Analysis of hydro- and thermopeaking in the Upper Rhone River during the SmallFlex experiment in November 2018

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1. Background

Between 8 and 30 November 2018, a series of hydropeaking experiments were conducted on the Upper Rhone River in the framework of the SmallFlex project. For three weeks, a specific experimental program was imposed on the Gletsch-Oberwald hydropower plant by Eawag and EPFL to explore its potential flexibility. Approximately 2'460 m^3 of water were stored in the settling basin and the forebay tank and released at specified times within release peaks of 15 to 60 min duration. For the first two weeks (8 to 22 November) Eawag requested an experimental program in order to assess the recovery of the benthic macroinvertebrates downstream (Eawag program). During the third week of experiments (26 to 30 November) the schedule was defined by EPFL to test the entire capacity of the newly installed hydropower plant for flexible power production (EPFL program).

2. Data

2.1. In-situ temperature and pressure measurement

Temperature and pressure were continuously recorded from 1 to 27 November 2018 with a time resolution of 2 minutes using HOBO U20L-04 Water Level loggers. Measurements were performed in the main channel at an upstream site, at the hydropower plant outflow, and at a downstream site (Figure 1), and an additional logger was fixed on a tree next to the downstream measurement site for recording air temperature and pressure. The relative downstream water level (cm) was calculated by taking the difference between the pressures (kPa) recorded at the downstream site and the air pressure, multiplied by 9.8 cm / kPa.

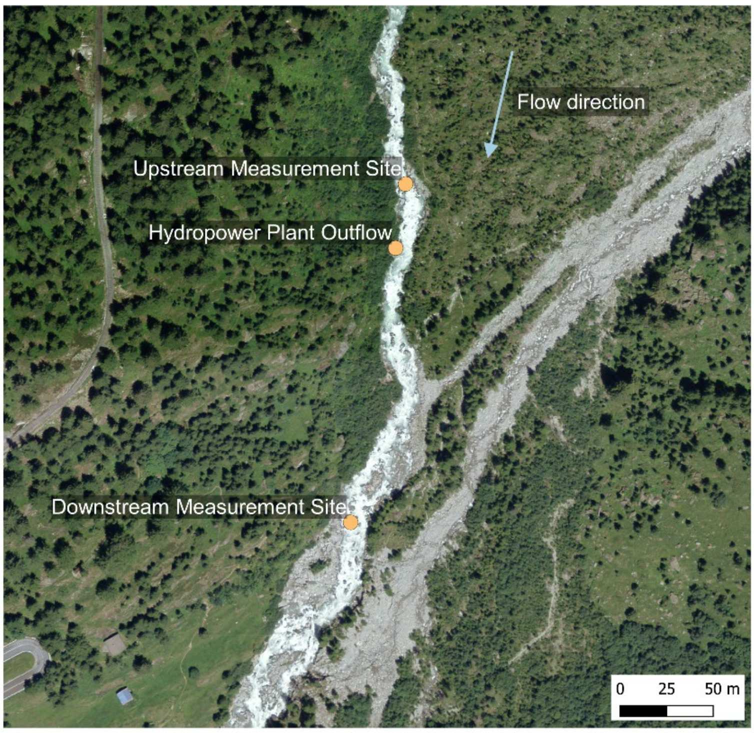

Figure 1: Measurement sites on the Upper Rhone River (Aksamit et al., 2021).

2.2. Hydropower plant discharge

The time series of the hydropower plant discharge for the entire experimental period with a time resolution of 15 minutes was provided to Eawag by EPFL.

3. Results and discussion

3.1. Hydropower plant discharge

Using the existing infrastructure (i.e. the settling basin and the forebay tank) for sub-daily storage of limited volumes of water to meet fluctuating market demands, 16 experimental hydropeaks were produced over the three week period (Figure 2). During the Eawag program (8 to 22 November) five 15 min long peaks were generated in order to assess the influence of rapid flow releases of high amplitude from the Gletsch-Oberwald hydropower plant on the downstream environment. The same experimental hydropeak was replicated five times over 14 days with decreasing recovery times between peaks (8 days, 3 days, 2 days, and 24 hours). Each peak lasted 15 min, as this duration has been determined as the most likely option for the future Gletsch-Oberwald Hydropower plant. During the EPFL program (26 to 30 November) several peaks of different amplitudes and of different durations were imposed: two 15 minute peaks on 26 November, two 30 minute peaks on 27 November, two 1 hour peaks on 28 November, four 15 minute peaks on 29 November and one 2 hour peak on 30 November (Figure 2).

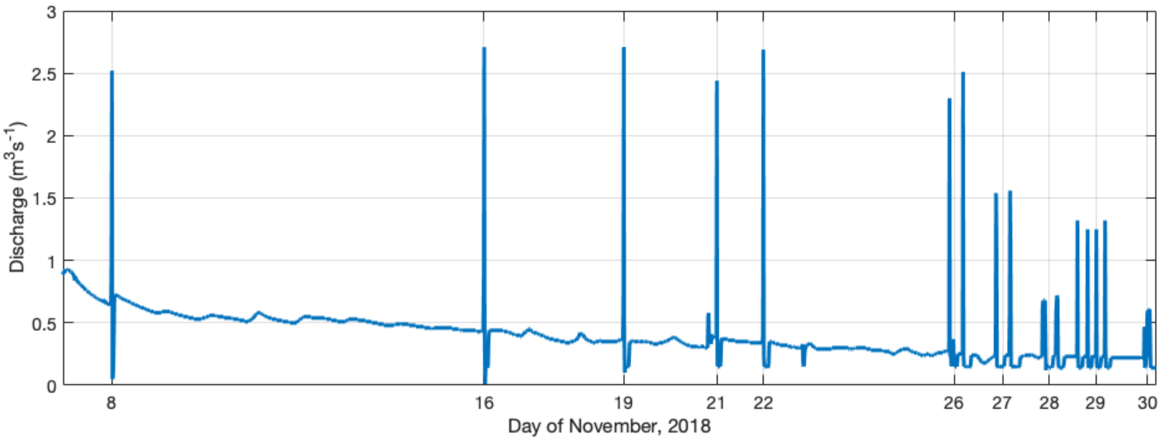

Figure 2. Discharge of the Gletsch-Oberwald powerplant from 8 to 30 November 2018. Eawag requested experimental discharge between 8 and 22 November, EPFL requested experimental discharge between 26 and 30 November.

The discharges from the hydropower plant before the peak, during the peak, after the peak, during the refilling of the settling basin and the forebay tank, and after the refilling are given in Table 1. After each peak event, the refilling lasted approximately 30 minutes where hydropower discharge was lowest. After the refill, the hydropower discharge would increase to pre-peak discharge on all days except for 30 November (Table 1). On 30 November the hydropower discharge was not increased back to normal directly after the refill and remained at 0.14 m^3 s^{-1} for the entire rest of the day.

Table 1. Pre-peak, peak, refill, and post-refill discharge values for all experiment days. November 26 to 29 list values for the multiple peaks.

Day in November	**Hydropower Discharge [m^3s^{-1}]**			
	Pre-peak	**Peak**	**Refill**	**Post-Refill**
8	0.65	2.52	0.05	0.73
16	0.44	2.71	0.01	0.44
19	0.35	2.71	0.10	0.36
21	0.38	2.44	0.15	0.37
22	0.34	2.69	0.15	0.35
26	0.28; 0.22	2.30; 2.51	0.14; 0.15	0.24; 0.23
27	0.23; 0.24	1.54; 1.56	0.14; 0.14	0.23; 0.24
28	0.23; 0.24	0.68; 0.72	0.15; 0.14	0.24; 0.23
29	0.23; 0.23; 0.23; 0.23	1.32; 1.25; 1.25; 1.32	0.14; 0.14; 0.15; 0.14	0.23; 0.23; 0.23; 0.23
30	0.22	0.60	0.14	0.14

In addition to the discharge from the hydropower plant, the downstream location also received the residual flow from upstream. This flow was not quantified, but was at least 0.2 m^3 s^{-1} according to the residual flow regulations for the power plant. A flow of 0.2 m^3 s^{-1} in the residual flow reach was therefore assumed for the following calculations.

According to the Swiss Waters Protection Ordinance, article 41e, "*there is serious harm to indigenous flora and fauna and to their habitats due to hydropeaking where a) the flow rate for upsurge is at least 1.5 times greater than for downsurge; and b) the site-specific quantity, composition and diversity of the plant and animal communities are changed to their detriment, in particular because regularly and in an unnatural manner fish are run ashore, fish spawning grounds are destroyed, aquatic animals are washed away, turbidity arises or the water temperature is altered in an unlawful manner*". In the present case, the peak flow exceeds the baseflow by more than a factor of 1.5, implying a risk for serious harm, although it would have to be tested whether the second condition is fulfilled.

Following the criteria of Pfaundler et al. (2011), the impact of hydropeaking is considered substantial if the installed capacity is > 50 kW and significant if the peak discharge during low flow (winter) conditions exceeds 25% of mean average annual discharge (MQ). MQ at the FOEN station in Gletsch for the period 1956 to 2017 is 2.77 m^3 s^{-1}. The catchment area at the FOEN station in Gletsch is 39.4 km^2, that of the Rhone above the inflow of the Goneri in Oberwald is 49.0 km^2. Scaling the discharge with the catchment area yields an estimated MQ for the measurement location of 3.44 m^3 s^{-1}. The peak discharge is expressed as a percentage of MQ for all individual peaks in Table 2, and exceeds 25% for all but the last peak on 30 November. Based on the criteria of Pfaundler et al., (2011), the impact of the experimental hydropeaking in the floodplain downstream was therefore both substantial and significant.

Table 2. Peak and minimum discharge as well as their ratios for all experimental peaks, and ratio of peak discharge to the estimated MQ of 3.44 m^3 s^{-1}. The minimum discharge refers to the discharge during refilling of the settling basin and the forebay tank, and a constant residual flow of 0.2 m^3s^{-1} was added to the peak and refill hydropower discharges from Table 1.

Day in November	Peak number	Peak duration (min)	Peak discharge [m^3 s^{-1}]	Min. discharge [m^3 s^{-1}]	Ratio Peak/Min [-]	Ratio Peak/MQ [%]
8	1	15	2.72	0.25	10.9	79%
16	2	15	2.91	0.21	13.9	85%
19	3	15	2.91	0.30	9.7	85%
21	4	15	2.64	0.35	7.5	77%
22	5	15	2.89	0.35	8.3	84%
26	6	15	2.50	0.34	7.4	73%
26	7	15	2.71	0.35	7.7	79%
27	8	30	1.74	0.34	5.1	51%
27	9	30	1.77	0.34	5.2	51%
28	10	60	0.88	0.35	2.5	26%
28	11	60	0.92	0.34	2.7	27%
29	12	15	1.52	0.34	4.5	44%
29	13	15	1.45	0.34	4.3	42%
29	14	15	1.45	0.35	4.1	42%
29	15	15	1.52	0.34	4.5	44%
30	16	120	0.80	0.34	2.4	23%

3.2. Water levels

Figure 4 shows the recorded relative water levels (compared to the location of the pressure sensor) as well as the rates of change of water levels for the five experimental peaks of the Eawag program in the main channel at the downstream location. The water level typically increased by 10 to 15 cm. Lower average increases of 2 cm and 5 cm were observed in side channels in a riffle and pool habitat, respectively (Aksamit et al., 2021). The rate of change was higher during the rising limb, typically reaching a maximum of around 4 to 5 cm/min. It should be noted, though, that the recording interval of 2 minutes was somewhat long for accurately quantifying the maximum rate of change of the rising limb. During the falling limb, the maximum water level decrease rate was about -1.0 to -1.5 cm/min.

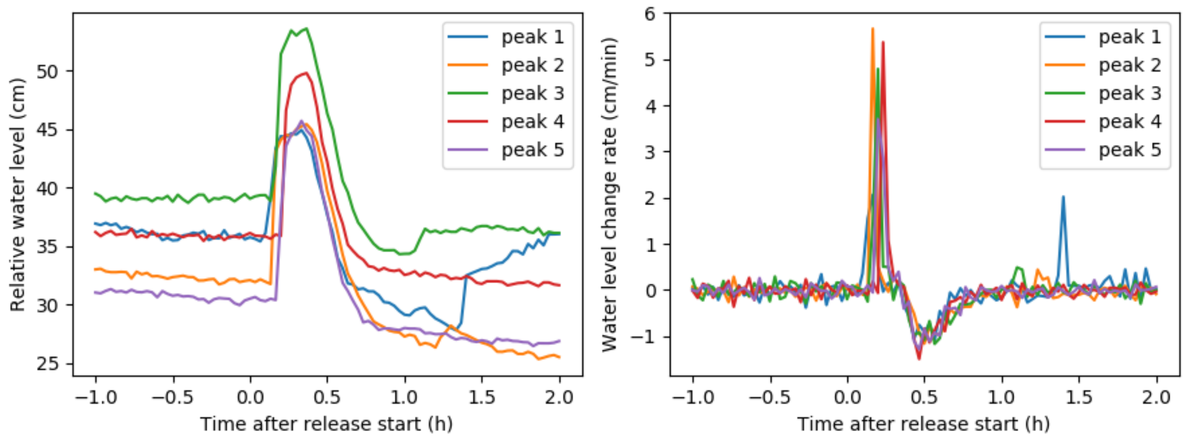

Figure 4. Relative water level (compared to the location of the pressure sensor) and rate of change of water level recorded in the main channel during the five experimental peaks from 8 to 22 November.

Figure 5 shows the same information for the first 4 peaks of the EPFL program. The first two of these peaks (Peaks 6 and 7) were similar to those from the Eawag program and also showed similar changes in water levels and similar rates of change of water levels. During peaks 8 and 9, the water was turbinated during 30 minutes rather than 15 minutes. The rise in water level was 14-15 cm for the 15 minutes peaks and around 10-11 cm for the 30 minutes peaks. Observed water level change rates reached peak values between 4 and 7 cm/min during the rising limb and again -1.0 to -1.5 cm/min during the falling limb.

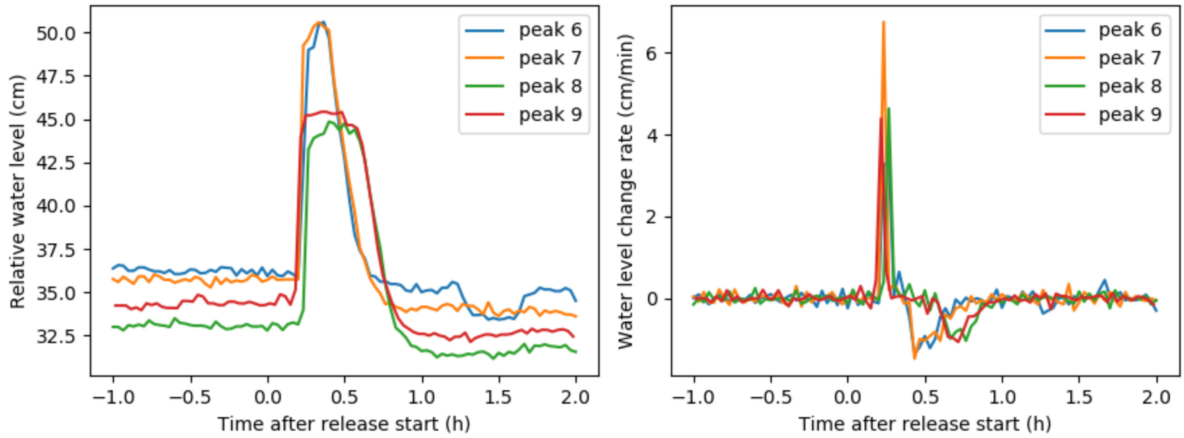

Figure 5. Relative water level and rate of change of water level recorded in the main channel during the four experimental peaks on 26 and 27 November.

3.3. Water temperature

Water temperatures were evaluated for the period from 8 to 28 November, including all five experimental hydropeaks of the Eawag program and the first four hydropeaks of the EPFL program (Figure 6). Until the second peak on 16 November, daytime air temperatures still reached maxima of 10 to 13 °C whereas air temperatures were clearly colder afterwards.

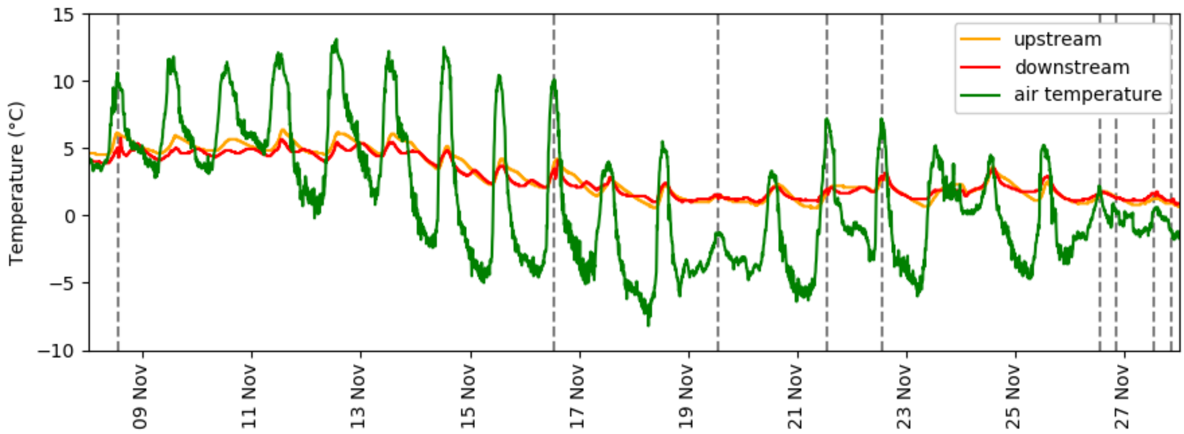

Figure 6: Observed temperature time series at the upstream and downstream sites and air temperature from the MeteoSwiss station in Ulrichen from 8 to 28 November. The dashed vertical lines mark the experimental hydropeaks.

Under warmer and sunnier conditions, the water in the residual flow reach is warmed up during the day as compared to the water transferred through the penstock. Consequently, the upstream temperature exceeds the downstream temperatures in the afternoon by a few degrees. During colder conditions, the two temperatures are much more similar. If the water released from a hydropower plant has a different temperature from the river, hydropeaking can cause sharp fluctuations in river temperature, termed thermopeaking (Vanzo et al. 2016, Zolezzi et al. 2011).

Figures 7 and 8 show the water temperatures observed at the upstream and the downstream site and just below the hydropower discharge for the 5 experimental peaks during the Eawag program, and for the first four experimental peaks during the EPFL program, respectively. Cold thermopeaks resulting from the peak discharge were observed at the downstream measurement site and at the outflow measurement sites in varying extents.

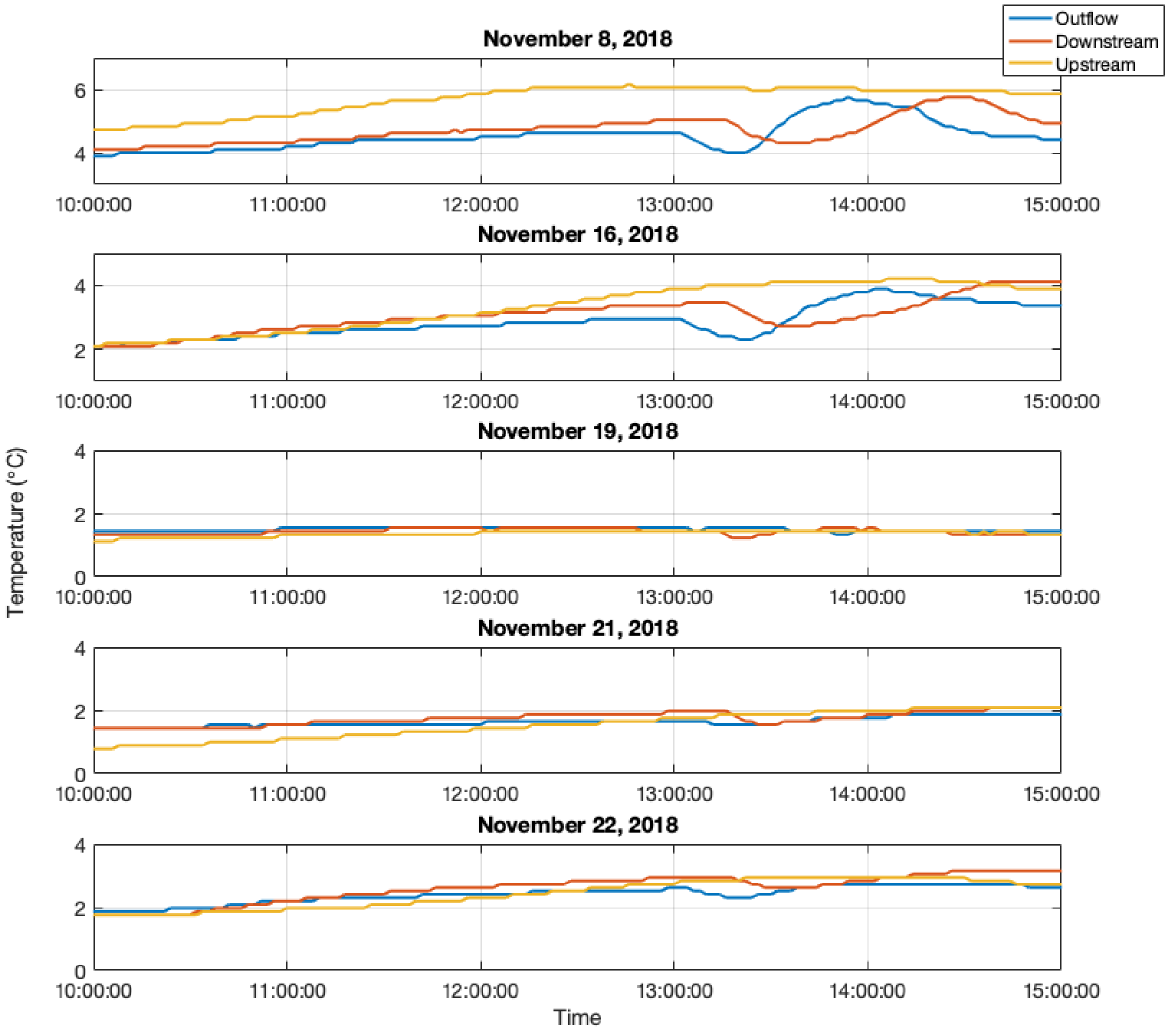

Figure 7: Observed temperature time series at the three measurement sites for the five experimental peaks during the Eawag program from 8 to 22 November. Peak water releases started on each day at 13:00 and lasted 15 minutes. The staircase-like structure of the lines results from the resolution of the HOBO sensors.

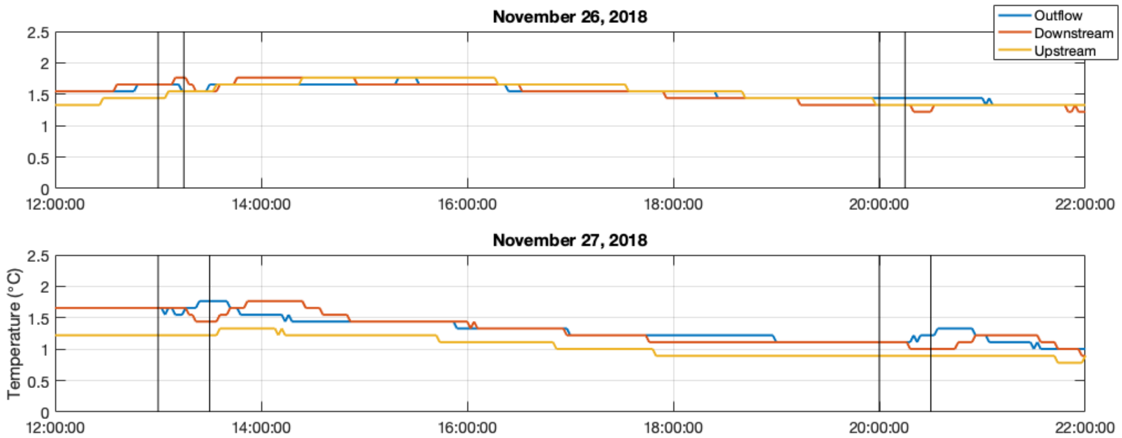

Figure 8: Observed temperature time series at the three measurement sites for the first four experimental peaks during the EPFL program on 26 and 27 November. Peak water releases started on each day at 13:00 and 20:00 and lasted 15 minutes on 26 November and 30 minutes on 27 November.

The thermopeaking effects were clearly weather-dependent. The peaks were more pronounced on 8 and 16 November, when air temperature was high and the temperature difference between the residual flow and the water released from the hydropower plant was consequently large. If we assume that without the hydropeak, the river temperature would have continuously increased to the post-peak level, the observed thermopeak caused maximum temperature deviations of approximately 1.0 °C on 8 and 16 November. During the following hydropeaks, the temperature decreased only by a few tenths of a degree and could not be accurately quantified given the resolution of ~0.1 °C of the temperature loggers.

Two limitations should be considered when assessing the data. First, the sensors were not cross-calibrated directly before and after the measurements, and their typical absolute accuracy is a few tenths of a degree. Later cross-calibration of the same sensors showed an accuracy of about 0.2 °C. Therefore, smaller temperature differences between different sites are not necessarily real. However, this does not affect the temporal evolution (i.e. the thermopeaks). Second, the sensors have a typical response time of 10 minutes. This means that the observed thermopeaks are somewhat flattened compared to the real thermopeaks.

3.4. Hydropeaking and thermopeaking indicators

Section 5.8.2 of the Pfaundler et al. (2011) describes two indicators that can be used to assess to what extent the hydrological regime in a river stretch influenced by hydropeaking differs from a natural state. The hydropeaking state of a river stretch can then be classified into one of five classes, ranging from near-natural (class 1) to far from natural (class 5) according to Figure 25 in Pfaundler et al. (2011). The two indicators can be roughly estimated from the results presented above.

The indicator for the **intensity of hydropeaking** is calculated from the ratio of maximum to minimum discharge (Table 2) multiplied with a correction factor that depends on the maximum water level change rate. The correction factor is 1.50 for the present case, with water level change rates exceeding 4 cm/min (Figures 4 and 5). This indicator reaches values between 4 and 20.

The indicator for the **hydraulic stress** caused by the hydropeaking is calculated from the ratio of peak discharge to MQ and a correction factor of 0.5 for a catchment size <250 km^2. The peak discharges for the 15 minutes peaks are approximately 80% of the estimated MQ of 3.44 m^3 s^{-1} (Table 2), and the resulting indicator therefore takes a value of approximately 0.4.

Based on these two indicators, the hydropeaking state of the floodplain downstream of the hydropower plant release would be classified, according to Figure 25 in Pfaundler et al. (2011), in class 5 (red, far from natural) for the peaks of 15 or 30 minutes duration, where the indicator for hydropeaking ranged between 6 and 21, and in class 3 (yellow, significantly modified) for the peaks with durations of 60 to 120 minutes, where the indicator for hydropeaking ranged between 3.5 and 4.1. Distributing the discharge from the available storage volume over a longer peak duration therefore clearly reduces the effect on the downstream river stretch. For a more thorough assessment of the potential ecological impacts of the hydrological changes caused by hydropeaking, specific indicators accounting for the local reach morphology should be developed following the hydropeaking rehabilitation guidelines of Tonolla et al. (2017).

For the thermopeaking, Tonolla et al. (2017) suggests to use the rate of change of temperature caused by the hydropeaking as an indicator. Due to the comparably slow response time of the temperature loggers, we cannot exactly quantify this indicator for the observations made here, but on the warmer days, the artificial drop in temperature was approximately 1°C within 10 to 20 minutes, corresponding to a temperature decrease rate of -3 to -6 °C / hour. According to the classification of Tonolla et al. (2017), this would be considered between poor and bad. Conversely, during the cold days, the absolute rate of change in temperature was probably mostly below 1 °C, and the value of the indicator would be considered as very good.

In summary, this analysis indicates that, despite the small reservoir volume, hydropeaking resulting from flexible operation of a small hydropower plant can have a significant impact on the hydrology and the water temperature of a river stretch downstream the hydropower release. Before implementation of such a flexible operation it is therefore recommended to conduct a more detailed analyses of the expected effects for the entire range of expected boundary conditions (meteorological conditions, discharge, duration and frequency of hydropeaks). Depending on the outcome of such an analysis, operational and/or structural measures to reduce these effects need to be implemented according to the hydropeaking rehabilitation guidelines of Tonolla et al. (2017), and their costs need to be considered when assessing the profitability of the implementation.

4. References

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