 (0.52)	<0.0001
M4	−0.009 (0.11)	1.89 (0.39)	<0.0001
G1	0.16 (0.26)	0.33 (0.47)	0.35
G2	0.12 (0.16)	0.25 (0.29)	0.33
G3	0.05 (0.64)	−0.25 (1.25)	0.03
G4	0.31 (0.36)	0.68 (0.24)	<0.01

Overspill responses were not obvious in most groundwater stream water temperature time series (Fig. 3) but analysis of the random disturbances (Table 5; Fig. 5) highlighted low magnitude changes at G2 in 2008, and G3 and G4 in 2009 (Table 5). At G3 in 2009 a stepped decrease of ~2 °C was evident (Fig. 3b) coinciding with rerouted glacial river flow.

3.4. Water temperature dynamics (winter)

Daily mean water temperatures generally declined into autumn 2008 at all sites, punctuated by fluctuations associated with meteorological variation (Fig. 3). Daily mean water temperatures at M3 and M4 continued to be elevated relative to M2 during the autumn due to ongoing overspill from the Weiβsee (Fig. 3a). Over winter, water temperatures at M2 stabilized close to freezing after day 323, 2008 (Fig. 3a). Daily mean water temperature at groundwater sites stabilized around day 330, 2008 at between 1.5–4.0 °C while G1 apparently ceased flowing on day 242 (Fig. 3b).

A series of reservoir drawdown releases from day 332, 2008 through to day 44, 2009 (Fig. 2) caused dramatic stepped increases in mean daily water temperature at M3 and M4 (Fig. 3) in contrast to the constant temperature at M2. The maximum daily mean water temperature in the Eisboden main river during this period was 3.3 °C on day 346. Temperature fluctuations were also evident at the alluvial groundwater stream G4 during drawdown events, in contrast with stable temperatures recorded at G2 (Fig. 6). From day 44 to 100, 2009, water temperature at M4 fluctuated in the range of 0.5–1.7 °C whereas M3 temperature was relatively stable.

From day 100, 2009, water temperature began to rise across the catchment but the nature and timing of temperature increases dif-

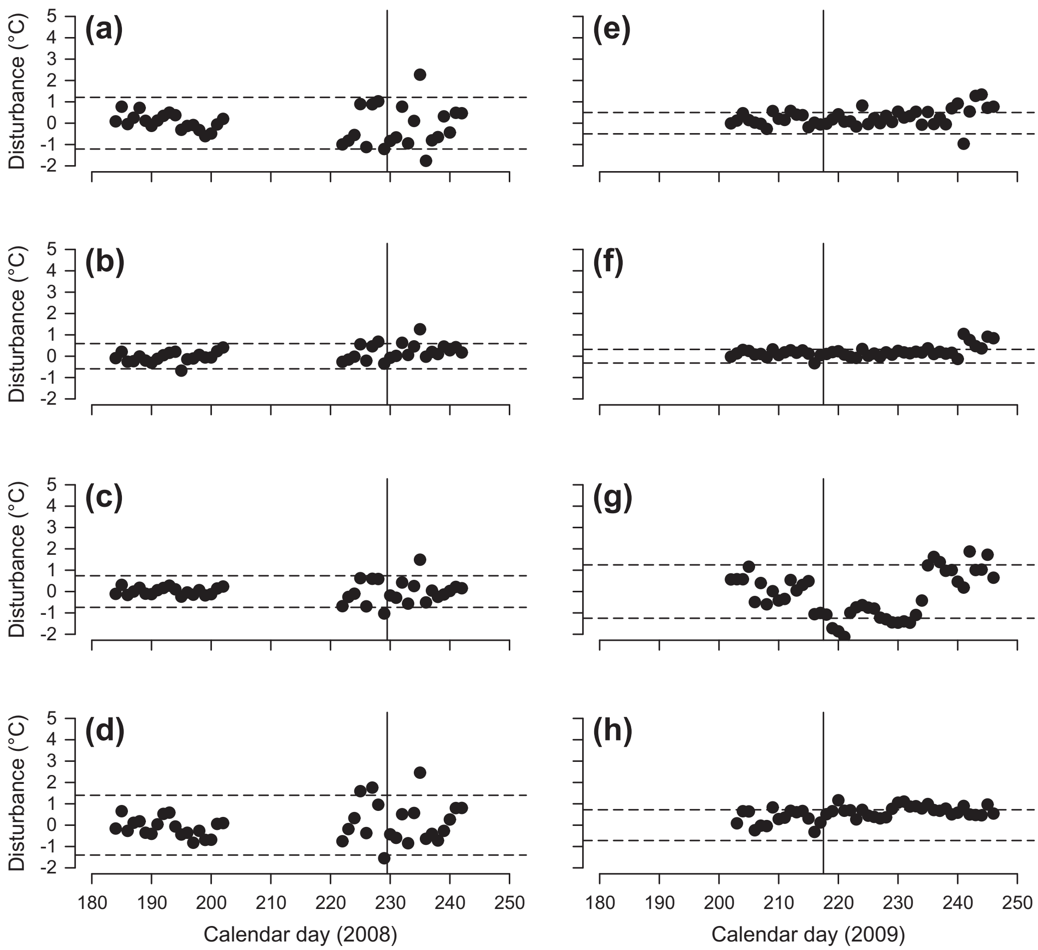

Fig. 5. Random disturbances to daily mean water temperature during unregulated and overspill periods (transition denoted by solid vertical lines) for: (a) G1, (b) G2, (c) G3, (d) G4 during 2008, and (e) G1, (f) G2, (g) G3, (h) G4 during 2009. Broken horizontal lines denote 95% confidence intervals (based on unregulated period data).

fered between river locations. For example, water temperature at M4 began to rise gradually from day 100, 2009 with pronounced diurnal fluctuations evident (Fig. 3a). In contrast, water temperature rose gradually at M2 from day 100, 2009 but diurnal variations were not evident until day 147. Water temperatures remained relatively stable at the groundwater sites until ~day 125 when a marked drop in temperatures occurred during a period of rising air temperature.

4. Discussion

This study has expanded on previous alpine water temperature research by analysing a spatial network of rivers partially affected by regulated flows. In contrast to previous year-round research in alpine glacier-fed catchments (e.g. Uehlinger et al., 2003), the type and magnitude of anthropogenic impacts from an alpine reservoir on river thermal regimes were evaluated by studying both overspill and drawdown flow events. The most significant findings were: (i) the interactive influences of meteorology and water source controlled year-round spatiotemporal variability in flow permanency, resulting in high thermal heterogeneity; (ii) water entering the river system from the Weiβsee hydropower reservoir caused significant *increases* in water temperature, resulting in a large longitudinal thermal discontinuity during both late summer and early winter, (iii) thermal responses to flow regulation extended laterally to some groundwater streams even where there was no direct surface connectivity, and (iv) river thermal regimes continued to be altered even after the reservoir drawdown event had ceased. These findings are considered in turn in the subsequent discussion.

4.1. Water temperature dynamics (summer unregulated periods)

During the unregulated summer monitoring period, longitudinal thermal gradients in the Eisboden main river (M2–M4), reached up to 2.4 °C km^{-1}, while warming rates from M1 to M4 (based on inferred mean temperature of 1 °C at M1) reached up to 1.6 °C km^{-1}, thereby supporting part of H_1. However, rates contrasted markedly with those reported from other alpine proglacial rivers during summer; for example Brown and Hannah (2008) observed 7.6 °C km^{-1} increases in the Taillon basin, French Pyrénées, while Uehlinger et al. (2003) and Cadbury et al. (2008) found only 0.6 °C km^{-1} warming along the Roseg River, Switzerland, and Rob Roy Stream, New Zealand, respectively. Brown and Hannah (2008) suggested that the smaller glacierized area, and consequently lower glacial discharge in the Taillon basin, were more conducive to warming. This suggestion was supported in this Eisboden study because the catchment has a moderate glacierized area (19.5%) and mean unregulated summer discharge (~2.2 $m^3\ s^{-1}$) relative to the Roseg River (30% and 2.8 $m^3\ s^{-1}$), Rob Roy Stream (30% and 2.8 $m^3\ s^{-1}$) and Taillon catchments (4% and 0.2 $m^3\ s^{-1}$). However, warming rates in the Eisboden varied markedly with climatic conditions as would be expected given river energy budget dynamics (Caissie, 2006; Chikita et al., 2009;

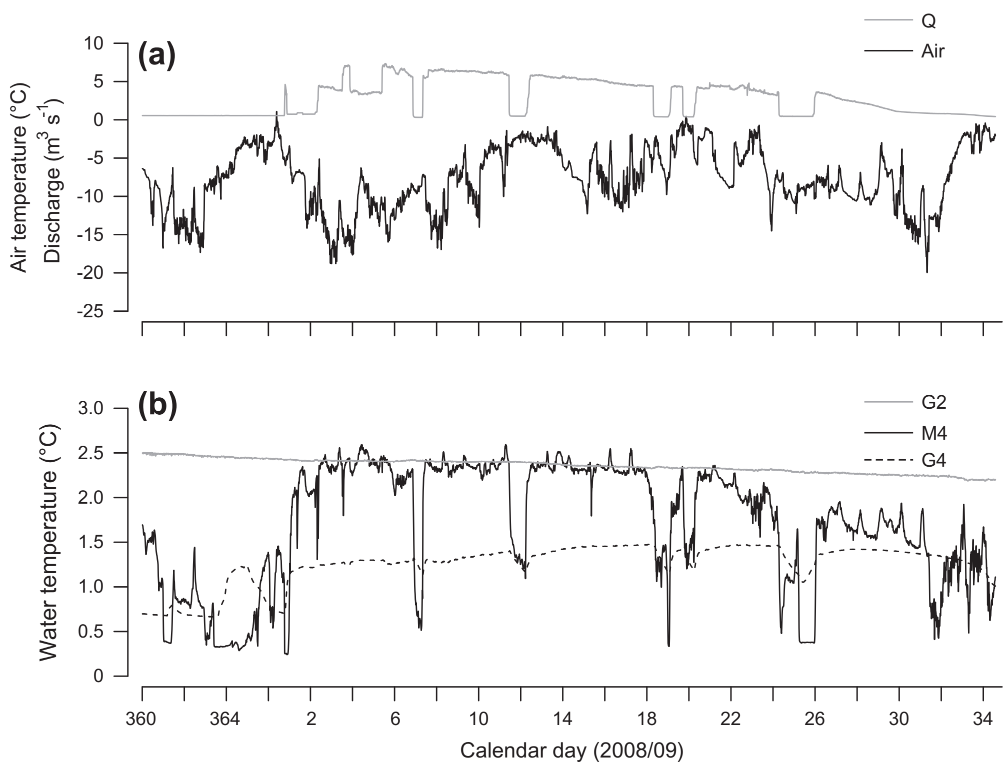

Fig. 6. Water temperature dynamics during a series of Weiβsee drawdown events (day 360, 2008–day 35, 2009) at the inundated main river Site M4, thermally stable groundwater stream G2, and groundwater stream G4, exhibiting thermal responses associated with drawdown events.

Evans et al., 1998; Hannah et al., 2004). For example, during summer prior to reservoir overspill, longitudinal warming rates varied with daily incoming radiation (Brown and Hannah, 2008; Uehlinger et al., 1998). Local climatic conditions are clearly a significant factor in addition to glacial cover and river discharge when accounting for differences in longitudinal thermal heterogeneity between proglacial rivers (Uehlinger et al., 2003).

In alpine basins, discharge and the ratio of meltwater to groundwater from hyporheic upwelling/tributary inputs are considered to be major controls on river water temperature (Brown et al., 2005, 2006a; Malard et al., 1999, 2000). Water source was seen to have a strong influence on thermal heterogeneity across the Eisboden, and so the second part of H_1, that predominantly groundwater-fed steams would have higher and less variable water temperatures than meltwater-fed rivers, was upheld. This observation is supported by findings from other alpine catchments (Brown and Hannah, 2008; Robinson and Matthaei, 2007). During unregulated summer periods, groundwater streams were generally warmer than the Eisboden main river, with the highest mean daily water temperatures (12.2 °C; mean 15 min temperature 7.7 °C) observed at G4. The exposure of upwelling groundwater to warm atmospheric conditions can lead to rapid temperature changes in small streams due to equilibration, or direct energy inputs (Danehy et al., 2005); this effect was observed at G3 where clear diurnal fluctuations, and warming of up to 3.5 °C, were observed over 50 m distance from the spring source to the monitoring site.

4.2. Water temperature dynamics (summer overspill periods)

During overspill from the Weiβsee, flow regimes changed markedly compared with those observed in other studies of hydropower schemes, particularly because flow periodicity and amplitude were dependent on reservoir inflow and overspill rather than abstraction (see Petts and Bickerton, 1994) or hydropeaking (see Carolli et al., 2008; Céréghino et al., 2002; Zolezzi et al., 2010). While we hypothesised (H_2) that reservoir release water would lead to river cooling during summer, the opposite was found with maximum temperature increasing by 3.4 °C (2008) and 2.3 °C (2009) at M3 during overflow. This contrasted sharply with previously observed declines in water temperature in sub-alpine rivers under hydropeaking conditions (cf. Carolli et al., 2008; Céréghino et al., 2002). Two factors likely contributed to this phenomenon. First, the Eisboden is located at much higher altitude (>2110 m.a.s.l) compared to previous studies cited above (all < 1265 m.a.sl). The proximity of the rivers to snowpack and glacial melt sources results in relatively cold river water temperatures prior to mixing with Weiβsee overspill water. Second, the warmer surface waters of the Weiβsee overtopped into the Eisboden during summer. This is in contrast to cooler waters that are discharged from the hypolimnetic zone during hydropower generation (Carolli et al., 2008; Céréghino et al., 2002; Maiolini et al., 2003; Toffolon et al., 2010; Webb and Nobilis, 1995; Webb and Walling, 1993, 1997; Zolezzi et al., 2010).

During summer 2008, relatively similar hydroclimatological conditions were observed across the Eisboden catchment in the days immediately before and after overspill commenced. This provided an opportunity to assess the spatial extent of regulation effects on river thermal regimes, compared with previous 1-dimensional (upstream–downstream) studies of anthropogenic flow alteration (cf. Carolli et al., 2008; Céréghino et al., 2002; Zolezzi et al., 2010). As expected, a large increase in mean daily water temperature was evident at Sites M3 and M4 inundated directly by flows from the Weiβsee, in marked contrast to M2 upstream and the majority of groundwater streams which showed no change cf. before overspill.

In 2009, significant disturbances were evident during overspill at five of the seven sites, but the magnitude of effect was typically minimal except at Sites M3 and M4. Interestingly, the random disturbance analyses identified significant water temperature *decreases* at M2 despite the lack of any upstream surface connection to the Weiβsee overspill river, and concurrent temperature *increases* at M3 and M4 in 2009. This finding can be attributed to the generally warmer meteorological conditions and associated increase in glacial melt (and thus water temperature decreases at M2), and is indicative of how variation in melt and thus river flow can moderate the air–water temperature relationship (cf. Webb et al., 2003). Minor decreases in groundwater discharge at G2 (2008) and G4 (2009) may also have accounted for the significant (but minor magnitude) thermal disturbance between unregulated and overspill periods. At G3 in 2009, field observations indicated that this increased melt flow caused re-routing of a braidplain channel into the groundwater stream as is common in alpine systems (Malard et al., 2006), and this was responsible for observed negative thermal disturbance rather than overspill from the Weiβsee.

4.3. Water temperature dynamics (winter)

In comparison to summer overspill flows, winter drawdown releases caused even greater shifts in the thermal regime at M3 and M4. Alpine river flow would naturally be at a minimum during winter months (Jansson et al., 2003; Röthlisberger and Lang, 1987) with low water temperature and some rivers being snow covered, frozen or 'dormant' (as observed at M2 cf. Brown et al., 2006b; Irons and Oswood, 1992; Malard et al., 2006). Uncharacteristically warm water temperatures were recorded at M3 and M4 from December, 2008 until mid-February, 2009 supporting H_3 that winter regulated flow would lead to water temperature increases. These temperatures contrasted with near freezing temperatures observed at M2 on day 343, 2008 when flows were receding, and during its dormant state as observed on day 65, 2009. They are also high compared with minimum mean monthly temperatures of 0–1.3 °C observed along the Roseg River by Uehlinger et al. (2003). The finding that discharge from reservoir drawdown during winter significantly increased water temperature is consistent with other studies examining sub-alpine river systems in winter (cf. Carolli et al., 2008; Céréghino et al., 2002; Frutiger, 2004; Zolezzi et al., 2010). Regulation caused winter water temperature increases that were comparable in amplitude to those observed by observed by Zolezzi et al. (2010) in the Noce River, Italy at 217 m.a.s.l ($\sim$3 °C). Increases were however sustained for several weeks in the Eisboden and were above a lower base temperature of $\sim$0 °C (cf. $\sim$3 °C; Zolezzi et al., 2010).

When thermal responses to reservoir drawdown releases were strong relative to the stable water temperature of unregulated sites during winter, the influence of Weiβsee water appeared to be evident on some groundwater stream thermal regimes. This contrasted with H_4 that channels without a direct upstream connection to the main outflow would not respond to regulation. Responses extended to the eastern side of the lower Eisboden braidplain (G4) which is fed predominantly by a hillslope tributary during summer and has no upstream surface connection to the main river. We infer that hyporheic linkages (most likely advection due to the coarse alluvium, and conduction) between the Eisboden main river and some groundwater streams were responsible for this observation. We consider that, while these were only observable during winter due to the strong thermal pulse in the main channel at a time when the thermal regime was otherwise stable and cold, they must occur year round. Extensive hyporheic connections have been inferred in alluvial floodplain rivers based on synchronous changes in river stage and water table level up to 2 km from the main river (Stanford and Ward, 1988) so these processes should be in operation over the much smaller distances in the Eisboden. It is likely that thermal signals are masked by stronger diurnal patterns of energy receipt in summer compared with winter. Further study with additional collection of hyporheic hydrology, temperature and/or chemistry datasets would help to deduce the extent of subsurface linkages between these rivers, and any effects of anthropogenic disturbance.

Notably we found that river thermal regimes continued to be altered even after the winter reservoir drawdown events had ceased. Drawdown events were of such large magnitude that snow cover was removed in entirety from river channels with direct upstream connections to the Weiβsee outflow. These rivers also continued to receive water from the recharged alluvial groundwater underlying the lower part of the central braidplain, when it is likely that they would otherwise have ceased to flow (Malard et al., 2006). These channels subsequently showed diurnal water temperature fluctuations for a period of up to 47 days, during which other river channels were snow covered and thus thermally stable, or dormant/dewatered. These effects of alpine river regulation have not been considered prior to this study.

5. Conclusions

This study has illustrated some major effects that flow from hydropower storage reservoirs can have on the thermal dynamics of rivers in high altitude alpine basins. In particular, previously observed hydropeaking patterns of reduced summer river temperatures may not apply to rivers that experience periodic overspill flow from high-alpine reservoirs. This suggests that conclusions from previous studies examining the thermal response of sub-alpine rivers to flow regulation, and the consequences of flow regulation for ecosystems (see Bruno et al., 2009; Céréghino et al., 2002), are not necessarily applicable to river systems at higher altitudes where: (1) antecedent water temperatures may be cooler due to a strong influence of glacier ice and snow meltwater, and (2) the timing and duration of flows discharged from reservoirs may differ considerably from hydropeaking events. Additionally, this study of a high alpine floodplain river suggests that the effects of flow regulation on water temperatures may extend laterally across floodplains, impacting thermal regimes of rivers even where there is no direct surface connectivity. Effects can continue for periods of several weeks after the regulation events have ceased, particularly where high magnitude releases of reservoir water lead to the removal of snow cover from river channels, with likely knock-on effects on aquatic organisms (Schütz et al., 2001).

It is known from many studies of glacially influenced river ecosystems that water temperature is a key factor influencing biological communities (e.g. Brown and Milner, 2012; Milner et al., 2009), and 'discontinuities' such as inputs from lakes or tributaries (Brown et al., 2007; Knispel and Castella, 2003; Saltveit et al., 2001; Uehlinger et al., 2003) are particularly important influences on spatial distributions of organisms. The releases from hydropower reservoirs as exemplified herein can be expected to alter river ecosystem structure and functioning in similar ways. More so, anthropogenic regulated flows may exert stronger effects on alpine basins than natural discontinuities because they are often active during winter, when river discharge, water temperatures and disturbance occurrence should naturally be at a minimum (Malard et al., 2006; Schütz et al., 2001; Tockner et al., 2010). More year-round research is required to establish clearly how alpine river flow regulation may impact upon aquatic ecosystems. In addition, pressures on alpine environments are likely to grow in the future due to the need for increased anthropogenic flow regulation as well as climate change (Brown et al., 2009; Fette et al., 2007; Jacobsen et al., 2012). In the face of such pressures, it is vital that the full ecosystem effects of hydropower activities are understood better to inform management and the conservation of these environments.

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