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Effects of thermopeaking on the thermal response of alpine river systems to heatwaves

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HIGHLIGHTS

- Impact of extreme heatwaves on the thermal regime of alpine rivers assessed at sub-daily time scales
- Hydropower operation in alpine rivers acted as local thermal protection to heatwave effects
- Duration and frequency of thermal stressful events for cold-stenotherm fish greater in unregulated streams
- Hydropower operations offer potential mitigation solution to extreme weather like heatwaves.

ABSTRACT

Within the past 30 years there have been two major heatwave events (in 2003 and 2006) that broke 500-year-old temperature records in Europe. Owing to the growing concern of rising temperatures, we analyzed the potential response in a number of river sections that are subject to hydropeaking and thermopeaking through the intermittent release of water from hydropower stations. Thermopeaking in alpine streams is known to intermittently cool down the river water in summer and to warm it up in winter. We analyzed the response of river water temperature to air temperature during heatwaves at 19 gauging stations across Switzerland, using a 30-yr dataset at a 10-min resolution. Stations were either classified into "unpeaked" or "peaked" groups according to four statistical indicators related to hydropeaking and thermopeaking pressure. Peaked stations were exposed to reduced temporal variability in river water temperature, and it was determined that correlations between river water and air temperature were weaker for peaked stations compared with unpeaked stations. Similarly, peaked stations showed a much weaker response to heatwaves compared

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with unpeaked stations. It is important to note that this “cooling effect” created by hydro-thermopeaking was most pronounced during the two major heatwave events that took place in 2003 and 2006. Furthermore, results from thermal stress events on the growth of a typical cold eurythermic fish species (brown trout) increased continuously in rivers subject to peaked station water release during heatwaves. While hydropower operations that take place high up on mountains releasing hypolimnetic water may mitigate the adverse effects of heatwaves on downstream alpine river ecosystems locally, our results show the complexity of an artificial physical template associated with flow regime regulation in alpine streams.

Key words: Hydropeaking; Thermopeaking; Heatwaves; Thermal habitat; Alpine rivers

1. Introduction

Data from meteorological observations over the last hundred years have shown significant accelerations resulting from climate warming (Crowley, 2000; Schär et al., 2004). It is important to note that forecasts of summer heatwaves predict more frequent and extreme heatwave events in Europe, which is in accordance with trends already observed in recent decades (Barriopedro et al., 2011; Rebetez et al., 2009). Records from the 2003 and 2006 extreme heatwaves events showed that maximum air temperatures increased by greater than 19°C. The adverse effects over large areas from the extensive magnitude and spatial scales of these two heatwave events have caused concern (IPCC, 2007). As stated, it is predicted that such summer heatwave events will occur with more frequency and with greater magnitude in Europe this century (Della-Marta et al., 2007; Meehl and Tebaldi, 2004), which could potentially result in severe adverse effects to human health (Fischer and Schär, 2010) as well as on aquatic ecosystems (Hari et al., 2006).

Previous studies have reported on a significant increase in the effects of climate change on river water temperature (RWT) compared to historic average values over the past several decades (Bourqui et al., 2011; Chen et al., 2012; Null et al., 2013; Sinokrot et al., 1995). This warming trend has been attributed to rising air temperatures (AT) (Edinger et al., 1968; Webb and Nobilis et al., 1995) and extreme heatwave effects caused by global climate change (Hammond and Pryce, 2007). River ecosystems are subject to a number of stress-related problems resulting from climate change, such as peaked hydrology, accelerated biochemical metabolism, and increasing anthropogenic activity, including damming or water abstraction, which are expected to severely affect aquatic biodiversity and ecosystem functions (Praskievicz and Chang, 2009). However, RWT sensitivity to the increased AT during extreme heatwave events is at present not well understood (Luce et al., 2014). For example, heatwaves that result in extreme temperatures may severely affect populations of cold -water stenotherm aquatic biota (Hari et al., 2006; Yates et al., 2008), which negatively responds to extreme high temperatures by the cessation in growth, inability to reproduce successfully, or even mortality.

The increase of RWT may differ considerably for different rivers given that RWT is influenced by river size, channel depth, flow velocity, as well as other variables (Arismendi et al, 2012). Additionally, RWT is also influenced by anthropogenic alterations to river systems, especially by the construction of reservoirs and associative hydropower operations. In the Alps, hydropower operations impact 79% of river systems (Truffer, 2010). The hydropower production potential has already largely been exploited in most countries in which the Alps lie, and accounts for a significant proportion of the national electricity production in several countries, such as Switzerland (57%) (Crettenand, 2012). Therefore, in order to meet peak demands for electricity, especially during working hours when energy-intense industries operate or private demands increase, hydropower flow and water temperature are modified through the intermittent release of flow that takes place mostly at daily and sub-daily frequencies; referred to as “hydropeaking” (e.g., Moog, 1993) and “thermopeaking” effects (Zolezzi et al., 2011). Reservoir operations utilize thermopeaking in the form of hypolimnetic release, which is the release of water that typically causes a reduction in downstream RWT in summer and an increase in winter.

Hence, it has been suggested that reservoirs that perform hypolimnetic operations may partially offset increases in RWT associated with climatic factors in downstream sections of rivers (Null et al., 2010), and therefore may paradoxically contribute to the survival of cold water stenotherm fish species, such as salmon during their summer migration period (Yates et al., 2008). However, such potential effects have to date not been quantitatively studied in a group of targeted river systems. The aim of this study was therefore to investigate the effects of hydropower regulated thermopeaking operations by addressing the following objectives: (1) to quantify the effects of select summer heatwaves on water temperature for a set of alpine river systems, focusing on sub-daily timescales; (2) to determine differences in thermal response to heatwaves between river systems affected by hydro- and thermopeaking measures and those that are not affected by the intermittent release of water (hypolimnetic release) from hydropower operations; and (3) to propose quantitatively the potential ecological implications of different responses to the physical habitat of fish species. We answer these questions by investigating the hydro-thermopeaking characteristics of a group of alpine rivers in Switzerland and by characterizing the response of water temperature of these rivers, with special attention paid to the 2003 and 2006 heatwave events that resulted in the significant signatures they left in European river systems (Beniston and Diaz, 2004; Fischer, 2014; Rebetez et al., 2009).

2. Materials and Methods

2.1. Study area and dataset

This study was based on a multi-decadal and high-temporal resolution dataset of river streamflow, RWT, and AT time series from 19 gauging stations in the Swiss Alps, covering the last 30 years (Fig. 1). These gauging stations span an elevation range for catchments from 262 to 1645 m AMSL, with a catchment glacier covering from 0% to 21% (Table 1). We collected AT records measured at a 2 m height from meteorological stations in Zurich, Basel, and Geneva and further averaged the data to obtain a representative averaged AT time series for Switzerland given the similar elevations (AMSL) of the three stations (Beniston and Diaz, 2004; Kuglitsch et al., 2009). All datasets were monitored and collected by the Swiss Federal Office for the Environment (FOEN) at a 10 min time interval between 1984 and 2013. Data were checked for potential outliers resulting from monitoring or processing mistakes.

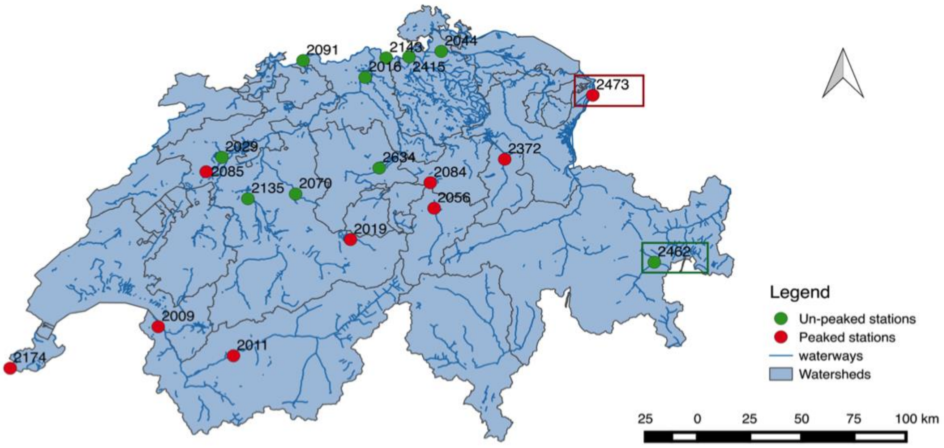

Fig. 1. Locations of the Swiss gauging stations used for analysis in this study. Stations are categorized as either peaked stations (in red) or unpeaked stations (in green) that are subject to hydro-thermopeaking effects. A select number of station codes are shown in Table 1.

Table 1

Geographic information of the 19 gauging stations this study used for both discharge and water temperature analysis with outcomes of hydropeaking (HP) and thermopeaking (TP) classification (Section 2.2).

Station code	**River**	**Reach**	**Station elevation (m a.s.l.)**	**Mean catchment elevation (m a.s.l.)**	**Drainage area (km ²)**	**Catchment Area Glaciation (%)**	**Coordinates (CH1903/LV03)**		**Group**
2425	Kleine Emee	Emmen	431	1050	477	0	664220	213200	Unpeaked
2016	Aare	Brugg	332	1010	11726	2	657000	259360	Unpeaked

2029	Aare	Brugg -aegaerten	428	1150	8293	2.9	588220	219020	Unpeaked
2044	Thur	Andelfingen	356	770	1696	0	693510	272500	Unpeaked
2070	Emme	Emmenmatt	638	-	443	-	623610	200430	Unpeaked
2091	Rhein	Rheinfelden	262	1039	34526	1.3	627190	267840	Unpeaked
2135	Aare	Bern-Schonau	502	1610	2945	8	600710	198000	Unpeaked
2143	Rhein	Rekingen	323	1080	14718	0.57	667060	269230	Unpeaked
2415	Glatt	Rheinsfelden	336	498	416	0	678040	269720	Unpeaked
2462	Inn	S chanf	1645	2466	618	10.1	795800	165910	Unpeaked
2009	Rhone	Porte du Scex	377	2130	5244	14.3	557660	133280	Peaked
2011	Rhone	Sion	484	2310	3373	18.4	593770	118630	Peaked
2019	Aare	Brienzwiler	570	2150	554	21	649930	177380	Peaked
2056	Reuss	Seedorf	438	2010	832	9.5	690085	193210	Peaked
2084	Muota	Ingenbohl	438	1360	316	0.08	688230	206140	Peaked
2085	Aare	Hagneck	437	1380	5104	4.5	580680	211650	Peaked
2174	Rhone	Chancy	336	1580	10323	8.4	486600	112340	Peaked
2372	Linth	Mollis	436	1730	600	4.4	723985	217965	Peaked
2473	Rhein	Diepoldsau Rietbrucke	410	1800	6119	1.4	766280	250360	Peaked

2.2. Classification of peaked and unpeaked stations

All gauging station analyzed were subject to a preliminary screening to detect the presence of “hydropeaking” (HP) and “thermopeaking” (TP) phenomena. To this aim, we applied the statistical methods proposed by Carolli et al. (2015) to characterize sub-daily hydropeaking features. We calculated indicators of the magnitude of hydropeaking (HP1; dimensionless; Eq. 1) and the temporal rate of change (HP2; $m^3 \cdot s^{-1} \cdot h^{-1}$; Eq. 2) from 10-min discharge records for each gauging station.

$$\mathrm{HP1} = \frac{\mathrm{Q_{max}} - \mathrm{Q_{min}}}{\mathrm{Q_{mean}}} \qquad \text{(Eq. 1)}$$

$$\mathrm{HP2} = \frac{\Delta \mathrm{Q}}{\Delta \mathrm{t}} = \frac{\mathrm{Q_k} - \mathrm{Q_{k-1}}}{\mathrm{t_k} - \mathrm{t_{k-1}}} \qquad \text{(Eq. 2)}$$

where Q_{max}, Q_{min}, and Q_{mean} are the daily-scale statistical values, and Δt are the sub-daily time steps (Δt = 10 min in this study).

Likewise, we used two indicators to detect sub-daily thermopeaking variation from the 10-min interval river water temperature records for each gauging station. The first indicator is the sub-daily rate of change for water temperature, which is equivalent to the absolute value of maximum sub-daily variation divided by daily temperature variation (TP_{Δ}; Eq. 3).

$$TP_{\Delta,i} = \frac{max|T_{k+\Delta t} - T_k|}{T_{max_i} - T_{max_i}} \qquad \text{(Eq. 3)}$$

where $TP_{\Delta,i}$ is the daily indicator, and Δt is the calculation time step (we used a 15 min default resolution). For each gauging station, the representative TP_{Δ} indicator for a given period is defined as the median value of $TP_{\Delta,i}$ distribution.

The second indicator is the frequency of sub-daily temperature fluctuations (TP_{en}; Eq. 4). It represents the scaled averaged power spectral density oscillation in relation to the daily averaged power (Vanzo et al., 2015). In this study, the short-scale *n* equates to 6 h.

$$TP_{en} = \frac{P_n}{P_{24}} = \frac{\int_{f_n}^{f_1} S(2\pi f)df}{\int_{f_{24}}^{f_1} S(2\pi f)df} \qquad \text{(Eq. 4)}$$

After calculating the values of these four hydro-thermopeaking indicators, we classified each gauging station as either a thermo peaked or unpeaked station (Table 1; last column) according to the distribution of indicators in reference to their corresponding threshold values. We also calculated thresholds from gauging stations that were not subject to upstream intermittent water release from hydropower plants for comparison.

A more intuitive illustration of peaked and unpeaked gauging stations with distinct distributions of hydro-thermopeaking indicators is provided in Fig. 2. We divided quadrat plots (sectioned into four) by the threshold values of the indicators on the x-axis and y-axis, respectively. We represented indicator locations either as a minor or no alteration class in the lower left corner, a high-alteration class in the upper right corner, while we represented the other two sections as mid-alteration classes. Gauging stations that fell into the mid-alteration classes were subject to further investigation as it pertains to detailed hydrograph/thermograph factors before they were eventually grouped as either peaked or unpeaked stations. We only included one “peaked” station (Code=2372; the Mollis Station on the Linth River) that showed hydropeaking influence downstream from a hydropower plant but no outstanding thermopeaking effects due to the extenuating influence of an incoming tributary above the gauging station. After further examination of the detailed hydrograph and thermograph we produced, we determined it to be a peaked station given that the effects of hydropeaking and thermopeaking showed more clear patterns, especially in winter (January).

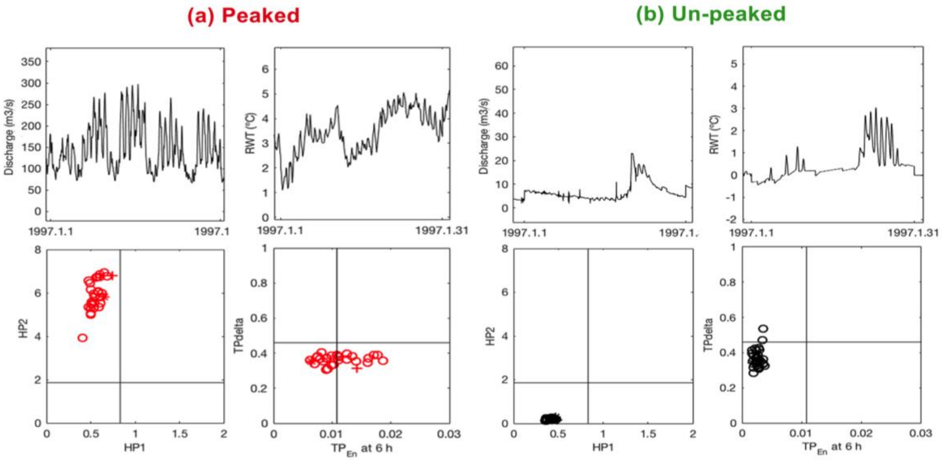

Fig. 2. Hydrograph and thermograph examples for the (a) peaked station (Code 2473) and (b) unpeaked station (Code 2462) are plotted for January 1997. The lower two panels of each station represent hydropeaking indicators (HP1; HP2) and thermopeaking indicators (TP_{en}; TP_{Δ}) in reference to their threshold levels. The upper panels are the river discharge and water temperature records generated in order to obtain direct observations of hydro-thermopeaking effects, respectively.

2.3. Temperature variability analysis

We computed monthly and daily maximum AT and RWT as well as their anomalies from the original observation dataset produced in order to analyze temperature dynamics of the two pre-classified groups at different temporal scales. Special attention was given to the summer months when heatwaves typically occur. More specifically, the extent of the 2003 heatwave event spread throughout the whole summer (from June to August, referred to as JJA, i.e., June, July, and August) with the highest temperature values measured between June and mid-August. On the other hand, the 2006 heatwave event only took place during the month of July (Rebetez et al., 2009).

We conducted statistical analysis to investigate variability in maximum, minimum, and mean air and water temperatures at different timescales (daily, monthly, seasonal, and yearly). We calculated another metric that measured the accumulated heat budget in degree days (Cesaraccio et al., 2001) based on a 10-min RWT time series to indicate the total amount of heat during each monthly period, this being directly correlated to mean RWT.

For each of these site-specific datasets, we computed temperature anomalies as the difference between measured values and the standard baseline value, which is equivalent to the historical average value of the consecutive 30-yr period (from 1984 to 2013 in this study) (WMO, 1989).

2.4. Correlation analysis between air and water temperature

In order to account for RWT response to AT, we first applied linear regression of the ordinary least squares (OLS) model to daily maximum RWT as a response variable and AT as an explanatory variable for each station. Afterwards, we applied the non-linear least squares (NLS) method (Zenklusen Mutter et al., 2010) to the logistic S-shaped function (Eq. 5; Mohseni et al., 1998) to reveal the nonlinear correlations between the daily maximum air and water temperatures.

$$RWT = \frac{\alpha}{1+e^{\gamma(\beta-AT)}} \qquad \text{(Eq. 5)}$$

where RWT is the measured river water temperature used for the correlation; AT is the measured air temperature; the coefficient α is the fitted maximum RWT; β is air temperature at the inflection point; and γ is a measure of the steepest slope of the function.

2.5. Ecological thermal stress evaluation

To investigate one of the potential ecological impacts of extreme heatwave events, we analyzed the thermal habitat vulnerability of fish, especially during their growth period. To this aim, we selected brown trout (*Salmo trutta*), a typical cold water stenotherm species found in the alpine region of this study, as the representative species. The upper limit of the daily maximum temperature for *S. trutta* was set to 19.5ºC (Elliott and Hurley, 2001), whereby temperatures above this critical threshold will interrupt *S. trutta* growth periods and lead to harmful effects (Olden and Neff, 2001). Thus, we conducted an analysis of the continuous duration and frequency of thermal events exceeding this threshold for peaked and unpeaked stations separately. Specific focus was given to their characteristics during the 2003 and 2006 heatwave events.

On a monthly scale, we calculated the days in which temperatures exceeded this threshold (exceedance values) as the total number of days within each month that daily maximum temperatures were higher than the baseline threshold. We computed the maximum consecutive days when the exceedance value was higher than zero as the persistence (days) of that month.

In addition to frequency, thermal stress events could become seriously harmful or even lethal when extended over long continuous periods. As well as such cumulative metrics, we also calculated the continuous duration of individual thermal events characterized by RWT rising above established ecological thresholds, referred to as the uniform continuous under threshold (UCUT) methodology (Parasiewicz et al., 2012).

3. Results

3.1. River water temperature variability in peaked and unpeaked stations

The analysis of RWT variability yielded analogous results for all three examined variables (minimum, mean, and maximum daily RWT). Accordingly, we chose to show the daily maximum AT and RWT results in this study. Statistical distributions of daily maximum summer temperatures throughout the past 30 years (1984–2013) for all stations are shown in Fig. 3. Maximum RWT values of the unpeaked group correspond to the 2003 and 2006 heatwave events as shown by the AT distributions (Fig. 3a). For all months and throughout the whole summer (from June to August), peaked stations yielded significantly lower mean standardized values compared to unpeaked stations. This pattern was the same for standard deviations. The higher variability of peaked stations was systematically associated with an expansion in distribution of lower-end daily maximum RWT values, which was consistent with a reduction in means in comparison to unpeaked stations. This reflects a generalized and significantly different cooling tendency in intermittent hydropower release.

This behavior had immediate consequences for the 2003 and 2006 heatwave events, which were almost invariably associated with the highest three RWT values on record for unpeaked stations, while not evident for peaked stations (Fig. 3b, c). This showed a significantly reduced impact from extreme heatwave events on RWT records resulting from hydro-thermopeaking effects.

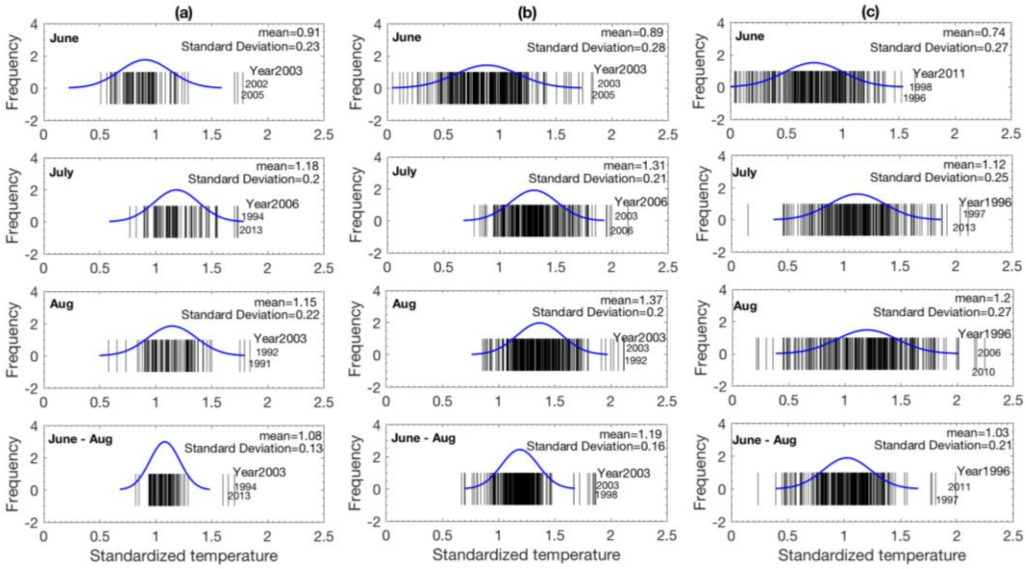

Fig. 3. Statistical distribution of daily maximum temperatures in June, July, and August, and from June to August (the summer as a whole) over a 30-yr period (from 1984 to 2013), respectively. Columns represent (a) averaged AT from meteorological stations at Basel, Geneva, and Zurich; (b) RWT from all unpeaked stations; and (c) RWT from all peaked stations. All datasets were standardized by subtracting mean values and dividing them by standard deviations before extracting the mean value for

each selected month. Within each panel are rug plot-derived mean monthly values over a 30-yr period, with the three highest values labeled by the corresponding year. Fitted Gaussian distributions (blue curves) with mean values and standard deviations are given for each panel.

We calculated the accumulated monthly heat budget for the rivers investigated at the selected gauging stations from the RWT time series (degree days), which measure the level of heating effects on river systems. In Fig. 4, we computed degree day anomalies for the summer months (JJA) for all stations of both groups throughout a 30-yr period. Results indicated that below the water release point, degree day anomalies from hydro-thermopeaking peaked stations yielded 56.0%, 56.0%, and 43.2% lower mean values, and 25.0%, 11.4%, and 37.9% standard deviations in June (ANOVA; $F_{1, 29} = 54.53$; $p<0.001$), July (ANOVA; $F_{1, 29} = 27.56$; $p<0.001$), and August (ANOVA; $F_{1, 29} = 34.07$; $p<0.001$), respectively.

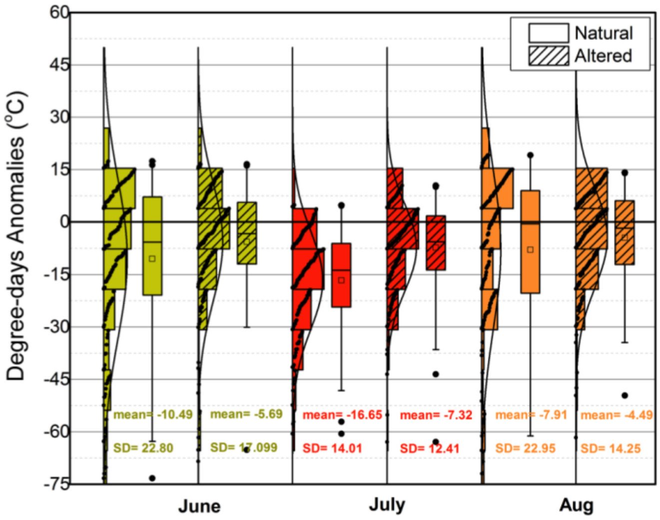

Fig. 4. Degree day anomalies for June, July, and August (JJA) between 1984 and 2013 for the dataset as a whole. Anomalies were calculated relative to the deviation of the 30-yr (1984–2013) baseline, and normal distributions are shown, respectively. Box plots represent unpeaked stations (solid color) and peaked stations (filled pattern) for June, July, and August, respectively.

3.2. Correlation analysis resulting from heatwaves

Figure 5 synthesizes the nonlinear correlation results between AT and RWT from peaked and unpeaked stations. Monthly variation in correlation coefficients highlighted the differences between hydro-thermopeaked and unpeaked stations. In contrast to the unpeaked group, peaked stations showed decreased coefficients of determination for both station-wide comparisons and monthly averaged values. Such differences in response to changing AR appeared to be more pronounced during periods of summer heatwaves (from June to August). In summary, the impact of hydro-thermopeaking showed noticeable effects in diminishing the homogeneity of the relatively higher correlations that could be observed between RWT and AT, and this effect was more evident during heatwaves where the warming rate of water temperature was reduced.

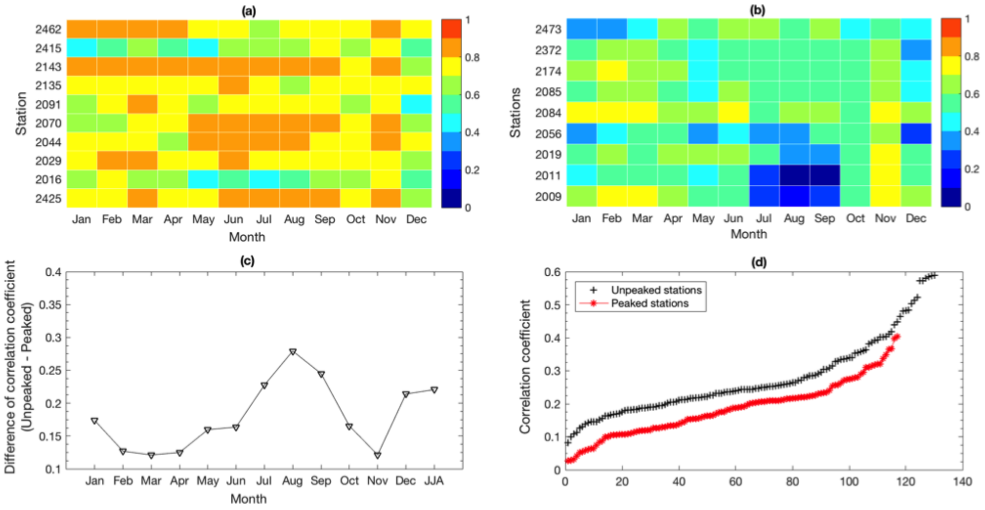

Fig. 5. Monthly variation in correlation coefficients between daily maximum AT and RWT for (a) unpeaked stations and (b) peaked stations using non-linear least squares analysis. Differences between monthly average correlation coefficients of the two groups are plotted in (c) from January to December and the summer period as a whole from June to August (JJA). (d) Correlation coefficients of the two groups depicted in a sorted order.

3.3. Ecological threshold exceedances

Observed differences in heating effects between hydro-peaked and unpeaked stations during the summer months could imply as yet unknown ecological effects. We made a first attempt to address this question by assuming a RWT upper limit of 19.5ºC for *S. trutta*, a typical fish species found in alpine streams in the study area, and analyzing differences in threshold exceedances between peaked and unpeaked stations and between years when heatwaves took place and years when no heatwaves took place during summer months. Figure 6 shows the monthly average number of exceedance days over this critical ecological threshold for all stations of each group. Against a background of AT exceedance days under the same threshold (Fig. 6a), peaked stations (Fig. 6b) showed a distinctively smaller number of exceedance days compared to peaked stations (Fig. 6c), and such differences were more prevalent in June (ANOVA; $F_{1, 29}$ =11.95; $p< 0.01$), July (ANOVA; $F_{1, 29}$ =7.33; $p< 0.05$), and August (ANOVA; $F_{1, 29}$ =8.66; $p< 0.01$), respectively.

In 2003, exceedance days of unpeaked stations during the hottest months (JJA) were 19.7, 23.5, and 28.2 d, respectively, on average. However, exceedance days of peaked stations were considerably less, that is, 4.6, 7.2, and 10.2 d, respectively. In July 2006, peaking operations diminished the effect of the heatwave event, with a difference of 3.48 d, which likely resulted in less harmful consequences for fish species. Overall, intermittent hydropower release operations have been observed to mitigate extreme heatwave effects on thermal growth thresholds of *S. trutta* by reducing the number of exceedance days.

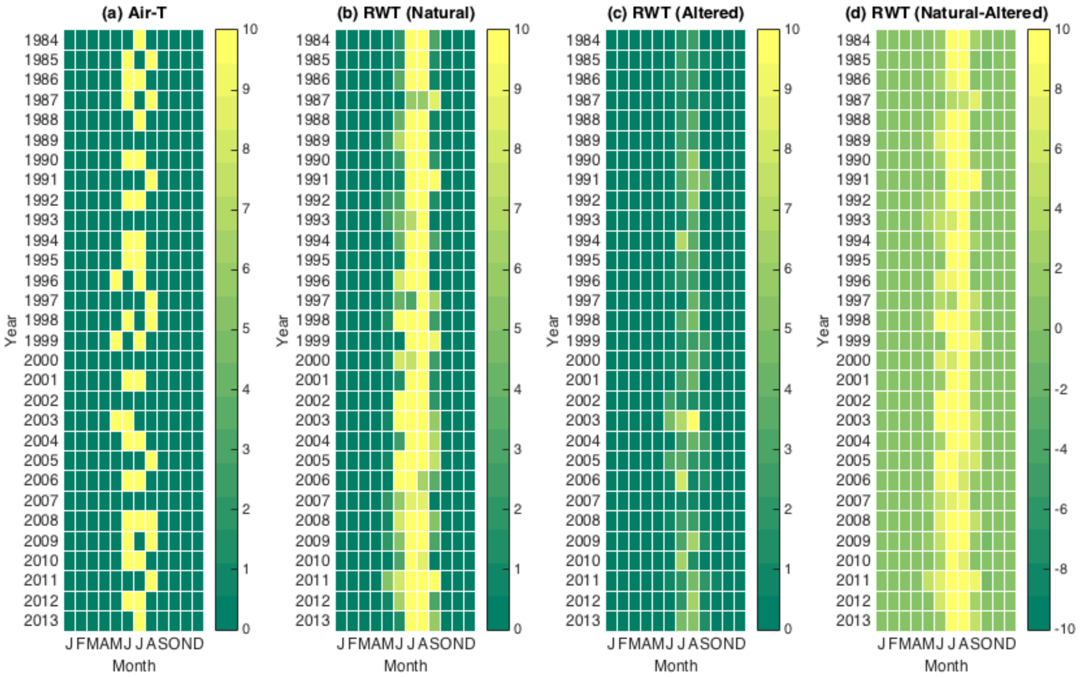

Fig. 6. Number of exceedance days over the upper limit of the temperature threshold determined for *Salmo trutta* (19.2°C). Monthly average exceedance days for (a) the three meteorological stations where AT was averaged; (b) RWT at unpeaked stations; (c) RWT at peaked stations; and (d) differences between the two groups, calculated as the number of exceedance days of the unpeaked group subtracted by the peaked group.

To quantify possible losses or gains in thermal habitat for *S. trutta*, we combined two variables related to the number of exceedance days and the duration of each exceedance event. Statistics related to exceedance events along with their days of continuous duration throughout 2003 and 2006 and the 28 years where no heatwaves took place were calculated and compared between peaked and unpeaked groups (Fig. 7). The probability of long-term exposure to high temperatures showed clear deviation between peaked and unpeaked stations with an increase in continuous duration days. Under the same probability, peaked stations were found to have less temperature exceedance days. This advantage, resulting from hydro-thermopeaking effects, was more obvious during years when heatwaves occurred, especially under long durations of extreme thermal exposure.

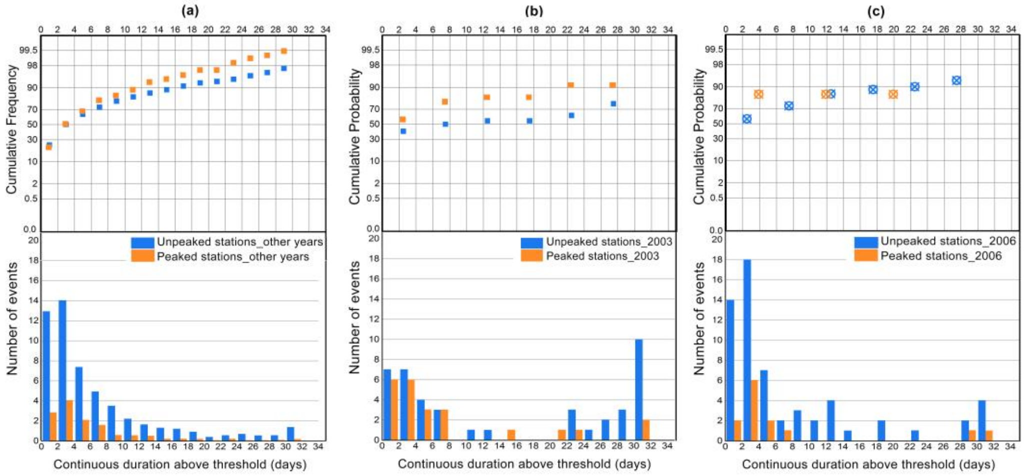

Fig. 7. Continuous exceedance events when maximum daily temperatures were above the tolerance threshold (19.2ºC). Histograms of continuous exceedence duration days were calculated for all peaked and unpeaked gauging stations during (a) years when no heatwaves took place, (b) 2003, and (c) 2006. The upper figure shows the corresponding cumulative frequencies of events.

In light of the evaluation of thermal habitat conditions, we used the above events (continuous exceedance days) to create the UCUT curves illustrated by Parasiewicz (2008). Rather than analyzing conditions of low flow, we modified the river thermal regime UCUT curves for conditions of high flow (referred to as uniform continuous above threshold (UCAT) curves) and applied them to an evaluation of habitat suitability for cold water stenotherm species.

The UCAT curves describe the duration and frequency of significant thermal events when continuous duration days of RWT are above the growth threshold for *S. trutta*. We summed the cumulated exceedence days of each continuous duration day, which ranged from 1 to 31 d, per year and divided them by the total number of assumed heat periods. Horizontal differences (e.g., right shifts) in curves for the same continuous duration depict an increase in the frequency of occurrences. The smaller the frequency of the duration is, the less that RWT will be above the upper growth threshold limit, which means greater suitability in thermal habitat for *S. trutta*. This allows for the evaluation of habitat suitability at a range of thermal regimes using suitable temperature duration days, which managers could use to determine thermal habitat bottlenecks.

In Fig. 8, peaked stations (in red) yielded steep curves with small changes and consistently small frequency magnitudes compared to all unpeaked stations (green) for corresponding years. Under the same climatic background, we determined a temperature-indicated habitat suitability benefit for river sections under peaked stations.

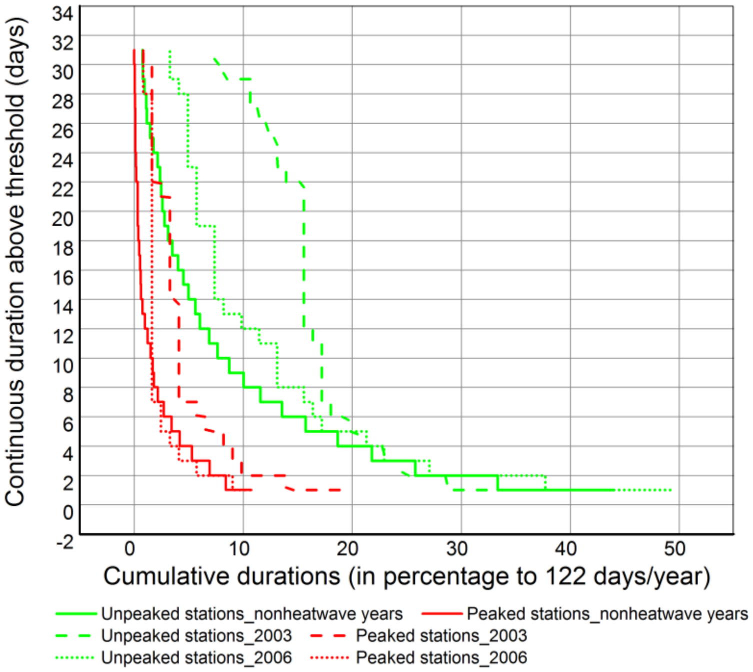

Fig. 8. Uniform continuous above threshold curves for suitable thermal habitat growth of *Salmo trutta*. Each curve represents the cumulative duration and frequency of the number of events when RWT is higher than the upper growth limit for the continuous duration days depicted on the y-axis. The x-axis is a comparison of the total number of assumed heat days (from June to September; 122 days) per year (in percentages).

4. Discussion

4.1. Correlations between air and water temperature

Despite the good results produced by OLS analysis, the autocorrelation within datasets and the interactive influence from topological and geological variations reveals the necessity of nonlinear analysis. The performance of the nonlinear logistic model was better than OLS (higher Nash–Sutcliffe efficiency (NSC) and lower root-mean-square errors (RMSE)); therefore, for the river systems studied, nonlinear logistic function is recommended to build a relationship between air and water temperature. However, the model has disadvantages, such as decreased performance during warm seasons due to unevenly distributed water temperature. A growing number of investigations on long-term trends highlight the complexity of climate change and interactions with other anthropogenic impacts (Webb et al., 2008). While the S-shaped function has been well explored in the study of air-water temperature relationships, it has been suggested that this model is inadequate when applied to river systems, such as reservoir outlets or where effluents influence stream temperature (Mohseni et al., 1998). It is important to note that it is useful to separate free-flowing rivers from those that are regulated.

Previous studies have reported that predictions of water temperature using paired air temperature can generate poor results in both linear and nonlinear models under extreme climatic events but often have high biological significance (Arismendi et al., 2014; Benyahya et al., 2010; Kvambekk and Melvold, 2010; Webb and Nobilis, 1995). Based on this assumption, our study alternatively focused on the analysis of water temperature and its associative biological significance under extreme heatwave events. Instead of faithfully focusing on exact predictions of water temperature using linear or nonlinear models, our study focused on the disturbance in the equilibratory relationship between air and water temperature. We applied an unconventional perspective, that is, hydro-thermopeaking, to capture the hydrological and thermal regimes of rivers. This disturbance in the equilibratory relationship could also be interpreted as an adaptation period for river water temperature to normalize with different time lags as a response to changing AT (Letcher et al., 2016; Stefan and Preud'homme, 1993; Van Vliet et al., 2011). The physical interpretation of these different time lags could be dependent on infrequent environmental or operative circumstances, such as cloud cover that is often highly variable between different stations or the specific times that hydropower plants are in operation.

4.2. Extreme climatic mitigation using hydropower

During summer, the cooling effect of water released from reservoirs could be used to mitigate detrimental effects of climate change, which has already been suggested by Yates et al. (2008) in their modeling application conducted in California’s Sacramento Valley, USA, but has yet to be demonstrated in alpine river systems. Effects of climate change on the hydrology (Beniston, 2012; Middelkoop et al., 2001; Jasper et al., 2004) and the temperature of river systems in the Alps have been investigated on both experimental and modeling levels (Brown and Hannah, 2008; Caissie, 2006; Hari et al., 2006; Null et al., 2013; Toffolon and Piccolroaz, 2015). However, few studies have investigated such effects; for instance, the warming of river water resulting from other anthropogenic impacts that could potentially be combined with climate-induced effects (Gobiet et al., 2014).

Results from this study indicated that thermal regulations of rivers associated with hydropeaking and thermopeaking during summer months could result in cooling and lag effects on the thermal response of recipient streams to changing AT. Our results are consistent with existing studies on the thermal dynamics of river systems (Piccolroaz et al., 2016), which suggest that in comparison to other river systems, hydropower-regulated rivers may be more resilient to variations in AT, that is, non-regulated rivers, which have been determined to behave more reactively. A similar concept was previously demonstrated by Null et al. (2013) by means of their modeling study of reservoir operations and release into downstream water bodies, explicitly focusing on assessing whether dams may mitigate the effects of climate change on stream temperatures. Their study suggested that on a weekly timescale during summer months the release of water from reservoirs should result in a cooling effect to recipient streams, though such an effect may be dampened further downstream resulting from the continued effect of temperature warming trends associated with climatic effects. Our study moves beyond these acquisitions and, differing from previous analyses, it focuses on heatwaves, another element of climatic change, whereby an increase in temporal frequency has been forecast in alpine areas.

A second distinctive feature of our study is that our analysis was conducted on a much finer timescale, that is, a sub-daily scale, by means of the analysis of a high-temporal-resolution RWT dataset. This is a key requirement for the scope of the analysis because the cooling effect generated by the release of hypolimnetic water from reservoirs is typically associated with intermittent flow release that responds in real-time to peaking demands from the energy market. Released hypolimnetic water causes cold thermopeaking effects during summer months because such water is known to be cooler than the stream water that receives it in summer and, similarly, such water is known to be warmer in winter (Carolli et al., 2012; Zolezzi et al., 2011). Hydropower regulation produces a significant weakening influence on the equilibrium relationship between RWT and changing AT. Moreover, it is interesting to note that the mitigated impact of extreme heated AT on RWT from peaked stations has a smaller overall magnitude but a bigger range as it pertains to the time necessary for RWT to be warmed by AT on both annual and inter annual scales. This agrees with our findings from the statistically broader distribution of RWT anomalies against our observations from unpeaked stations.

Finally, when considering climatic effects on river ecosystems as a whole, it must also be taken into account that besides temperature, climate change also influences river runoff dynamics (Woodward et al., 2010), and specific relevant analyses have already been conducted in mountainous and snowy regions, such as in Himalayan rivers (Kaltenborn et al., 2010). Alpine rivers are particularly sensitive to climate change, as runoff magnitude and timing is determined by melt and accumulation cycles of snow packs and glaciers (Khamis et al., 2014). A reduction in summer river temperatures may not apply to rivers that experience periodic inflow or influence from glaciers and groundwater spills (Dickson et al., 2012). In our study, however, special attention was paid to extreme summer heatwaves, during which glacial impacts are less prominent as they would be in winter and early spring. From the point view of hydropower management on riverine ecosystems, alterations in the thermal regimes of rivers affected by glaciers may require further examination within a specific context.

4.3. Implications for cold water stenotherm river habitat

We found that correlations between AT and RWT were weaker in river sections downstream of reservoirs. This effect is due to the temperature of the water released from reservoirs, which typically is significantly different from river temperatures, especially if hypolimnetic water is released. While such hypolimnic water released from reservoirs usually alters the natural thermal regime of downstream river sections in undesirable ways, it could also mitigate extreme temperature peaks that could be produced during summer heatwaves.

Heatwaves that last for several days may especially affect the integrity of river ecosystems, causing unusually long warm periods that may led to insupportable thermal stress on aquatic biota. For alpine streams, in particular, fish species have adapted to habitats characterized by the preference of cool temperatures and only exhibit limited tolerance towards warmer temperatures. High temperatures generated by heatwaves could be fatal to river biotas that are adapted to cold water habitats (such as cold water stenotherm organisms), particularly when temperatures exceed the threshold levels tolerated by such organisms.

The temperature threshold of stream fish (e.g., salmon or trout) varies somewhat from the duration time and fluctuation of extreme temperatures that organisms are exposed to (Wehrly et al., 2007). The duration and the number of events that exceed temperature thresholds affect the survival of specific cold water stenotherm species. When taking into account the fact that several alpine river fish species have been documented to live very close to the upper limit of their thermal survival range (Hari et al., 2006), even small increases in RWT may result in an extension in the duration of harmful thermal events on such fish species (*S. trutta* in the case of this study).

Our results indicated that in the absence of heatwaves, unpeaked stations have already exhibited a much longer duration of thermal stress on *S. trutta*. During the 2003 and 2006 heatwave events, their continuous duration increased considerably, especially during the long summer heatwave of 2003, with a one week maximum increase. It has been argued that climate-induced warming trends in river water temperature in mountainous regions may trigger a migration of cold water stenotherm species in an upstream direction (Bunt et al., 1999; Hari et al., 2006). Our results point out an additional effect that may alter conditions of fish migration in alpine rivers, that is, a tendency for fish species to move towards artificially and intermittently cooled riverine habitats. Such a hypothesis would however require careful verification, because, depending on channel morphology, river systems subject to hydropeaking may on the other hand present high stranding risks (Vanzo et al., 2015) or reduced food supplies for fish due to a decrease in macroinvertebrates resulting from increased catastrophic drift (Bruno et al., 2010).

4.4. Multiple stressors from reservoirs and hydropower water release

The projected increase in heatwave frequency and future duration may represent an additional threat to already vulnerable river ecosystems. There are increasing discussions (e.g., Bruder et al., 2016) on how to effectively conjugate the need of renewable energy production from hydropower stations while mitigating its impacts on freshwater ecosystems. Results from our study seem to suggest a paradox: where hydro- and thermopeaking may protect cold water stenotherm aquatic biota from the adverse effects associated with a projected increase in heatwave events. Does this mean that more power storage plants should be constructed to protect fish in alpine streams?

Clearly, mitigation effects of reservoirs on alpine river systems during heatwaves represent only one of the numerous effects that reservoir operations have on river systems. Given that hydropeaking is a typical operation of such reservoirs, which leads to multiple known adverse effects on the integrity of river ecosystems, it is needless to say that considering the construction of new reservoirs as ideal agents for thermal mitigation is not a straightforward approach. In addition to hydropeaking, reservoirs even exert multiple other adverse effects on the integrity of river ecosystems, such as the interruption of longitudinal connectivity for sediment transport and fish migration, changes in water quality, and the migration of fish and aquatic invertebrates (Truffer et al., 2003).

Our results add some complexity to the existing picture of the biophysical processes involved in hydropower-regulated alpine streams. It should be noted that hydropower facilities vary in their functions with regard to their water intake procedures, which are related to the thermal stratification of water columns behind dams. Newer hydropower facilities are increasingly upgraded with a selective intake structure to meet downstream temperature requirements. The hydropower facilities included in our study are generally too old to have had these selective withdrawal systems installed. The range of years for which most of the hydropower plants investigated were constructed was between 1902 and 1968. Three hydropower plants that were newly built are of very small size and are located beside a major but old hydropower plant. Furthermore, impacts of selective temperature control systems on ecological indicators have been widely studied (Fontane et al., 1981; Ma et al., 2008; Martinez et al., 2014; Olden and Naiman, 2010; Rheinheimer et al., 2014; Weber et al., 2017; Zheng et al., 2017). By using temperature selective schemes in the future, hydropower plants could perform more target-specific mitigation strategies against the adverse effects resulting from climate changes.

At the same time, further implications should be explored in the near future. Our analysis had, in principle, a very restricted spatial focus because analyzed data were collected per station, and river or river segment-scale information would be needed to assess how long actual river sections are. An analysis in line with the one we proposed in this study is therefore needed with regard to spatial and timescale characteristics of thermopeaking propagation for specific case studies, which would allow for the quantification of actual length, connectivity, and spatial distribution properties from river system catchments in which detected thermal protection via thermopeaking from heatwaves would occur. At the same time, the hydromorphology of these rivers has extensively been modified through anthropogenic activity, and this is a result of their enormous potential in providing a variety of ecosystem services, such as hydropower production, multipurpose water supplies, and cultural and recreational activities.

5. Conclusions

Alterations to aquatic environments through anthropogenic activity are unavoidable and are under dispute. Moreover, taking mitigation to climate change into consideration adds to the complexity of anthropogenic influence via hydropower regulations. This study analyzed the sub-daily thermal regime of alpine river systems and their response to extreme summer climate events (heatwaves) with the aim of comparing a set of river systems subject to intermittent hydropower production with a set of river systems where such peaking regimes do not occur. Through sub-daily hydropeaking and thermopeaking analyses focused on a set of 19 river gauging stations in Switzerland, we quantified to what extent water temperature in alpine rivers exhibited predicted summer warming for both peaked and unpeaked rivers at the gauging stations investigated. Such effects were mostly amplified during heatwave events but not for all correlated parameters. During heatwaves, especially for long-lasting, continuous above-threshold events, sub-daily thermopeaking showed a much smoother response to river water temperature in unpeaked streams. We quantified how much this would translate into a surprisingly advantageous environment for cold water stenotherm river biota under a continuous duration of thermal stress events.

Such hydro-thermopeaking alterations to downstream river sections are discovered as a potential mitigation strategy to take to increase thermal suitability by providing a reduction in the range of oscillation water temperatures. Our results provide important data on the effects of heatwaves and add to the complexity of climatic effects on river water temperatures for river systems regulated by hydropower production activities. Although an apparent paradox, we suggest that anthropogenic interference could be used as a potential mitigation measure in response to extreme climatic events. The implications of the results from this study are related to the temporary selection of thermally protected areas within regulated river systems under a projected future increase in heatwave frequency in alpine areas.

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