Mitigation measures for unsteady flow effects on riverbeds during hydropower peaking

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ABSTRACT: Recent findings concerning the effects of hydropower peaking on the riverbed are summarized. A special focus is set on newly discovered lift force variations during unsteady flow. Both constructional and operational mitigation measures for hydropower peaking are stated and evaluated with regard to those effects. In addition to conventional linear flow variations, the possibility of non-linear hydropeaking is discussed. An experimental investigation on non-linear hydropower peaking is performed. The results prove that progressive flow increases cause less lift force variations than digressive and linear ones, making non-linear hydropeaking a valuable mitigation measure.

1 INTRODUCTION

The energy supply and demand in any electricity net should be kept in balance at any time. Hydropower is a comparably flexible energy source that can contribute to this balancing with so called hydropower peaking operations, in which the power production and therefore the water discharge through the hydropower plant, is changing significantly over a short amount of time. Thus, in the case that the hydropower plant discharges the water into an adjacent river, the water flow in this river is following similar fluctuations as the power production.

This flow variation can lead to several problems in the downstream river. During flow decreases, the lower water level exposes large areas of the riverbanks and higher elevated bed surface to the atmosphere. Juvenile fishes can be in danger to strand and spawning areas might dry out (Bradford, 1997). Rapid flow increases on the other hand increase the stress on the riverbed (Spiller & Rüther, 2013). This might lead to rearrangements or even a total breakup of the armor layer (Vericat, Batalla, & Garcia, 2006), a common protective layer in regulated gravel bed rivers.

However, regular flow fluctuations are common in a river. To a certain degree, hydropower peaking can simulate periodic flood events that would occur naturally and are today often impeded due to river regulation. Natural floods cause regular surface rearrangements at the riverbed and therefore facilitate fish spawning activity.

Whether hydropower peaking acts as an advantageous scenario that helps a regulated river to regain natural behavior or a disadvantageous scenario that implies unnaturally quick water level fluctuations and causes the above-named threats, is dependent on the degree of flow fluctuation. Two aspects of flow fluctuation need to be considered: (1) how large the difference between highest and lowest flow depth is, and (2) how fast the water flow shifts between those two states. To set different hydropeaking scenarios in perspective, Spiller, Rüther, and Friedrich (2014) introduced the unsteadiness parameter Γ'_{HG} for a single flow increase or decrease (eqn. 1). It is a modification of Γ_{HG}, the unsteadiness parameter for a hydrograph with a consecutive flow in- and decrease, introduced by Graf and Suszka (1985). Γ'_{HG} and Γ_{HG} are directly comparable.

$$\Gamma'_{HG} = \frac{1}{u_0^*} \frac{\Delta d}{2 \cdot \Delta t_R} \qquad (1)$$

With $u_0^* = \sqrt{\tau_0/\rho}$: shear velocity at the initial uniform flow, $\tau_0 = \rho g d S_0$: bed shear stress, ρ: density of water, g: local gravitational acceleration, d: flow depth, S_0: bed slope, Δd: difference between minimum and maximum flow depth and Δt_R: time duration of the flow variation.

A higher unsteadiness parameter implies a major flow in- or decrease in a short time. Mitigation measures can help to keep the unsteadiness parameter in a certain range to avoid negative impacts of hydropeaking on the river as an ecosystem, as well as on the stability of the riverbed, banks and hydraulic structures.

The present study summarizes recent findings regarding the effect of hydropower peaking on riverbeds and sets conventional mitigation measures in perspective. Furthermore, it introduces an alternative mitigation measure that offers an equally flexible hydropower production while it reduces the flow's impact on the riverbed. The study deals exclusively with increasing flow.

2 HOW RAPID FLOW FLUCTUATIONS AFFECT THE RIVERBED

To perform the most effective mitigation, it is necessary to understand what the effects of flow fluctuations on the riverbed are. Looking at the problem from a steady perspective, higher discharges cause higher stress on the riverbed in form of drag and lift forces acting on the surface grains. This effect is present at any constant discharge, so that fluctuating flows coincide with fluctuating bed shear stress and lift force. For further reference, the expression “steady effects” or consequences of hydropeaking will be used to address this phenomenon.

In addition to the steady consequences of hydropeaking, additional unsteady effects might occur during the actual flow increase or decrease. Currently ongoing research tries to describe those, further named “unsteady effects”. Spiller and Rüther (2013) performed direct shear- and lift force measurements by attaching a force sensor to an artificial riverbed and showed that for unsteady flow it is essential to observe shear stress and lift force independently. Also Einstein and El-Samni (1949) stated that both shear stress and lift force are crucial to the incipient movement of bed load.

2.1 *Shear stress during unsteady flow*

Spiller and Rüther (2013) compared the directly measured bed shear stress during flow increases to a theoretical value, calculated by the Saint-Venant equation, which is known to be a quasi-steady assumption. The measured shear stress during unsteady flows was clearly following the Saint-Venant equation. Only for extremely high unsteadiness parameters, a minor deviation of the measured to the theoretical quasi-steady shear stress occurred. Thus, the effect of the flow increase on the shear stress appears to be independent from the unsteadiness.

2.2 *Lift force during unsteady flow*

Compared to the shear stress, the lift force was more affected by the unsteadiness of the flow (Spiller & Rüther, 2013). The lift force performed a series of three significant peaks during a rapid flow increase, exceeding their steady counterpart considerably. Figure 2 *left column* shows the result of such an experiment. The experimental procedure, described in detail in Spiller et al. (2014), can be summarized as follows: In the presented case, the discharge at the upstream end of the flume was increased linearly within 30 s. The hydrograph at the test section (top graph) appeared deformed and significantly longer, which is a typical behavior (Song & Graf, 1996; Spiller et al., 2014). The unsteadiness parameter, in this case $\Gamma'_{HG} = 0.062$, was calculated according to the hydrograph at the test section. Simultaneously, the lift force on a 100 mm x 100 mm piece of artificial riverbed was recorded using a force sensor (bottom graph). If quasi-steady assumptions would apply to this scenario, the lift force would linearly drift from its initial to its final value, showing no significant deviations from the straight line drawn in the figure. The measurement however shows three significant deviations (peak 1 to 3) from the quasi-steady reference line. To emphasize this deviation, the area between the peaks and the reference line is shaded in grey. These three distinctive peaks were clearly recognizable for any linear flow increase with an unsteadiness parameter of $\Gamma'_{HG} > 0.02$ (Spiller et al., 2014).

A possible consequence of such strong lift forces, combined with consistent shear stress, can cause increased sediment transport in the form of a sudden mobilization of numerous grains or even the breakup of the protective armor layer.

Furthermore, Spiller et al. (2014) found a way to estimate how single hydrograph characteristics, such as initial flow depth and ramping rate, relate to the lift force that acts on a riverbed during flow increases. It can be concluded that: The observed lift force peak, being an unsteady effect of hydropeaking, can be reduced by 1.) A higher initial water level, 2.) A smaller difference between maximum and minimum discharge and 3.) A lower ramping rate, i.e. a larger amount of time between beginning and end of the hydropeaking operation. Each of those parameters affected the lift force variations in a very specific way, but generally all three reduced the observed peaks.

3 MITIGATION MEASURES

The present study proposes measures to mitigate the negative consequences of hydropeaking and to minimize the forces acting on the riverbed, implying that less sediment transport or a stable riverbed wants to be achieved. On the other hand, if a controlled armor layer breakup is required to endorse bed morphology out of ecological reasons, then the same findings can be utilized vice versa.

In general, mitigation measures can be divided into two groups: constructional and operational methods (VAW & LCH, 2006). Constructional methods indicate structural measures at or in the riverbed to minimize the effects of a hydropeaking scenario. Operational methods indicate that the flow fluctuation, i.e. the hydrograph itself, is designed to have a minimized effect on the downstream river.

3.1 *Constructional methods*

Constructional methods to mitigate the effect of hydropower peaking exist in different forms. Enforcements of the riverbed and banks to avoid the sudden mobilization of sediments are one example. Others actively regulate the hydrograph that exits a hydropower plant, such as a compensation basin. The purpose of a compensation basin is "to retain turbine water during peaking hours and to release it during hours with little discharge" (Oberrauch & Terrier, 2013). Thus, a compensation basin can reduce both the ramping rate of flow variations and therefore mitigate unsteady effects, as well as the maximum flow, and therefore steady effects of hydropeaking. Its effectiveness depends on the capacity of the compensation basin.

Constructional mitigation methods are often expensive and involve additional interference into the river as an ecosystem.

3.2 *Operational methods*

Operational methods to mitigate hydropower peaking involve any kind of adjustment of the hydrograph discharging through a hydropower plant into an adjacent river. They can mitigate both steady and unsteady effects. VAW and LCH (2006) state that such methods reduce the flexibility of the power production.

In a scenario where a certain increase in power production is demanded at a certain time, a linear flow increase through the hydropower plant, and into the downstream river, is scheduled (solid line in figure 1). Such a flow increase causes a direct increase in shear stress and lift force (steady effect), as well as the earlier described lift force variations (unsteady effect). To reduce the impact of this event, several alternative operational solutions can be performed.

Alternative 1: Reducing the maximum discharge in the hydrograph mitigates both steady and unsteady effects. Applying the findings of Spiller et al. (2014), this operational method will in fact reduce peak 3 of the lift force variations. Peak 1 and 2 however will not be affected. This alternative is the only operational method capable to mitigate steady effects on the riverbed, however a reduction of the maximum flow depth means that the demand will not be fulfilled.

Alternative 2: Increasing the time duration of the hydropeaking operation mitigates unsteady effects. According to Spiller et al. (2014), it reduces all three lift force peaks, observed during rapid flow increases. Furthermore, the demand can be fully satisfied. However, the increased operation time for a hydropeaking scenario results also in a lower response time to

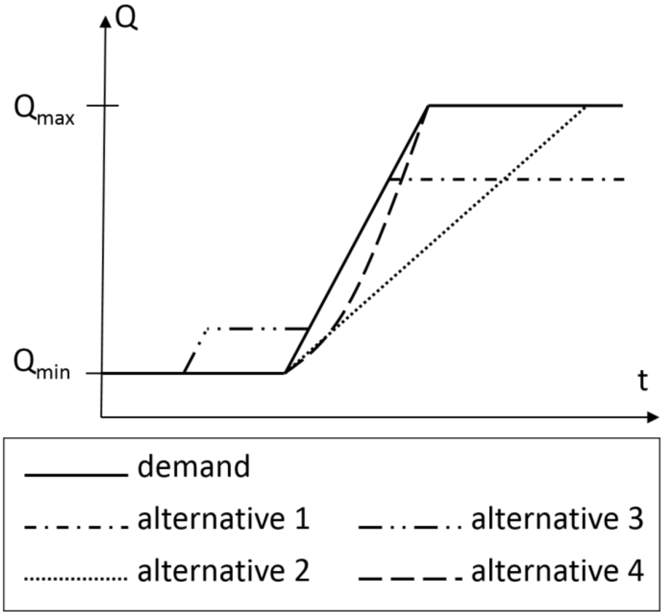

Figure 1. Demanded flow increase and four alternative hydrographs to mitigate the effects of hydropeaking presented as discharge over time.

changes in the net. Thus, the power production loses part of its flexibility.

Alternative 3: If a forecast for the demand could provide a rough prediction about when the next hydropeaking event will have to take place, then the initial flow depth could be adjusted a short while in advance to mitigate unsteady consequences of upcoming the flow fluctuation. Spiller et al. (2014) showed that an increased initial flow depth significantly reduces all three lift force peaks acting on the riverbed. To increase the initial water level, water can be turbinated through the power station or bypassed along the spillways, which would imply a certain loss of resources for a limited amount of time.

Alternative 4: All alternatives stated so far mitigate true unsteady effects by designing a hydrograph with a lower unsteadiness parameter than the demanded one. All of them unfortunately also reduce the flexibility of a power station. They are all based on a linear flow increase and therefore a constant ramping rate. A fourth alternative offers the mitigation of true unsteady effects, without cutting back on flexibility: a non-linear or progressive hydrograph. Compared to the linear peaking operations mentioned so far, this alternative starts out with a low ramping rate and increases the ramping rate subsequently. The slowly increasing water level in the beginning causes less lift force variations, just as presented in alternative 2. When a certain water level is reached, the ramping rate can be increased, but the lift force will remain low, since the flow depth is already much higher than in the beginning of the hydrograph, a similar effect as in alternative 3. A high enough ramping rate towards the end of the hydropeaking operation makes sure that the demanded discharge is achieved in the desired time. Figure 2 *middle column* shows

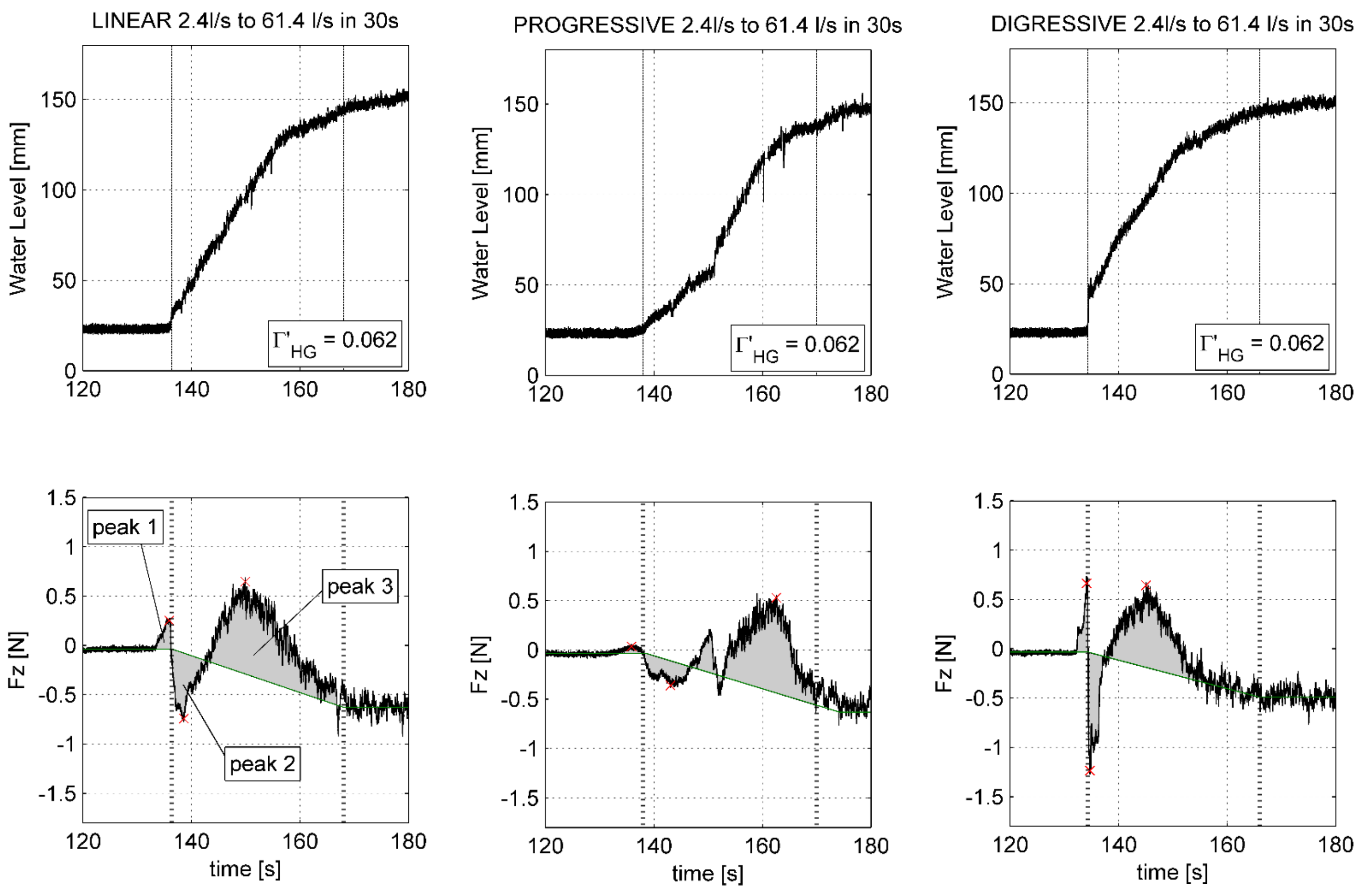

Figure 2. Three different hydrographs from left to right: linear, progressive, digressive. For each one: flow depth over time in top graph and lift force on a piece of bed surface over time in the bottom graph.

how the lift force develops for a progressive hydropeaking operation, performing the same flow increase in the same time as a linear hydrograph, with the same unsteadiness parameter (Fig. 2 *left*), and therefore fulfilling the same demand. In this progressive case, 25% of the desired discharge increase at the upstream end of the flume were performed in 20 s at a constant ramping rate. Afterwards the ramping rate was suddenly increased so that the remaining 75% of the flow increase lasted 10 s. Figure 2 *right* shows that a digressive curve has the opposite effect, with the first 75% of the discharge increase performed over 10 s, followed by a lower ramping rate to reach the desired flow rate after an additional 20 s.

The maximum deviation $\Delta F_{Z,max}$ from the quasi-steady reference line for each peak is marked by an x in figure 2. Comparing $\Delta F_{Z,max}$ for the three experiments shows the following: Peak 1 is largest for the digressive case and still significant for the linear approach. Progressive peaking reduced this peak to a minimum. Peak 2 was still clearly recognizable in all three experiments, but could as well be mitigated by progressive hydropeaking. $\Delta F_{Z,max}$ in peak 3 on the other hand did not show significant differences for either of the three experiments. The progressive peak, however, caused some additional lift force variation at about 155 s experimental time, which is caused by the sudden increase of ramping rate to achieve a progressive curve.

Figure 3 shows those $\Delta F_{Z,max}$ values in peak 1, 2 and 3 for digressive, linear and progressive peaking (circles = dataset 1) and does the same for an additional dataset (squares = dataset 2). This second dataset corresponds to a similar flow increase (2.4 l/s to 61.4 l/s), in twice the time (60 s), resulting in an unsteadiness parameter of $\Gamma'_{HG} = 0.042$. Note that because of the earlier described hydrograph deformation: doubling the time duration of the hydrograph at the inflow does not necessarily halve the unsteadiness parameter, measured at the test section.

For peak 1 and 2 (top and middle graph), a clear trend of decreasing $\Delta F_{Z,max}$ from digressive hydrographs over linear ones to progressive hydrographs is present. This means that the lift force deviations from a quasi-steady reference line, which were earlier described as unsteady effects, are significantly mitigated through progressive peaking. Concerning peak 3 (bottom graph), dataset 2 shows a similar trend, which results in peak 3 being mitigated through progressive peaking. Why peak 3 in dataset 1 remains unaffected is unclear. A larger number of experiments in future could confirm these findings and provide estimations on the potential of non-linear peaking as a mitigation measure for hydropower peaking.

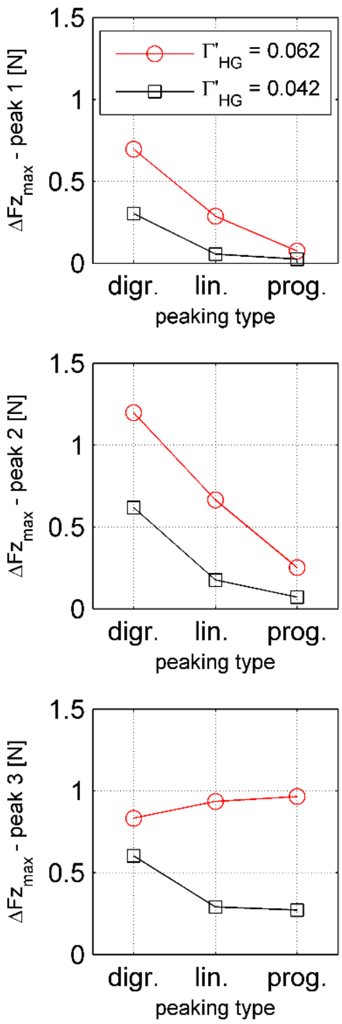

Figure 3. Maximum lift force deviation for each peak in a digressive, linear and progressive hydrograph. Dataset 1 marked as circles, dataset 2 marked as squares.

4 CONCLUSION

The effects of hydropower peaking can be divided in two groups: 1.) "steady" effects, which imply the alternate presence of high and low flow rates in a river. These cause a diversity of flow depth, wetted perimeter and flow velocity over time, which affects the river as an ecosystem, as well as the sediment transport processes. 2.) "unsteady" effects. These imply any additional physical effects due to the unsteadiness of the flow during the flow increase or decrease. Unsteady effects are a matter of current research.

To mitigate the effects of hydropower peaking on the riverbed, both constructional and operational methods are applicable. Conventional operational methods generally reduce the flexibility in power production. Non-linear peaking is a promising alternative, to the conventional operational methods. As part of the present study, non-linear peaking was investigated in two sets of physical experiments, and proven to mitigate observed unsteady effects of hydropower peaking.

A broader investigation, with a larger variety of hydrographs, is recommended for future investigations to gain a better understanding of estimating the mitigation potential of non-linear hydropower peaking.

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6 NOTATION

$d =$	flow depth over roughness tops
$\Delta d =$	total depth increase in a hydrograph
$\Delta t_R =$	duration of flow variation
$\Gamma_{HG} =$	unsteadiness parameter for symmetric hydrograph
$\Gamma'_{HG} =$	adjusted unsteadiness parameter for one sided hydrograph
$u_0^* = \sqrt{\tau_0/\rho} =$	initial shear velocity of initial flow condition
$\tau_0 = \rho \cdot g \cdot d \cdot S_0 =$	initial bed shear stress for uniform flow
$\rho =$	water density
$g =$	local gravitational acceleration
$S_0 =$	bed slope ($S_0 = 5‰$)
$F_z =$	force in vertical direction ; lift force
$\Delta F_{z,max} =$	maximum deviation of F_z from the quasi-steady reference line (absolute value).
$Q =$	discharge
$\Delta Q =$	total discharge increase in a hydrograph
$x =$	streamwise coordinate
$z =$	vertical coordinate (positive in upward direction)

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