The effects of hydropeaking on hyporheic interactions based on field experiments

Roser Casas-Mulet[1,2], Knut Alfredsen[1], Byman Hamududu[1] and Netra Prasad Timalsina[1]

[1]Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, N-7491

[2]corresponding author: roser.casas-mulet@ntnu.no

Abstract

Hydropeaking power production has the potential to pose serious challenges towards hydrology, water quality and ecology in the downstream water bodies. The effects of such abrupt changes of flow in hyporheic exchange have been explored in a few cases in the literature. This paper extends previous works with a study of finer time resolution in a river of a smaller size and with different climatic characteristics, adding to the current knowledge of peaking-hyporheic interactions. A high frequency logging field experiment measuring hyporheic flow and temperature was conducted on a ~30 by 20 m gravel bar frequently exposed to dry conditions due to fast and abrupt flow changes. This study demonstrates that hyporheic processes are sensitive to hydropeaking with respect to rates of change, durations and temperature. Differences individual events, seasons, watering and dewatering processes and positions in the river bed that can be potentially relevant to ecology were investigated. Understanding the complexity of those processes at the fine scale from the physical point of view is both important for the judgment of potential ecological impacts and for the future management of such regulated systems.

1. Introduction

Renewable energy production from wind and solar energy sources have put an increasing emphasis on storage potential and load balancing needs in the energy system. Hydropower is a well suited source for load balancing being the only renewable with a feasible storage potential and production flexibility. Norway has at present 50% of storage potential in Europe and shows vast possibilities for further increase (Catrinu-Renström and Knudsen 2011).

Hydropower load balancing and peak production (hydropeaking) poses a challenge in the downstream river systems due to sudden water level fluctuations. Such dam operations can alter hydrological, thermal and geochemical processes in the HZ (Sawyer *et al.* 2009). Thermal alterations due to hydropeaking may result in potential ecological implications (Toffolon *et al.* 2010, Zolezzi *et al.* 2011). Short regulation regimes can significantly influence hyporheic exchange flows (Hancock 2002). Particularly sudden flow fluctuations result in large water level differences governing surface water- groundwater interactions that ultimately drive hyporheic dynamics (Maier and Howard 2011).

The hyporheic zone (HZ) plays an important role in freshwater ecology. Hyporheic exchange is fundamental to vertical connectivity, transporting mass and energy between the sediment and the water column, resulting in a mixing chemistry that contributes to the energy and nutrient cycles (Malard *et al.* 2002). The HZ supports unique communities of benthic organisms (Boulton 2001) and serves as spawning grounds for fish (Power *et al.* 1999). The HZ has the potential to act as refugia against drifting for macroinvertebrates during sudden high flows (Bruno *et al.* 2009), to serve as thermal benthic shelter (Wood *et al.* 2010), and as potential refugia for stranded fish (Saltveit *et al.* 2001) during low flows. However, living conditions in the hyporheic can also be negatively affected, such as fish embryo mortality due to hypoxic groundwater dominated HZ (Malcolm *et al.*, 2008).

Hyporheic water quality change naturally on inter-annual basis (Soulsby *et al.* 2009), but sudden flow changes due to regulation may alter such dynamics (Nyberg *et al.* 2008). High-frequency field logging studies of the physico-chemical processes in the HZ have been proved to be the right approach to examine hyporheic dynamics (Malcolm *et al.* 2006, Malcolm *et al.* 2009), providing means to capture short-term and abrupt changes. Several studies on hyporheic exchange in regulated river have been undertaken (Arntzen *et al.* 2006, Fritz and Arntzen 2007, Gerecht *et al.* 2011, Hanrahan 2008, Sawyer *et al.* 2009), particularly focusing on such abrupt flow fluctuations. On them, emphasis is made on the need of further site-specific and high temporal resolution data. More knowledge on the interaction between fluctuating flow and hyporheic processes is needed to fully understand the potential impacts of peaking river flow. Of particular interest are the consequences of sudden stops in hydropower production flow (later referred to as "production") on hyporheic processes at scale relevant for the response of hyporheic fauna. Findings will be both important for understanding impacts and for mitigation of adverse impacts and management in regulated rivers.

This paper aims to evaluate whether the current findings in the literature are valid for a small heavily regulated stream in a cold climate context. It focusses on the low flow periods between sudden production stops and starts and it extents previous approaches by studying hydropeaking with faster stage changes in a finer time resolution on a smaller spatial scale. Specific objectives are: (i) to assess the changes in hyporheic water elevation in the HZ by characterizing dewatering (falling limb) and flooding (rising limb) in using key hydrological parameters; and (iii) to investigate the extent of temperature changes in the HZ due to surface thermal alterations caused by hydropeaking..

2. Methods

2.1.Study site

The Lundesokna River (central Norway) is a regulated tributary to the Gaula River with a hydropower system of 395 km^2 in catchment consisting of three regulated reservoirs, three power plants and three interbasin transfers mainly located in the headwaters, characterized by high gradient streams (Figure 1A). The lower parts of the Lundesokna mainstream are characterized by average channel widths between15 and 25 m and mild gradient. The soil surface in the Lundesokna catchment is dominated by thin moraine with fluvial and fjord depositions. The aquifer consists of alluvial deposits or eskers with relatively shallow groundwater (Hilmo, 2007).

Sokna, the lowermost of the power plants in the system, operates according to daily and weekly market price fluctuations *vs* water availability in the reservoirs, resulting in the lower 4 km being subject to periodical hydropeaking operations that result in flow fluctuations with a typical range from 20 $m^3 s^{-1}$ to 0.45 $m^3 s^{-1}$. This translates into changed in stage of up to 1 m in less than 20 minutes.

The study site was a 30 m by 20 m (at maximum exposure to dry conditions) side gravel bar located on the left bank of a bend 700 m downstream Sokna hydropower plant outlet (Figure 1C). Grain size distributions in the upstream and downstream of the side bar were 33-36 mm in D_{95} and 12-17 mm in D_{50}, and gradient along the bend was 0.29%.

2.2. Experimental design

We established a network that consisted of 12 piezometers installed across and along the study site at several depths below the streambed, ranging from 0.25 to 0.65 m at the time of installation. They were inserted in the upstream and downstream part of the gravel bar in groups of 1 and 3 vertically nested piezometers across the transect slope (Figure 1D). A specially designed metallic instrument consisting on an outer casing and a pointed driver rod fitting inside the casing with a sturdy top (Baxter *et al.*, 2003) was used for installation. A sledgehammer aided insertion of the instrument in the ground. Once the instrument was inserted into the ground, the inner driver was pulled out and a piezometer was inserted. The outer casing was later pulled out with the help of its two lateral handles leaving the piezometer in the ground. Installation was carried out during low flows. Piezometers ABC were located along the exposed gravel and were in contact with hyporheic water. Piezometers W were used to measure stage as they were located at the permanently wet area. Coordinates and elevations were surveyed using a Leica® GS10 differential GPS (Leica Geosystems, USA) with a reported accuracy of 10 mm.

Several 0.032 m inside diameter Durapipe® (Durapipe UK, UK) were used to construct the piezometers. They were sealed at the lower end allowing a small aperture for drainage. The bottom 0.15 m was perforated with several 5 mm holes and a 1mm mesh was placed on top to prevent excessive sediment intrusion. Eijkelkamp® (The Netherlands) Divers water pressure transducers with integrated temperature loggers were inserted at each of the piezometers and provided 1 to 4 minutes resolution in water pressure (±0.5 cm accuracy) and temperature (±0.1°C accuracy) data. All loggers were previously calibrated in the lab for accuracy and resolution. The experimental design was based on Malcolm *et al.* (2004).

Additionally, one VEMCO® Minilog-II-T (Vemco Group, Australia) temperature logger (±0.1°C accuracy) was installed 400 m upstream the study site at Sokna power plant outlet to measure surface water temperature (Figure 1B), and one Eijkelkamp® Baro Divers was located at the left bank of the site to measure air pressure (±0.5 cm accuracy) to compensate the absolute pressure readings in the piezometers, and air temperature (±0.1°C accuracy).

All data was collected between December 2011 and June 2012. Additional geometric and discharge data were collected at the selected site between 2010 and 2011. Geometric data were obtained during several low flow events with means of laser scanner (Topcon® GLS-1000, Topcon Corporation, Japan) for dry areas combined with Topcon® RTK differential GPS xyz point data (for water covered areas).

2.3.Data analysis

Data analysis was done focusing on the low flow period between a production stop and the end of the rising limb following production start. Figure 2 illustrates a typical hydropeaking event describing the use of nomenclature in 4 identified periods: (i) high flow period, (ii) falling limb, (iii) low flow periods and (iv) rising limb; and five key time steps: (i) start of the falling limb, (ii) end of the falling limb, (iii) minimum stage, (iv) start of rising limb and (v) end of rising limb.

Hyporheic water elevations variations with stage changes

Stage (positions W) and hyporheic water elevations (positions A, B, C) changes were first analyzed for the full-length of the studied period (December 2011 to June 2012), followed by analysis on specific periods and individual events assessment. Water elevation data measured in the pipes was compensated against air pressure and adjusted to field measured water elevations along and across the study site. All data (except data from positions A due to its exposure to dry conditions for some of the episodes) was input into a Visual Basic based tool to obtain the 5 key time steps for each individual hydropeaking event. A minimum stage value of 30.8 m.a.s.l. was used to identify significant low flow periods (in which great part of the gravel bar was exposed) and to obtain two threshold points (point 1 and 2) in each individual hydropeaking event. The start of the falling limb was identified as the maximum point within 10 minutes before point 1; and the end of the rising limb as the minimum point within 10 minutes after point 2 (ten minutes was considered the maximum time lap in which the water was rising or falling from the 30.8 m.a.s.l. threshold). The minimum point between points 1 and 2 was identified as the minimum water elevation of the hydropeaking event. The stop of the falling limb and start of the rising limb were then found as the first derivative of the water elevation respect to time (Figure 2). The results of the analysis were plotted and visually checked. Following the application of the mentioned tool, data obtained was used to calculate the following parameters for each of the hydropeaking events: maximum and minimum stage/water elevation, maximum stage fall/rise, duration of falling/rising limb and low flows, rates of falling/rising limb change, maximum water depth below the ground and time to reach the minimum stage/water elevation after the falling limb.

Two representative hydropeaking events with full data availability were selected for further analysis. Hyporheic water elevations were analyzed for an event of average duration occurring in January and a long duration event occurring in February. The above mentioned parameters were then calculated for the upstream and downstream piezometer transects including pipes A1, B1, C1 and W1 and A4, B6/B7, C3 and W2.

Differences in head pressure and VHG variations with stage changes

Measurements of surface and hyporheic water elevations for all positions were used to estimate differences in head pressure for all hydropeaking events occurring during the study period, and Vertical Hydraulic Gradient (VHG) for a selected event in February. They were calculated for each of the 5 key time steps of a single event, and in addition both the middle of the falling and rising limbs.

Water temperature analysis

A total of three hydropeaking events were chosen to analyze hyporheic water with stage changes. The chosen events occurred in January, April and June respectively. Temperature at positions ABCW and surface water was plotted against stage.

All data process and analyses were carried out in the software package R, version 2.14.1 (*R Development Core Team*, 2012). Sigma Plot version 12.0. was used for graphical presentations.

3. Results

3.1. Hyporheic water elevations variations with stage changes

Figure 3 illustrates the hydropeaking regime in Lundesokna for the study period with the correspondent air temperatures. A total of 54 low flow episodes were identified. Forty-seven of those occurred between December and March, when air temperatures reached the minimum of the period. This followed a period of natural flooding in spring and less frequent peaking was detected towards the summer. Fifty four events occurred during the night, 20 of which extended to the next day.

Table 1 summarizes key hydraulic parameters for the whole study period at positions B1, C1, W1 and B6, C3, W2. High variability in both the time to reach the minimum stage after decrease and the total low flow duration was detected for the whole period. This was due to the variant patterns in production and operation strategies, ranging from very short events of zero minutes low flow duration to some very long events of more than 10 hours duration.

Table 2 and Figure 4 summarize and illustrate durations and minimum stages the two selected hydropeaking events occurring in January and February at positions A, B, C and W in the upstream and downstream cross sections. Minimum stages in the event in January reached stages down to 30.27 m and had an average duration of some 5 hours, whilst the one in February showed higher minimum stages of 30.39 m and a duration of >18 hours. In both cases, minimum stage was achieved towards the end of the low flow episode after a progressive slow decrease between 1 and 16 cm from the end of the falling limb. This indicated a slow emptying in the ground during low flows as stage continued to decrease down to a minimum level, at which it could hold the water until production started again. In the January episode, stage increased slightly from the river to the banks after reaching the minimum and it is thought to be due to an increase on residual flows.

Despite evident variability between individual events, in general rates of changes were slower during the falling limb (between 1.2 and 2.6 cm min^{-1}) than during the rising limb (3.2 - 5.2 cm min^{-1}) for all positions. Differences can be explained by higher total stage increase and lower durations in the rising limb.

Longitudinally (upstream *vs.* downstream cross sections), differences were minimal by comparing positions B1and B6, C1 and C3 and W1 and W2 (positions A1 and A4 were at slightly different positions in the cross section level). However, consistent differences in low flows minimum stages and falling and rising rates were detected between cross sectional positions. Falling and rising rates generally decreased from positions closer to the river thalweg (W) to positions closer to the banks (A). Minimum stages were in all cases progressively higher from positions W to A, showing a sloping water level towards the river in all cases. In positions C, the water level was found some mm below the ground, whilst in positions A, it could be found down to 0.6 m (Table 2).

Along the cross section, water fell and rose faster at positions W and progressively slowed down at positions A. In both cases, the first minutes of the fall and rise were the quickest, illustrated by a major separation between lines, and they slowed down at the end of the event, lines being closer. Falling and rising limb durations showed quick responses in W and C in comparison to B and A positions.

This general tendency shows an exception in position C1 located at the upstream transect, that showed higher rates of change than those in W1. In this position, an influx of lateral interstitial flow was observed during field campaigns. The above results and observations support the initial hypothesis of lateral inflow from the ground occurring.

3.2. Differences in head pressure and Vertical Hydraulic Gradient (VHG) variations with stage changes

Figure 5 illustrates the differences in head pressure between the river and the piezometers. At the cross section level, the mean difference in head pressure was in most cases higher in the pipes that were closer to the bank (A and B), during all the stages. Longitudinally, the mean difference is head pressure kept almost the same for all B positions with few exceptions. In both cases, the highest variability was shown in the middle of the rising limb and the highest values at the end of the falling limb. The highest mean values of head difference were found at the end of the falling limb.

Figure 6 illustrates that VHG is positive from the start of the falling limb until the start of the rising limb, showing potential upwelling. In the middle of the rising limb, VHG becomes highly negative and this potential downwelling is shown until the end of the rising limb. At stable high flows, VHG is almost zero.

Figure 7 illustrates changes VHG in relation to water elevation for the mean three stages of a hydropeaking event including the falling limb, the minimum stage and the rising limb at positions A, B and C. The relationship between river stage and VHG demonstrates hysteresis in all positions. As the river stage decreases (falling limb), VHG is positive indicating potential upwelling. As the river reached the minimum stage, VHG reached almost zero, but continued positive in all positions. During the rising limb, VHG became negative indicating potential downwelling. Absolute VHG values were greater in all cases during the rising limb than during the falling limb, indicating a greater downwelling potential than upwelling.

At the transect level (Figures 6 and 7), positions C present greater VHG in all stages than positions B and A progressively. The closest to the river thalweg, VHG changes are more sudden, presenting higher values both during upwelling and downwelling.

3.3. Water temperature analysis

Water temperature changes with stage variations are illustrated in Figure 8 for several hydropeaking events occurring in January, April and June, representing cold, temperate and warm periods respectively. Those are illustrated for positions W1 and B1 only, limited to full data availability. Figures 9 illustrate such temperature changes for an individual hydropeaking event occurring in each of the periods.

In January, with minimum air temperatures reaching -0.9 ^{o}C, as water stage fell due to production stop, surface water temperature immediately decreased from 0.8 ^{o}C to 0.2 ^{o}C and continued to slowly dropping down to 0 ^{o}C. This can be explained by the dominance of river water that is cooler in comparison to the water that was released from the reservoir. During stage rise, temperature suddenly increased up to 1.2 ^{o}C and quickly reached back the original 0.8 ^{o}C. An increase in surface temperature due to production start can be expected due to a dominance of water from the reservoir. The sudden and short peak in temperature before reaching the original temperature can be explained by the initial release of the water that had been standing in the tunnel system and subject to warming. Surface temperature shows an expected thermo peaking pattern for the winter period. In the ground temperature changes were less obvious. They showed a slight increase as the water stage fell and reached initial values slowly after the stage increase. Temperatures in position W1 were lower than in C1 and B1, due to the influence of surface water. In A1, the lowest temperatures were result of the exposure to dry conditions and air temperatures below zero for longer periods than in the other positions.

In April the temperature in the river was higher than in the reservoir, therefore when production stopped, the influence of the natural river water increased temperature from 0.8 to nearly 2 ^{o}C. In the ground, as in January, water temperature increased slightly after the falling limb and increased 0.2 ^{o}C (in position B1) during low flows. After the rising limb, temperature fell back to the initial 1 ^{o}C. This behavior can be explained in positions B1 and C1 as a potential influence of ground/interstitial water. In position W1 due to a greater influence from the river water temperatures remained stable at ~1^{o}C. In June (minimum air temperature 9.6 ^{o}C), overall water temperatures were higher. Temperature in the river was also higher than in the reservoir. During the falling limb, surface temperatures started at 7 ^{o}C and rose to 2.5 ^{o}C due to natural flow dominance. After the rising limb, they fell with 2 ^{o}C. Positions A1 and C1 kept an almost constant temperature, A1 was 0.5 ^{o}C warmer than C1 due to the influence of air temperature. At position B1, temperature slowly decreased 0.5 ^{o}C as the river water recessed and suddenly increased 1.5 ^{o}C as the stage rose.

In all cases, temperature shows a slower rate of change during the falling limb than during the rising limb.

Figure 10 illustrates a summary of the above discussion in terms of hydraulic (upwelling/downwelling potential) and temperature development with stage changes at the cross section level on a typical winter (cold), spring (temperate) and summer (warm) hydropeaking scenario.

4. Discussion

The pattern observed in Lundesokna is representative of a typical hydropeaking regime in Norway, characterized by irregular flow patterns with important differences in occurrence and durations between events. The highest concentration occurred in the cold periods due to higher energy demand, and the high variability in low flows durations can be explained by the operation strategies of the power company. Such variable patterns poses a challenge for the prediction of potential environmental impacts of hydropeaking events and to enable a simple assessment based on one characteristic event. Hanrahan (2008) emphasizes the difficulties to measure surface-subsurface exchange due to the spatial and temporal complexity of the hyporheic zone. In this paper, the spatial scale is much smaller and the logging frequency much shorter allowing catching the variability in single hydropeaking time steps, and therefore contributing to a better knowledge of the processes at this scale. Some general patterns in terms of the hydraulic behavior at the small scale can be drawn.

During any individual hydropeaking event, the falling and rising limb showed remarkable differences in terms of hydraulic behavior, as expected. The falling limb decreased significantly slower than the rising limb increased. The slow decrease during the falling limb can be explained as a combination of bank seepage but mainly subsurface return flows to the river that controlled the rated on which the water flowed out of the bar with a modest head gradient. In contrast, during the rising limb, a very steep vertical gradient from the overlying stream water to the bar surface results in a faster refill of the gravel bar with stream water. The quick response of subsurface flow paths to such dam operations was already discussed in Sawyer *et al.* (2009) and Francis *et al.* (2010). In the latter, they illustrated a case of indistinguishable bank storage from hyporheic exchange, which coincides with the results found in the present work.

Potential upwelling as a result of positive VHG was shown during the falling limb and during the minimum stage. Potential downwelling (negative VHG) appeared only between the middle and end of the rising limb, but with a greater absolute magnitude than during the falling limb, supporting the above explanation. The findings coincide with Gerecht *et al.* (2011), showing that an entire transect is gaining when the river at its lower stage and loosing when it is at its maximum stage. Moreover, low flows periods reached a stable minimum stage level after the end of the falling limb. A delay with a continuous but slow decrease until reaching the minimum was reported. Hanrahan (2008) showed the variations in head pressure and VHG between stable and unstable flows at different sites. Variability and magnitude of VHG was higher during unstable flows than in stable flows, coinciding with the findings in this paper. Variations in VHG showed a hysteretic relationship depending on whether the river stage was relatively high or relatively low as shown in some of the sites in Arntzen *et al.* (2006) and Gerecth *et al*. (2011). Such studies included data from a greater spatial scale, with variability between sites. In the present paper, little differences in VHG magnitudes between the downstream and upstream cross sections were found, as expected due to the scale of the field experiment. All locations showed a strong hysteretic relationship that could potentially be explained, as hypothesized in Arntzen *et al.* (2006), by a relative low hydraulic conductivity. Small differences observed between the upstream and downstream cross sections are however difficult to relate to hydraulic conductivity changes given the available data in this study, leaving only local differences in granulometry as the potential cause for such differences.

Both the falling and rising limb of a hydropeaking event pose a change on the natural environmental conditions. Whilst the rising limb means a variation from low to high flows; the falling limb translates into a change from wet to dry conditions. During the rising limb, the sudden increase in discharges have the potential to initiate "catastrophic drift" in some areas of the permanently wet stream bed as reported in Gibbins *et al.* (2007); but it also can contribute to a high exchange of nutrients or displacement of sediments due to the great downwelling potential (Malard *et al.* 2002). During the falling limb, the rate of change can be high enough to prevent organisms such as macroinvertebrates or juvenile fish from the chance to react to the water level sudden decrease and to be exposed dry conditions, resulting in stranding (Saltveit *et al.*2001, Bradford 1997). On the other hand, it is during the falling limb where the upwelling of subsurface water shows the greatest potential, likely to contribute to a higher diversity of lotic habitats (Malard *et al.* 2002, Stanford and Ward 1993).

Low flows can be seen as critical episodes in a hydropeaking event, especially in winter, when most of the production occurs in Norway due to the higher energy demand. Such episodes can be particularly critical for organisms if they have long durations (Halleraker *et al.*2003, Saltveit *et al.* 2001). During low flows, organisms such benthos and fish have been reported to search for potential shelter in the ground (Bruno *et al.* 2009, Saltveit *et al.* 2001). A delay on reaching the minimum water elevations and continuous upwelling might mean a better chance to find refugia; but the final hyporheic water elevation plays an important role for the survival of in-stream organisms with limited mobility such as fish embryo, as they can be left exposed to dry and freezing conditions for long periods and die (Skoglund *et al*., 2012; Casas-Mulet *et al.* submitted; Vollset *et al*., unpublished data); or for fish in entrapped pools that might not survive if the drainage period is too low (Irvine *et al.* 2009). In both cases, the duration of the productions stop becomes a key factor. This outlines the importance of hydropower operations management to be used for the benefit of freshwater organisms that depend on the hyporheic zone. Some examples include the adjustment of dam operations to protect salmonid embryos (Arntzen, *et al.* 2009), and the alteration of flows to prevent dewatering after spawning and reduce stranding following emergence (Skoglund *et al*., 2012; Harnish et al., 2014).

Differences in hydraulic behavior were found between cross sectional positions (ABCW positions) and very similar hydraulic behaviors were found between B positions (with a longitudinal arrangement). Positions closer to the thalweg (C and W) presented the highest falling and rising rates of change, those also presented the highest minimum stages, which meant water was found only a few cm below the ground. But in positions closer to the banks which presented smoothed rates of changes, the depth of hyporheic water below the ground reached down to 60 cm. This coincides with the findings in Gerecht *et al.* (2011), describing the extent of the hyporheic zone is much shallower and the exchange time is much smaller near the river thalweg than in the bank.

The specific location of the organisms across the bed transect when a low flows hydropeaking event occur can therefore be an important factor influencing their possibilities for shelter in the ground and hence for survival. In terms of rates of change, especially during the rising limb, organisms located closer to the thalweg will experience the changes much more acutely than those located closer to the banks. During the falling limb and low flows, positions closer to the thalweg water will hold at a higher hyporheic water elevation meaning a lesser loss of saturated hyporheic area and potentially a better chance of survival for organisms with low mobility or more closely available shelter for other in-stream organisms. In contrast, positions closer to the bank might face interstitial water losses of up to 60 cm depth, decreasing the chance for e.g. salmonid embryos to survive below their 30-45 cm threshold (DeVries 1997, Geist 2000). Refugia potential in the subsurface is reduced with increasing distance from the stream.

Surface water temperature responded to production patterns and time of the year, following the natural river *vs*. the production water temperatures differences. Water temperature in the ground showed slow increases during the cool and temperate period as the water level felt and slow decreases in values during the warm period.

Changes in temperature, although not significantly high, gave an indication of a potential lateral hyporheic water exchange across the hyporheic bar feature. Such changes responded to both hydropower production patterns but also to seasonal changes in hyporheic dynamics and quality as those reported in Krause *et al.*, (2007) and Soulsby *et al.* (2009). A slower increase and decrease of temperature as a response of stage falls and rises was reported, coinciding with the finding by Zolezzi *et al.* (2011) showing a slight delay in temperature waves in respect to hydraulic waves.

The idea of hyporheic refugia is discussed in Wood *et al.* (2010) for stream macroinvertebrates and with particular reference to low flow conditions. Heggenes *et al.* (2011) reported small fish may move vertically into the substrate to find thermal refugia. In Norwegian rivers, dominance of shallow groundwater with non-anoxic characteristics can provide a high potential for survival of organisms during such conditions (Brabrand *et al.*, 2002). Particularly, in the Lundesokna river, a pattern of changes in dissolved oxygen with hydropower operations could not be identified, dissolved oxygen levels in the hyporheic water were high around 12 mg l^{-1} and >90% in concentration, not significantly different from the river water (Casas-Mulet *et al.*, submitted). During an abrupt increase of discharge or rising limb, Carolli *et al.* (2012) and Bruno *et al.* (2012) highlighted the importance of thermo peaking to induce behavioral drift in macroinvertebrates. Although not significant temperature differences in tin a single event at the Lundesokna river, the change from above zero to below zero temperature became a limiting factor for survival of salmon embryo when the river bed changes from wet to dry (Casas-Mulet *et al.*, submitted).

Physical processes occurring in the hyporheic zone are especially important for hydropeaked rivers and the potential impact of changes on the hyporheos should be included in their management strategies. The hyporheic zone can alleviate some negative consequences of rapid flow fluctuations, but at the same time drought or frost in the hyporheic zone can be detrimental. Particularly, temperature variations should be taken in account in river management due to its important role both in freshwater organism’s behavior and potential survival.

5. Conclusions

This paper provides an assessment of the influence of hydropeaking on hyporheic exchange that can be used as a template to investigate potential ecological consequences. The high-frequency logging field data set shows for the hydraulic processes occurring at specific time stages in an individual hydropeaking event. The study demonstrates that hyporheic processes are sensitive to hydropeaking with respect to rates of change, durations and temperature, and that those changes are depending on both production patterns and seasonality. Understanding the complexity of those processes at the fine scale is both important for the judgment of potential impacts for ecology and for the future management of such regulated systems.

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