By-pass valves in hydropower plants: an ecologically important measure to mitigate stranding in rivers due to emergency turbine flow shutdown

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Abstract

Hydropeaking operations or accidental shutdown in hydropower plants lead to rapid reduction in river flows downstream hydropower outlets and cause severe stranding of biota. Stranding of fish in dewatered riverbeds is a major consequence of hydropeaking. To mitigate the direct negative impacts of accidental powerplant shutdown implementation of automated by-pass valves (BPVs) is suggested as an efficient measure. Proper configuration and operation of the BPV is crucial. At present, more than 110 Norwegian hydropower plants have BPVs as a license requirement. We found that the function of the BPVs in small-scale hydropower plants (HPPs; < 10 MW) were found to be inadequate. Re-configuration to better mitigate the ecological impacts were required to minimize stranding risk for juvenile salmonids. The valves were found to come into plat?? too late, did not open automatically, or were found to reduce the flow too rapidly. Hence, the function of the valves did not meet best practise. This is alarming seen both from a governance perspective as well as from an ecological standpoint. Our second objective was to develop a generic cost-efficient formula for BPVs configuration to dampen severe flow dewatering in case of hydropower fallout. Our configuration formula is adjustable to meet down-ramping flow rules, and hence helps mitigate stranding of key species in rivers. For most of the large-scale HPPs (> 10 MW), the BPVs seems to operate as expected, namely to secure base-flow until the HP turbine is re-started and hence mitigate the most severe dewatering events. Potentially more than 650 HPPs in Norway, and hence several thousand km of potentially impacted rivers downstream HPP outlets may need well operated BPVs to mitigate accidental stranding of riverine biota worldwide.

Keywords: hydropower mitigation, hydropower impacts, hydropeaking, accidental flow ramping, stranding

Running title: by-pass valves to minimize stranding of fish

1. Introduction

Hydropower today plays a vital role for ensuring access to reliable, clean, and sustainable energy. At the same time, restoration and promotion of sustainable use of ecosystems are among the United Nations Sustainable Development Goals (SDGs), namely SDG 6, 7 and 15, adopted also as part of the Norwegian regulatory policies. However, energy production to balance the net or price-optimalisation may need storage hydropower (HP) that can cause ecological impacts from hydropeaking operation creating non-natural sub daily flow pulsing (e.g. Young et al., 2011). Ecological impacts such as stranding are mainly of concern in river reaches downstream storage HP outlets (Harby & Noack, 2013; Moreira et al., 2019; Tonolla et al., 2022). These frequent rapid flow fluctuations may cause severe impacts on the physical conditions (Greimel et al., 2016) and ecosystem services in hydropeaked rivers (Alp et al., 2022). Ecological impacts from stranding (dewatered riverbed from down ramping) and flushing (up-ramping) of biota, are particularly addressed in alpine steep rivers (Batalla et al., 2021; Bakken et al., 2022). Stranding of juvenile fish from rapid dewatering episodes downstream HPPs are well documented (Bradford, 1997; Young et al., 2011), although Nagrodski et al. (2012) argue that ecosystem-scale effects is less understood. The severity of riverine ecological impacts may depend on down-ramping peed and flow ratio (peak flow vs base flow), functionality of relevant mitigation measures (Person et al., 2014), and the physical characteristics of downstream river (Bruder et al., 2016; Greimel et al., 2018; Melcher et al., 2017). These dewatering events may originate from planned hydropeaking operations, as well as accidental shutdown of HP turbine flow due to e.g. failure in the electricity system, extreme weather events, lightning events, blocking of HP intakes (e.g. ice run, woody debris) or human errors (Molkersrød et al., 2019; Ward, 2013). This may result in severe stranding of riverine biota, if there is a lack of adequate structural measures such as e.g. retention basins (Alfredsen et al., 2022; Hayes et al., 2022). Regardless of the cause, a sudden drop of the river flow may be detrimental to the fish populations, as such events do not occur naturally in rivers, especially if they occur irregularly (Halleraker et al., 2003). However, until now, flow ramping from planned hydropeaking operations, in particular down-ramping and effects on fish has by far attracted most studies and attention in management (Alp et al., 2022) and therefore mitigation efforts (Bejarano et al., 2018; Moreira et al., 2019). An abrupt shutdown of a turbine flow in HPPs might lead to a more severe drop in flow, often below the minimum base flow requirement for the reach if suitable mitigation measures are not put in place (Halleraker et al., 2005; 2007). Ecologically efficient measures for mitigation of rapid flow alterations in downstream rivers are already addressed in several European guidelines and policies to ensure sustainable hydropower (EU COM, 2021).

By-pass valves (BPVs) as illustrated in Figure 1 are included in the European mitigation measure library as ecologically efficient measures to reduce stranding of biota (EU COM, 2020; Halleraker et al., 2016). A BPV is normally a pipe-arrangement that shortcut or by-pass the flow from inlet tunnel/penstock around the turbine into the tailrace river (see Figure 1). Release of compensation flow from the penstock into tailrace river through a system such as is considered as good practise to reduce stranding from dewatered riverbanks downstream HPP. A well-functioning BPV should be automatically configured to perform intended operations even in case of blackouts (battery power might even be needed), through automatic opening of the valve and thereby release of "emergency" flow the by-pass arrangement. As the energy of the by-passed water is not utilised in the turbine, energy dissipation steps are needed, to avoid damage to the surroundings from high-pressure flushing velocities such as erosion and flushing aquatic organism. Higher HPP head (pressure) entering the BPV could necessitate additional energy dissipate steps; one for up to 200 m head, and then three above 500 m head (Noren & Elstad, 2008). Energy dissipation also generates loud noises and BPVs are therefore sometimes mounted in a separate isolated room to limit noise transmissions to the surrounding areas.

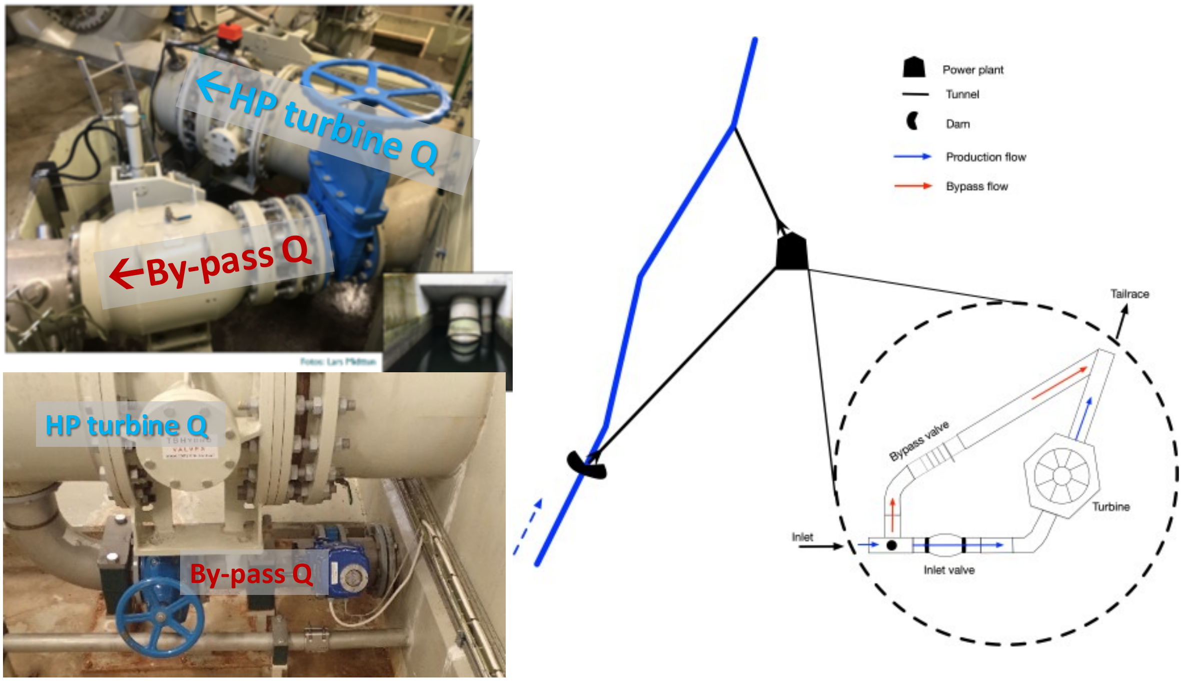

Figure 1. Pictures of differently designed BPV arrangements in a powerhouse on the left and the principle sketch of small scale BPV arrangements on the right (upper left photo L. Midttun, NVE; lower photo A. T. Bråten).

Field studies conducted in several Norwegian HPPs showed that bypass valves have the potential to mitigate stranding of biota from unplanned dewatering events (Bernardo 2017; Natvik & Vaskinn, 2020). To our knowledge, this is a type of construcional measure poorly descibed in the existing state of international scientific litterature in the research discipline. The by-pass valve must open automatically if the turbine stops and thereafter be in operation for sufficient time by adding flow into the river, to enable juvenile fish to migrate into deeper areas, and thereby, avoid stranding (see Figure 2). The BPV dewatering operation must be configured to meet relevant fish species stranding thresholds, by releasing bypassed flows to protect riverine fishes in their habitats downstream HP tailrace.

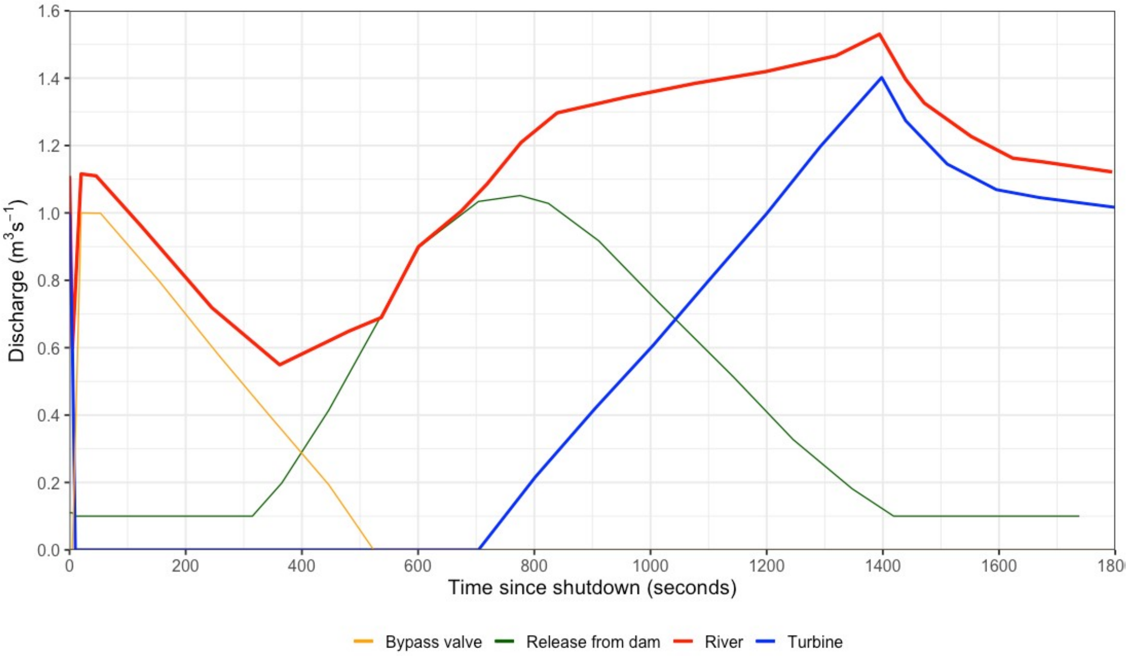

Figure 2. The principle flow component in a river reach downstream HP tailrace with BPV. The total river discharge in red. The turbine flow (blue) is cut due to an accidental shutdown, and the BPV start to release water to prevent rapid dewatering of the river (yellow). Water from the intake reaches the power plant outlet (green). Modified from Noren & Elstad (2008)

Energy security, from stable and reliable electricity supply to end-consumption is crucial for modern societies, and this is also part of the UN sustainable development goals (SDGs). Optimal maintenance and regular service of HPPs might therefore be beneficial both for river ecology and for stable and reliable electricity production. However, accidental, or unplanned shut down of HP turbines can also be due to external reasons outside the HP operators control (Molkersrød et al., 2019). External events affecting the electricity grid might be grid failures from extreme weather conditions (lightening, thunderstorms, heavy snowfall or icing), physical disruptions or failure of transmission lines (Ward, 2013; Statnett, 2022). In contrast to ecological impacts from planned hydropeaking operations, river flow level drops from accidental HPP turbine flow shut down, seems to be less studied or mitigated internationally (but see Yuba County Water Agency, 2012; Harby & Noack 2013). The main objectives of our work were to:

i) Document examples of accidental fallouts and illustrate stranding impacts on Atlantic salmon in Norway. This illustrates the effect of a fallout and the difference between this and regular down-ramping from planned hydropeaking.

ii) Describe the ecological relevance and functionality of a BPV and its current implementation in the Norwegian HP system.

iii) Present and test a novel method to optimize BPV operation to mitigate stranding of juvenile salmonids based on critical down-ramping thresholds.

The output of this work will be arriving at operational settings for the BPVs, which can in turn be implemented for the HPP under consideration. This can serve as a general technical guide for monitoring of ecological efficiency of the level of mitigation.

2. Material and methods

2.1 Study area

Norway has one of the highest shares when it comes to renewable electricity production in the world, ranked as the seventh largest HP producing country worldwide with 33 GW installed capacity. With multitudes of high-head storage HPPs, more than 50 % of the HP storage capacity in Europe (www.nve.no) and with a broad ranging spectrum of infrastructure and sizes, Norway can be stated as an ideal study area to investigate downstream impacts and mitigation solutions like BPVs.

The authors have compiled information about BPVs in Norway into an access database. The database contains data pertaining to license requirements, HPP characteristics, outlet location, HP no (from www.nve.no), required downstream mitigation measures and ecological information from the Norwegian WFD database, Vann-nett.no (Halleraker et al., 2022).

Until 2022, about 1739 HPPs were actively producing HP in Norway and 1392 of these were HPP with installed capacities < 10 MW (www.nve.no). Of these, about 800 were diversion HPPs plants where tailrace flow discharge could potentially affect river ecology in more than 3,000 km of downstream river reaches (Halleraker et al., 2022). The highest rise lately in new HPPs have been in the category less than 10 MW. For many of these HPPs, BPVs together with vague operational ramping restrictions on hydropeaking operation are common, although main intension has been to avoid stranding of fish from down-ramping (Halleraker et al, 2022).

2.2 Detailed case study

One of our case studies is river Surna in western Norway which has been impacted from Trollheim hydropower system for more than five decades (Halleraker et al.,2007). Surna is a national salmon river and has implemented restrictions on regular ramping and an environmental flow regime. Several accidental fallouts of Trollheim HPP have occurred in Surna. The hydropower outlet is located at the anadromous part of the river, about 19 km from the outlet in the sea.

An Excel based stranding model was established for assessing mortalities and effects on the salmon and trout populations arising as consequences of episodic fallouts. The following components were included (see also Harby and Noack, 2013):

1. The relationships between discharge, water levels and wetted width were established. Dewatered riverbeds were modelled using 1D hydraulic model HEC-RAS from transect data, and dewatering rates along the 19 km downstream were computed in cm/hr.
2. Juvenile densities of trout and salmon prior to the dewatering episodes were documented based on 3-years average electrofishing densities (Halleraker et al., 2005) and transect electrofishing (in 2008 and 2012) from wadable reaches to estimate the number of juvenile salmon and trout in the dewatering zone.
3. Stranding mortality rates for comparable light and temperature conditions were investigated based on experimental data on Atlantic salmon (median, range 25 percentile and 75 percentile) from an enclosure (Saltveit et al., 2001) and artificial flume experiments with brown trout (Halleraker et al., 2003) differentiated on ramping rates and juvenile year classes (see review by Moreira et al., 2019).
4. Density dependent mortality was integrated into population modelling to estimate the stranding consequences for the Atlantic salmon and trout populations, expressed as loss in smolt equivalents from stranding mortality of the juvenile salmonids.

2.3 Operational configuration of BPVs.

To develop a methodology for evaluation of BPVs functionality for small scale HPPs, we tested BPVs functionality prior to and after re-configuration of automatic operation of the BPVs by monitoring the downstream river reaches of 11 selected small-scale diversion HPPs in Mid- and Western Norway (Table 1). The functionality of the default setting of the BPVs in the five first HPPs in the table were evaluated in testruns, while the rest were tested after re-programming of the BPVs.

We installed sensors in several of the test rivers, Global water WL-16 water level and water temperature sensors were installed and the parameters were monitored under various flow ramping conditions (high, low residual and turbine flows). Time lapse cameras (UVISION UM 562 and Ltl Acron 6210M) was also deployed to monitor the dewatering process. Discharge measurements were carried out using dilution methods (Sommer Flow Tracer). The water level sensors were calibrated to a precision within +/- 2 cm error margin. During field testing prior to the dewatering events, the water level loggers were placed at seven spots in each river: 1) at the intake basin, 2) just downstream of the intake site (by-passed river reach), 3) just upstream of the HP tailrace (lower part of the by-passed river reach), 4) just downstream of the tailrace, and 5-7) three spots downstream, about 100 m, ca 2-500 m and ca 1000 m from the HPP outlet. We monitored dewatering trials with release of by-pass flows from the BPVs like an accidental shut down of the HPP turbine flows were monitored in each of the rivers. Each trial lasted until the restart of the HP production up to stabilization of measured discharges in all transects with water level sensors. Three replicates at different dates were conducted at each river to capture different inflow and residual flow conditions (see Vingerhagen & Vaskinn, 2017).

As salmonids are considered as the key species in most of these rivers. The critical flow ramping indices described *by* Bakken et al., (2022) were used to define critical levels for stranding. Based on these critical levels and measurement data, we developed a method to configure the release and time of operation for the BPVs. The method was developed by testing five BPVs with default setting and analysing the relationship between water levels, discharge and how fast these parameters dropped in the river downstream of the HPPs after shutting down the HPPs abruptly to test the BPVs functionality (more details given in next chapter)

The maximum BPV flow range in the power plants included in the study varied from 27 – 100 % of the maximum turbine capacity. Most of them (10 out of 11) had operational flow ramping restrictions, but the formulations are, without hydropeaking thresholds. The consequence of this has been that every HPP has adopted its own interpretation of how their BPVs should operate. These license requirements are intended to avoid hydropeaking impacts (stranding) and hence operate the power plants utilizing available inflow (RoR) without typical start/stop operation. Three of these have storage reservoirs with more than 1 m regulation height, while the rest have small capacity impoundments (Table 1).

3. Results

3.1 Overview of BPVs in the Norwegian hydropower portfolio

A review of the cumulative license requirement database of the Norwegian HP portfolio (Halleraker et al., 2022) reveals that most BPVs were issued or installed after 2001, primarily (about 82% of all installed BPVs) related to licensing of the many smaller scale HPPs (< 10 MW) issued in recent years (Vøllestad et al.,2018).

Characteristics of a selection of the largest HPPs with BPVs and storage HPPs are compiled in Table 2. Our survey of license requirements revealed that currently, there are 110 HPPs with BPV in active operation across Norway. However, the total number including planned installations of BPVs in HPPs under construction, or not yet in operation is closer to 150 (Vøllestad et al., 2018). In total, less than about 10% of all the HP licenses in Norway have incorporated this type of measure to mitigate stranding of riverine biota. Also, less than 20 % of all HPPs with outlet into longer downstream rivers have implemented BPVs as part of the plant design and operations (Halleraker et al., 2022). In recent years, BPVs have been installed in some storage HPPs (e.g. Lovik, Nedre Røssåga, Trollheim) after many decades of operation without any such mitigation measure. It is evaluated that implementation of BPVs might be relevant in about 650 HPPs across Norway to ensure best practise with regards to sustainable production of HP (EU COM, 2021; Nielsen & Szabo-Meszaros, *2023*).

There also exist alternative technical solutions to mitigate accidental stranding from HP turbine shutdown. An example of this are turbines that can by-pass flows without being in production mode (e.g. HPP Nedre Otta, HPP Sokna). A further example would be parallel -tunnel arrangements. The latter is included as part of the Brulandsfoss HPP in Jølstra, where a parallel tunnel with Q_{max} of 8 m^3/s (10 % of maximum turbine capacity) is activated when the HPP shuts down operations (H. Sægrov pers. comm). Until 2022, no retention basin or other similar structural measures (e.g. retention basins or ACUR – cavern) were incorporated to mitigate stranding from accidental or planned hydropeaking in Norway.

The main functionality of the BPV and operational time depend on the type of HPPs. Therefore, we have classified these into categories based on the storage potential vs the small-scale diversion run of the river (RoR) HPP. Most of the small-scale HPPs (< 10 MW) do not have storage reservoirs and therefore, larger volumes are usually not available for longer operation of the BVP. For RoR HPPs without storage, turbine drop out will eventually (depending on gradient and diversion tunnel characteristics) lead to flow spill over the dam (Størset, 2012).

Based on all the HPPs with BPVs in our database, about 75 % are related to small scale RoR HP turbines (1-10 MW), mainly installed after 2005, and most (80%) in diversion HP with head above 100 m. More than 70% of the HPPs with BPVs have potential ramping rate (Q_{max}/baseflow min) above a ratio of 10. A minimum baseflow requirement (annual basis) is put in place in 85 % of all these HPPs. This minimum flow is normally released from the dam. Some 80 % HPPs also have operational ramping restrictions as part of their licensing requirement, although the requirements are generally very vaguely formulated. BPVs with Q_{max} of less than 4 m^3/s are most common (83 %), although some BPVs Q_{max} are higher than 25 m^3/s with the highest documented capacity of 44 m^3/s (installed in 2021). In relative terms, a large majority of the BPVs have around 50% of max turbine capacity, but this varies from ca 20 % to 100 %. BPVs is required in both RoR HP and storage HP to mitigate hydrological pressures in both short rivers < 2 km (ca 45 %), medium sized rivers of 2- 5 km (ca 27 %), and longer downstream rivers > 5 km (ca 28%) (see Table 2 for more details).

Less than 20 Norwegian HPPs larger than 10 MW, including several larger 50 MW power plants (with turbine Q_{max} of >30-96 m^3/s) that have BPVs requirements have been identified (Table 2). It is a key observation that there is a huge variation in size-classes and % of Q_{max} that BPVs can by-pass.

Some have BPVs requested in the HP licenses but yet not built (e.g. HPP Lovik). The oldest BPVs in Norway were constructed in storage HPPs prior to 1990 with outlet into salmon rivers.

The main functionality of the large scale BPVs in storage HP is normally to automatically release a base flow during turbine flow shutdown, until the HP production is restarted or manual release of water from gates in the dam. So, in contrast to many small scale diversion HPP (with no or small storage), these large scale BPVs are operated to avoid the most severe dewatering or river beds completely related to HPP fall out. However, malfunction of BPVs in larger HPPs have also been reported in the past (e.g. Kongsfjord HP in 2014, www.nve.no). E.g. penalties of 10 000 EUR have been given by NVE to operators in case the BPVs do not automatically open due electrical shortcut and leads to drop of flow downstream HPPs tailrace below Eflow requirements.

The most frequent BPV requirements have been enforced in small high head diversion HPPs, combined with residual flow requirements released from the dam (from the lowermost common flow to typically Q_{95} summer/winter flow). Most of these (81 %) also have operational flow ramping restrictions incorporated in their license.

3.2 Examples of accidental stops and downstream impacts.

Under normal operating conditions, the base flow downstream of the tailrace of HP Trollheim is 15 m^3/s. The accidental drops (in 2005, 2008 and 2012) resulted in dewatering of riverbed areas in the range of 194,000 - 312, 800 m^2 over a reach of about 19 km of River Surna. The stranding models based on electrofishing densities in dewatering zones estimated considerable mortality in Atlantic salmon and brown trout juveniles (Table 3).

Some of the most detailed past studies in Norway investigating unplanned shutdowns have been carried out in the river Surna (Trollheim HP). Some noteworthy accidents occurred in 2005,2008 (Figure 3) and 2012. Forseth et al. (2009) estimated 80 % mortality of the stranded/pool-trapped fish in the dewatered zone. The resulting population effects on the Atlantic salmon represented 1.5 - 10 % of the total smolt production (Table 3). This was adjusted for density-dependent mortality rates as described by Hedger et al. (2018).

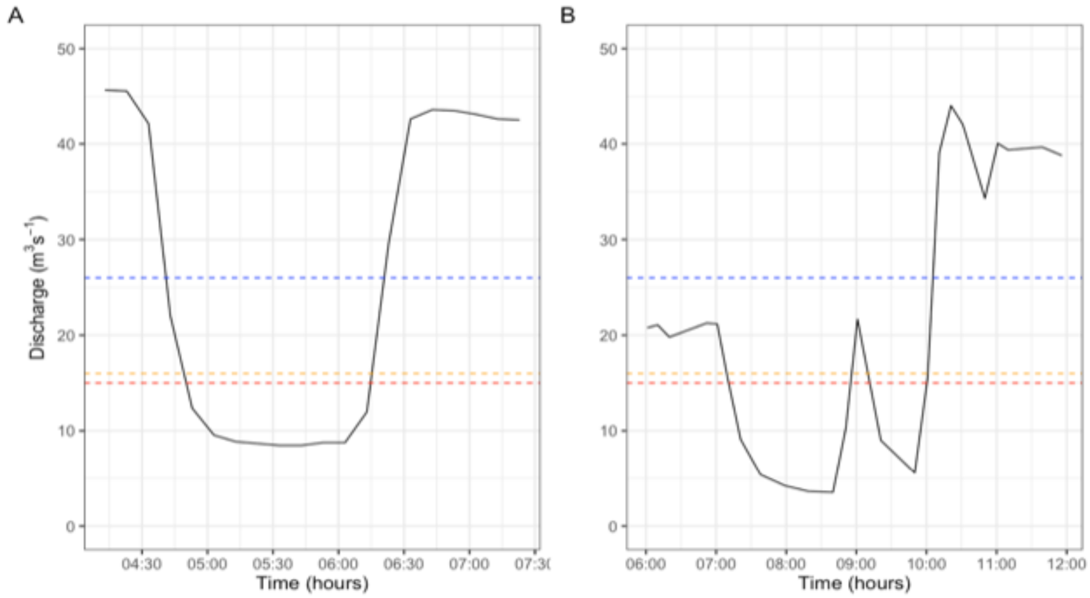

Figure 3. Accidental dewatering episodes in River Surna in a) 2005 and b) 2008. Discharge was recorded at Skjermo gauging station (ca. 1.5 km) downstream of Trollheim HPP. Red-dotted line is the Q_{base} requirement and Blue line, the max BPVs discharge including residual flow. Orange line represents the lowermost BPVs discharge.

A well configured BPV with Qmax of 30 m^3/s was installed in 2011 to minimize potential stranding of juvenile salmonids in river Surna. Yet, blocking of the tunnel intake still happened due to accidental closure of an upper valve on the 9th and 10th of April 2012 (Ugedal et al., 2013).

In our selection of accidental shut down cases (Table 3 and 4), most of the events have had dewatering rates far above the critical thresholds over longer reaches (10-13 cm/hr). Although the dewatered areas vary depending on bathymetry and morphological shape of the riverbeds, 10 – 48 %

of the river habitats were exposed to drying episodes during these dewatering events (Table 3 and 4). In some cases, the river flow could be re-established rapidly with severe flushing events (e.g. Gloppen). However, for most of the events, available records point towards the fact that the river reaches were subjected to drying over longer periods. The mortality among the stranded or pool trapped individuals is generally high. In the river Jølstra (Brulandsfoss HPP, Q_{max} 65 m^3/s), the frequency of HP fallouts has dropped drastically after 2004 (Sægrov et al., 2014). Prior to 2002, accidental drop outs were primarily due to internal errors in the HPP, although some episodes were related to failure in the grid. The ecologically most harmful turbine dropouts (> 10 cm/hr) have drastically decreased to none in 2010-2012, mainly due new operational systems and improved routines in the HPPs (Sægrov et al., 2020).

Alta HPP is a complex facility consisting of two turbines with capacities of 33 and 66 m^3/s, respectively. The smaller was installed with a BPV with similar capacity as in 1987. The frequency of accidental stranding events due to fallout of Alta HPP was on average quite low; 0,4 to 1.6 pr year for each of the turbines, during the first seven years of operation (1987-1994). Due to high juvenile Atlantic salmon mortality, an evaluation of installing an additional BPV with 33 m^3/s capacity was carried out. Forseth et al. (1996) estimated that this installation would reduce mortality and save 53-85 % of stranded juveniles.

3.3. A cost-effective formula for configuration of BPVs.

Our investigations and testing in the 11 rivers with small BPVs (Table 1) showed that all the small scale BVPs were operated at different settings. Our testing showed that the BPVs needed re-programming to meet dewatering thresholds (Vingerhagen &Vaskinn, 2017, Figure 4a). The investigated HPPs are small scale (1.2 - 4.9 MW) diversion HPPs, mainly (8 of 11) without storage reservoirs. BPVs could release from 27 – 100 % of the max turbine capacity (Table 1). Most of the HPPs have tailrace into longer rivers, while 4 of 11 have less than 1 km downstream river reaches. The five upper cases in Table 1 were used for testing and monitoring of the functionality of the BPVs default settings. The remaining six were used to test reprogramming of the BPVs configuration to meet ecological thresholds to reduce stranding of salmonids in the downstream river reaches.

Our testing and observations revealed:

- Malfunctioning of the BPVs configuration were widespread, so that reprogramming and improved maintenance was needed.
- Flushing events often occur; both due to dam overflow (mainly in RoR HPPs with impoundments) and from restart of HPP turbine flow (without any start-up restrictions)

- Thermopeaking of several degrees (∆ of 3-4.5 ^{0}C) occurs and this could be related to start/stop in several of the studied rivers (during testing in April and October), e.g. downstream the storage HPPs Brandåa and Sundli.
- Prior to reprogramming the BPVs, they either opened too late, did not open automatically (blackout and no battery backup) or in case of low production flow, reduced the flow abruptly (see Figure 4).

Without a BPV in operation, it takes ca 45 minutes from turbine shut down until spill over at the dam to reach downstream HP tailrace through the bypass reach, and hence, the water level is constantly rising (Figure 4a). When the BPV opened too late, first severe dewatering of riverbed (stranding) occurs, followed by rapid up ramping (Figure 4b).

As our 11 HPPs with BVPs in focus were stochastically chosen, these can be considered representative of the small scale BPVs in Norway. Thus, most of them needed optimisation procedures to ensure ecological mitigation. Therefore, a generic formula was developed to minimize the risk for stranding of juvenile salmonids as much as possible. In the testing, a down ramping threshold of 10 cm/hr was applied. This threshold might be adapted to species in focus.

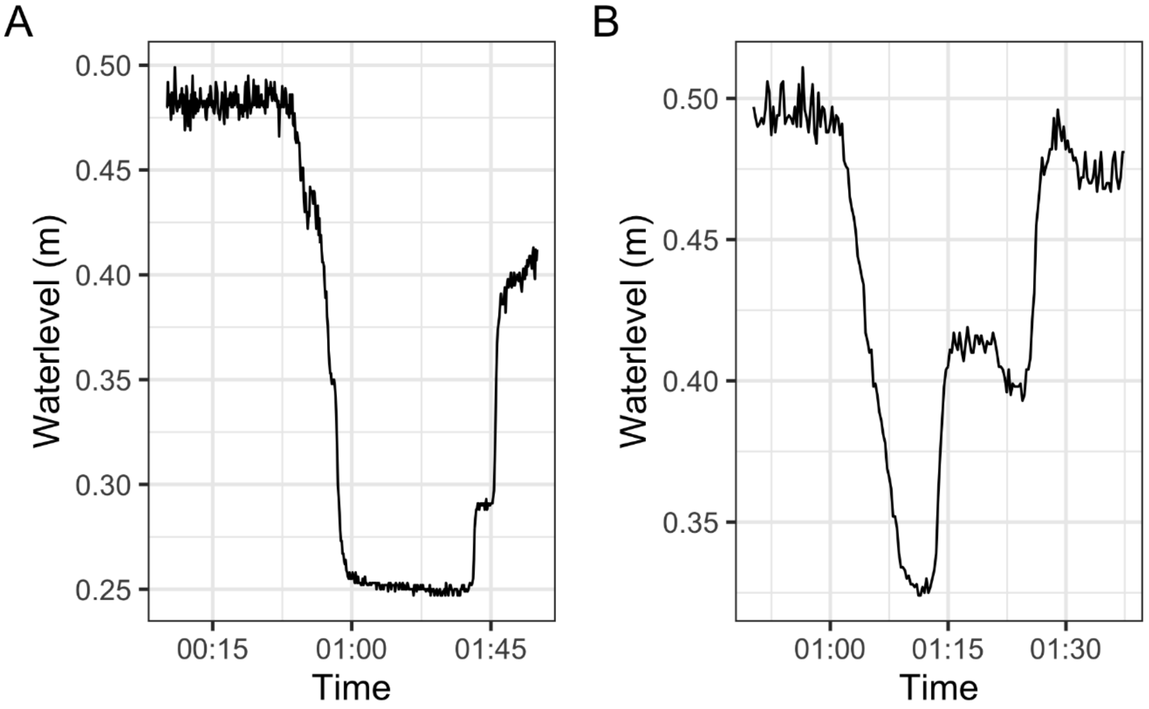

Figure 4. Two dewatering events from accidental shut down of a small-scale HP turbines. Time as hh:mm on x-axis. Water level monitored downstream HP tailrace. a) no bypass valve installed and b) bypass valve installed but configured to release flow too late.

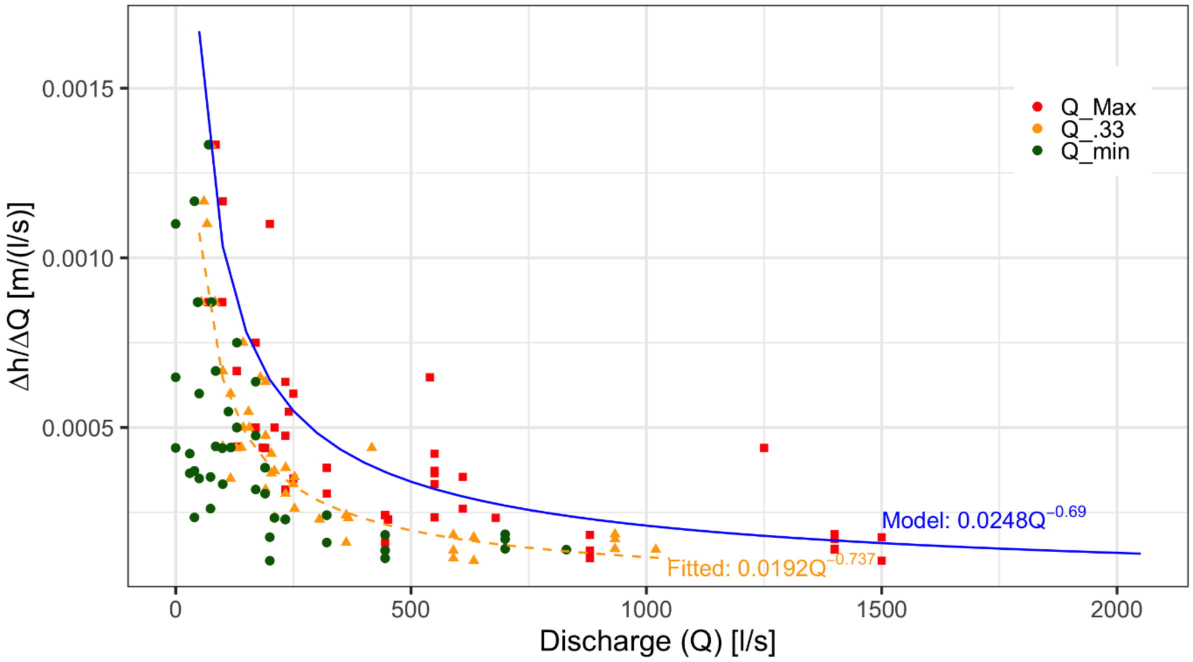

Figure 5. *Relationship between the change in stage – discharge ratio (Δh/ΔQ) and discharge, plotted for Q_max, Q_min and Q_33 (1/3 of the discharge between Q_max and Q_min). The yellow curve shows a relationship between Δh/ΔQ and Q based on Q_33, while the blue line shows the proposed model used in the derivation of the design equations for the bypass valve.*

During the experiments changes in discharge and changes in stage at several locations were recorded. Based on these data, the ratio between the change in stage and change in discharge was computed. Since the difference between the maximum (Q_max) and minimum discharge (Q_min) is sometimes large, and most of the changes happen close to Q_min, a discharge computed as 1/3 of the interval between Q_min and Q_max was used in the analysis (Q_33). Based on the data from the five gauging stations a model of the relationship between the change in the stage/discharge (Δh/ΔQ) relationship and the discharge was found as shown in Figure 5 (blue line). The formula for this relationship is shown in equation 1.

$$\frac{\Delta h}{\Delta Q} = 0.0248 \cdot Q^{-0.69} \tag{1}$$

Δh/ΔQ – change in stage per change in discharge (m/(l/s)), Q – discharge (l/s). This gives the relation between the change in discharge ΔQ and the change in stage Δh as shown in Eq 2.

$$\Delta \mathrm{Q} = \frac{\Delta h}{0.0248 \cdot Q^{-0.69}} \qquad (2)$$

Over a timestep of Δt we get the relation shown in equation 3.

$$\frac{\Delta Q}{\Delta t} = \frac{\Delta h}{\Delta t} \cdot \frac{1}{0.0248 \cdot Q^{-0.69}} \quad \left[\frac{l/s}{min}\right] \qquad (3)$$

For a limiting ramping rate Δh/Δt of 10 cm/hour we get 0.1 meter/hour and 1/600 meter/minute. Inserting this into equation 3 we get the equation for the change in discharge over time (Equation 4).

$$\frac{\Delta \mathrm{Q}}{\Delta \mathrm{t}} = 0.0672 \cdot \mathrm{Q}^{0.69} \quad and \quad \Delta Q = 0.0672 \cdot \mathrm{Q}^{0.69} \cdot \Delta t \; (4)$$

As Q is the discharge downstream the power plant and the bypass valve regulate the change in discharge, two equations can be formulated to compute the characteristics of the valve.

$$\Delta Q_{BPV} = 0.0672 \cdot (Q_{BPV} + Q_{min})^{0.69} \cdot \Delta t \qquad (5)$$

$$\Delta t = \frac{\Delta Q_{BPV}}{0.0672 \cdot (Q_{BPV} + Q_{min})^{0.69}} \qquad (6)$$

Where Q_{BPV} is the maximum discharge of the bypass valve in l/s, ΔQ_{BPV} is the change in discharge through the bypass valve, Q_{min} is the minimum flow in the bypass reach in l/s and Δt is the time step between adjustment of the valve in minutes. This is a conservative approach eliminating any residual flow downstream of the intake site and means that the valve operation is configured for the absolute minimum flow situation. Changes in the limiting ramping rate can easily be incorporated by adjusting the formula from equation 3.

To avoid to big single drops in water level, a maximum of 3 cm water level drop per change in discharge through BPV is required. Based on the hydrographs from four comparable gauging stations from the Hydra II database (www.nve.no), we found the relationship between ΔQ and Δh from stage discharge. These showed that for small rivers in Norway 20 l/s will limit vertical water level drops to maximum 3 cm. However, for practical use the minimum change in discharge through the BVP will in most cases be decided by the BVP design.

The consequence of a successful reprogramming is a smooth flow ramping curve (Figure 6). From Figure 6, we can see that there is an initial flow drop when the turbine stops before the valve is in action and subsequent to this, the reduction of flow is smoothed according to the criteria used to avoid stranding. The dashed line shows the estimated water level in the case of no installed valve, and there are possibilities that the lowest water level could be below 0.3 m. In this case, the valve is open for more than 30 min, gradually reducing the flow. Soon after the BPV is closed (before 23:40), the water level rises again. This is due to spill overflow reaching the river downstream of the HP tailrace through the bypassed river. Our testing of reprogrammed BPVs based on the generic formula resulted in acceptable dewatering speed in all the respective river reaches where the reprogramming was implemented correctly.

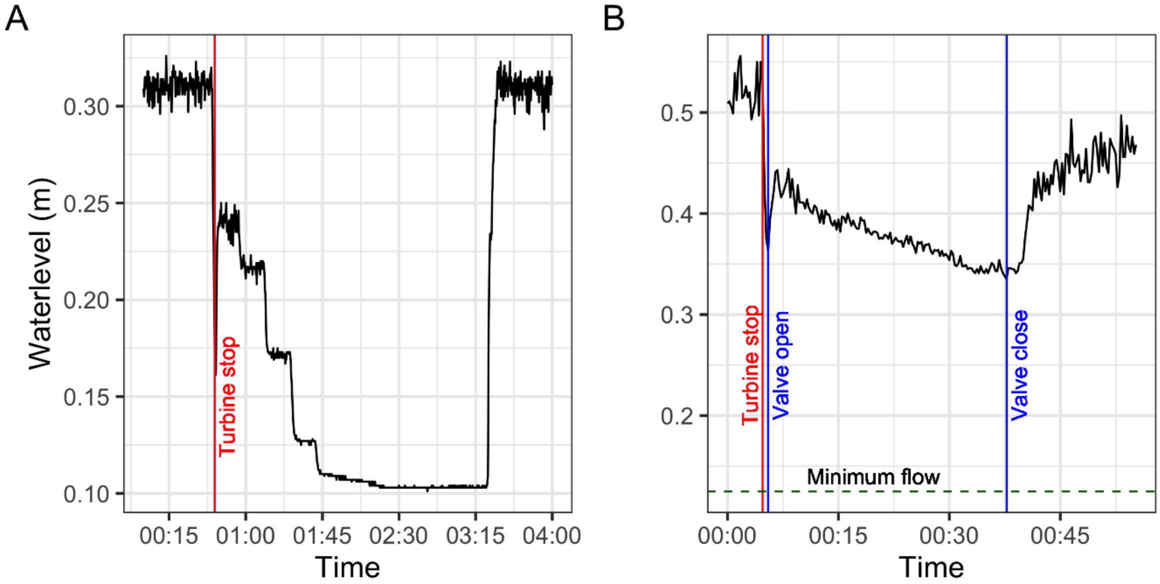

Figure 6. Examples of well operated BPVs to meet dewatering thresholds for minimizing risk for stranding, monitored with a water level sensor downstream of the small-scale RoR HP outlet. The dashed line (b) shows the discharge with no installed BPV.

4 Discussion

4.1 Experiences with BPVs in Norway

In this study, the authors have investigated the use of bypass valves to mitigate stranding of juvenile fish because of rapid dewatering resulting due to accidental shutdowns of hydropower plants. BPVs are implemented in a wide range of HPP types and size categories across Norway. At present, BPVs are required in most (82 %) small hydropower systems (< 10 MW) in conjunction with operational restrictions imposed on planned hydropeaking (81 %) and annual minimum flow requirements (85 %). Bypass valves might potentially mitigate severe stranding from accidental turbine shutdowns. However, our study of several smaller hydropower plants revealed that in many cases, the valves were not correctly configured and thereby did not perform to significantly reduce stranding of juvenile salmonids in line with national guidelines. Therefore, we developed a cost-efficient method to estimate the required shutdown time for a bypass valve in small scale HPPs with limited budgets for implementation of mitigation strategies, based on a defined stranding criteria which can ensure best practise.

Cost of BPVs

The costs of installation of BPVs depend on several factors such as the size and the available space in the power plant. The costs of installing BPVs in 2007 ranged from about 20 000 Euro for the smallest HP (up to 1 m^3/s) with low head to more than 0.1 mill Euro for HPPs of 5-10 MW (Norén & Elstad, 2008). In addition, especially in several large-scale HP plants (> 10 MW), BPVs have been required or installed many years after the HP turbine(s) were put into operation. The total costs of the BPV installed in the large Trollheim power plant were estimated to be around 2.2 mill Euro (Kgl resolusjon, 2021).

If need for extra cavern space in the power plant, the cost might raise considerably. It may be argued that such after installation of is much less cost-efficient. In the Yuba River (California, US), two large BPVs was installed to mitigate unscheduled shutdowns of the HPP (typically operated from 25.5 to 96 m^3/s) below the Englebright Dam. The first, was a partial BPV of Qmax 18.4 m^3/s was build when the powerhouse was constructed. Then a full bypass of 85 m^3/s, was added in 2008, with a project cost of about 12.4 mill Euro. Yuba County (2012) required this huge bypass project to automatically maintaining flow for downstream fisheries (e.g. spawning grounds for Chinook salmon and steelhead trout. As the frequency and intensity of operational flow ramping might have greater ecological effects, retention basin or relocation of HP tailrace into a larger water body is being planned (Person et al, 2014; Greimel et al., 2018). This will normally also mitigate the accidental hydropeaking occurrences from failures.

4.2 Prevention or mitigation of stranding

Our examples show that flow declines (like accidental turbine fallouts) may occur in most HP types and size-classes. We have documented considerable areas of dewatered riverbeds in several Norwegian rivers from accidental HP fallout (Table 4). Therefore, appropriate measures and strategies are needed to mitigate accidental drops in river flows across most types of HPPs with outlets into rivers. BPVs are a relevant and ecologically efficient mitigation measure in such HPPs. BPV cannot be considered a relevant measure when the outlet of the power plant is draining directly into fjords or lakes/reservoirs, or when a downstream retention basin is already in place (Tonolla et al., 2017; Reindl et al., 2022). We recommend countries to include BPVs as a mitigation strategy in existing HPPs, and as a good practise measure for new HP modifications of rivers in line with European policy documents (e.g. EU COM, 2020) and good management practise (Nielsen & Szabo-Meszaros, *2023)*.

We have not conducted a systematic literature review regarding frequency of unplanned HP turbine shutdowns internationally. However, English and German literature point to a hypothesise that this issue might not be as widespread as in Norwegian regulated rivers, although described in grey literature from N-America (e.g. Yuba County, 2012). The ecological impacts from accidental dewatering of riverbeds dependent on river type characteristics (e.g. river profile and gradients) or other pressures (e.g. morphological alteration) and the sensitivity of impacted fish species (Schmutz et al., 2015) and river-specific effects on macroinvertebrates in hydropeaked rivers (Tonolla et al., 2022). Based on information retrieved from the HyPeak research network (Alp et al., 2022) and the review by Schmutz & Sandzimir (2018), BPVs seems to be overlooked and less required as ecological mitigation measure internationally. We believe this might be due to lack of management requirement and inclusions of BPVs as a relevant mitigation measure (EU COM, 2020). Accidental failures (unplanned "faults") leading to stranding of riverine biota downstream HP turbines is likely to be a relevant issue also in other countries. The reason leading to such failures might even be an increasing problem related to more extreme climate (e.g. lightening, hurricanes, ice runs) impacting the grid or power system in the future together with others reason such as human errors (Ward, 2013). To our knowledge, more than 600 HPs in Norway, and several thousand km of hydropeaked rivers internationally may need well operated BPVs or alternative mitigation strategies to reduce severe stranding of riverine biodiversity related to accidental flow decline events.

4.3. Ecological functionality is crucial

Relevant monitoring is essential to evaluate the ecological effect of BPVs over time. Moreira et al. (2019) highlighted that ecologically based downramping thresholds are crucial. These thresholds should be based on the best available knowledge regarding life-stage effects from rapid flow ramping (Hayes et al., 2019). In the Norwegian good practise guidelines for BPVs (NVE, 2016), the wording 'avoid stranding' is used. We argue for a seasonal adaptation of hydropeaking thresholds related to configuration of the BPVs. Even down-ramping less than 10 cm/hr might lead to both pool trapping, increased predation (Hunter, 1992) as well as stranding of the smallest salmonids (larvae < 50 mm) (Moreira et al., 2019) or other riverine biota such as macroinvertebrates (Tonolla et al., 2022). Anyhow, evidence based dewatering thresholds as cm/hour or equivalent are a prerequisite to be incorporated into the HP licensing to ensure HP operation to be operated in an ecosystem-based mode. Vague restrictions like "as smooth as possible" or to reduce stranding do not ensure the ecological mitigation nor are usable for control of licence requirements (L'Abée-Lund & Otero, 2018). From our experience, vague formulations may give difficulties in control by responsible governmental institutions, and conflicts may arise due to different interpretations of the restrictions by different stakeholders. Therefore, we think explicit thresholds will improve the management of restrictions. Still, it is important to have the possibilities for adaptive measures (thresholds) and therefore adjust the threshold based on e.g. monitoring of fish population effects or new knowledge. Our BPV configuration formula is designed for this purpose as the cm/h related to discharge is one of the key parameters and can therefore be adjusted as knowledge on critical ramping rate is updated or if new species are included in the analysis.

Our monitoring during testing revealed both thermopeaking of several degrees in the storage HPP cases, as well as indication of flushing due to rapid up-ramping of river flow. The good practice recommendations for BPVs in Norway (NVE, 2016) do not address the up-ramping issue. We recommend acknowledging the accumulated ecological impacts from hydropeaking and thermopeaking and integrate evident-based up-ramping thresholds to mitigate flushing and potential catastrophic drifting of biota in the future (Auer et al.,2017; Gabbud et al., 2019; Hayes et al.,2019).

Until 2018, management practice was mainly focusing on reduced stranding of salmonids based on evidence-based recommendation from stranding experiments on some relevant species and life stages. In an ecosystem-based management practice, all impacted species needs to be handled to ensure ecological sustainable HP operations in line with the relevant EU policies (EU COM 2020; 2021). Thus, additional flow rules for non-salmonid species might also be relevant in the future. In addition, BPVs operational thresholds should be integrated in revised licence requirements in Norway as well internationally.

The Norwegian authorities have different sanctions to ensure HP operation in line with regulatory requirements, e.g. adequate functioning of BPVs. So far, financial sanctions like fines have rarely been imposed on large scale HP producers, and neither for dysfunctional small scale BPVs. L'Abée-Lund et al. (2022) found surprisingly no systematic or significant environmental improvements from the regulatory audits of HP licenses in Norway.

5 Conclusion and outlook

We argue that BPVs are ecologically justified measures for mitigation of the negative ecological impacts of hydropeaking/accidental hydropower plant shutdowns. This in turn entails reduced risks for catastrophic stranding of riverine biota. This is a relevant issue in most HPP types with outlets in rivers, in particular;

- Diversion HPPs with tailrace into (longer) rivers with lack of retention basins
- Storage HPP with only one turbine may have even higher ecological risk from fallout, especially where overflow passed dam will take time before reaching the downstream river
- HPP with limited or sensitive grid where accidental fallout is likely to be more frequent.

Automatised bypass flow solutions are an valuable additional measure in addition to other hydropeaking mitigation or baseflow requirements. We found that potentially, more than 600 HPPs with river outlets in Norway may need well designed and operated BPVs or other measures to mitigate severe stranding of riverine biota. Globally, this mitigation type seems to be overlooked in assessments of many regulated rivers downstream HP tailraces.

We found that BPVs are installed in more than 109 HPPs in Norway, which is less than 20 % of the HPPs with tailrace into longer rivers of the Norwegian HP portfolio. BPVs are most widely implemented in small to medium scale (< 10 MW) HPPs in Norway licenced after 2009, with turbine capacities less than 4 m^3/s. The authors have documented malfunctioning/design or operational issues with the configuration of every BPV in operation as part of all the small scale HPPs investigated as part of this study and have further introduced a novel cost-efficient formula for ecologically adjusted configurations of BPVs. As other HP related mitigation measures, ecological efficiency needs to be documented to meet good practical standards. Hence, evidence-based management routines are needed to be adopted in small scale BPVs. In larger scale HPPs (> 10 MW), BPVs with discharge capacities of up to 44 m^3/s have been in operation for several decades, and recently have been adopted as requirements in re-licensing of several old HPP schemes in Norway.

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Conflict of Interest

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

JHH; Conceptualization; design and analysis; data curation, Visualisation; Investigation; Methodology, Validation, Writing - original draft.**,**

EN; Investigation; Developed the method for BPV operation**,** Writing – review,

KV; Investigation; developed the method for BPV operation**,** Writing – review

JHL-L; Conceptualization, Investigation, data curation, Writing – review**,**

KA; Supervision, Conceptualization, Visualization, Writing - review & editing

Tables

Table 1. Key characteristics of HPPs with small scale BPVs used in the development of a BPV optimization tool. RoR – mainly brook intake, Stor; Storage reservoir. Two values in the Baseflow column indicate winter – summer environmental flow requirements.

	HPPs									
		Energy		Head	HP	Max Q	River	Baseflow	BPV	
No	Name	MW	GWh	(m)	type	(m^3/s)	km	(m^3/s)	m^3/s	% max
	Bele	2.9	8.64	379	RoR	0.94	< 1	0.05 – 0.09	0.25	27 %
	Gryta	1.49	4.6	223	RoR	0.8	1-2	0.02 – 0.1	0.8	100 %
	Brandåa	3.94	15.8	373	Stor**	1.3	2-5	0.1	0.65	50 %
	Sundli	1.35	5.3	208	Stor***	0.846	2-5	0.03	0.42	50 %
	Sya	1.2	4.9	193	RoR	0.78	> 10	0.02 – 0.05	0.39	50 %
	Tua	1.8	4.9	132	RoR	1.55	< 1	0.04	0.77	50 %
	Knutfoss	4.85	16.5	60	RoR	9.9	2	0.4	4	40 %
	Tverrelva	4.98	18.5	492	Stor*	1.18	2-5	0.035	0.59	50 %
	Gjønaelva	3.2	10.1	239	RoR	1.64	< 1	0.02 – 0.13	0.8	49 %
	Skyggeelva	4.76	14	-	RoR	1.6	< 0.5	0.03 – 0.1	0.8	50 %
	Kvamselva	2.67	8.8	247	RoR	1.3	1-2	0.05 – 0.09	0.57	44 %

Notes: * (Volume: 0.59 m^3, Height: 1 m),** (- , 1 m), ***(4 mill m^3, 1 m)

Table 2. Key characteristics of all HPPs > 10 MW and smaller storage HPPs with BPVs requirement in Norway (www.nve.no). Level of hydrological mitigation and length of downstream rivers sorted with the longest downstream rivers impacted first.

*Explanations: **Base flow**; No Eflow¤; no min eflow required, but residual flow from unregulated trib. Key fish species: **Anadr: anadromus** species: Atlantic salmon, brown trout and in some Arctic charr , **Gray**: grayling, **L trout** – Large (lake) brown trout, **NSR** – National Salmon Rivers ; ORR – Operational Ramping Restrictions*

								Baseflow			
		Cap	Head	HP	BPVs and ORR			(m^3/s)		River ecology	
Hydropower-plant					Year -						fish
(no-name)		MW	m	Qmax	install	Qmax	ORR	High	Low	km	spp
455	Tryland	5	133	4.75	-		No	0.22		> 10	Anadr
1060	Ålgård	0			-	2.25	No	No Eflow¤		> 10	Anadr
204	Kjosfoss	4	97	4.69	-		No	0.7		> 10	Anadr
35	Borgund	212	874	28	1974	12	Yes	10		> 10	NSR
557	Stuvane	38	156	28	1988		Yes	10		> 10	NSR

1578	Sya	1	193	0.78	2009	0.39	Yes	0.05	0.02	> 10	
619	Meråker	87	264	36.7	1994		Yes	9.5		> 10	NSR
3	Alta	150	185	96	1987	33	Yes	45	16	> 10	NSR
1949	Tolga	46	88	60	2021	7	Yes	12	7	> 10	Gray_trout
1739	Eiriksdal	80	570	16	2013	6	Yes	6	1.5	5-10	Anadr
47	Brulandsfoss	13	20	78	-	8*	No	Turb_flow		5-10	Anadr
63	Driva	140	566	30	1973	10	Yes	11		5-10	NSR
454	Trollheim	127	400	38	2011	30	Yes#	15 (5)		5-10	NSR
40	Brattset	80	269	36	1982	10	Yes	20	10	5-10	NSR
298	N. Røssåga	350	244	165	2022#	30	Yes#	15		5-10	Anadr
24	Bjerka	20	357	6.6	-		Yes	0.23	0.3	5-10	Anadr
1875	Tverrelva	5	492	1.18	2017	0.59	Yes	0.04		2-5	Anadr
241	Leinafoss	5	54	10.02	-	0.7	Yes	3 (summer)		2-5	Anadr
1382	Øyadalen	2	409	0.59	2008	0,18	No	0.06	0.01	2-5	Anadr
1544	Brandåa	4	373	1.3	2009	0,65	Yes	0.1		2-5	Anadr
1814	Sundli	1	208	0.846	2015	0,42	Yes	0.03		2-5	Anadr
1424	Skromma	2			2008	1	Yes	0.15	0.1	2-5	Anadr
210	Kongsfjord I	4	71	7.28	1946?	??	No	3	0.9	2-5	NSR
1815	Ø Forsland	9	155	7.04	2015	1	Yes	1	0.2	2-5	
1818	Storvatnet	2	103	2.6	2015	0.5	Yes	0.1		2-5	Anadr
253	Lovik	1	92	1.79	2021		Yes#	No Eflow¤		2-5	Anadr
1372	Gautvella	2	285	0.73	2007	0.4	Yes	No Eflow¤		1-2	Anadr
1738	Fossan	5	174	3.35	2013	2.42	Yes	0.5	0.2	1-2	Anadr
-	N. Jølstra	60	131	55	2021	45	Yes	12	4	1-2	L. trout
1543	Hopselva	5	161	3.3	2010	1.65	Yes	0.25	0.18	< 1	Anadr
1563	Gamle Tyin	49	688	8.8	2014		Yes	0.3		1-2	Anadr
1678	Bele	3	379	0.94	2013	0.25	No	0.09	0.05	< 1	Trout
1757	Venna	3	183	1.8	2013		Yes	0.05		< 1	Trout
1746	Voldsetelva	5	140	4.7	2013	2.5	Yes	0.17		< 1	Trout
1708	Forsanvatn	9	254	4	2013	0.4	No	0.4	0.2	0	Trout

 # new requirements regarding installation of BPVs and operational restriction on flow ramping

Table 3. Ecological impacts from stranding events related to accidental shutdowns of river flows downstream the Trollheim HP with tailrace into ca 19 km of River Surna (Halleraker et al., 2005; Forseth et al., 2009; Ugedal et al, 2013).

Factor	**Date** **unit**	**2005-08-25 (daylight)**	**2008-07-27 (daylight)**	**2012 – 04-09 (daylight)**
Discharge (m^3/s)	From	46	21	43
	To	9	3	9
	△Q	-37	-18	-34
Dewatering speed	cm/hr	54 cm/hr	< 20 cm/hr	10-29 cm/hr
Total dewatered area from outlet to the sea	m^2	194 000	270 000	312 800
	m^2/km river	10 211	14 211	16 463
	% of all reaches	17%	26 %	25 %
Stranded Atlantic salmon #	0+ no (% of pop.)	17 600 (11%, 5-22%)	7 900 (4 %)	15 400 (7 %)
	1+ and larger (% of pop.)	2 200 (6%, 1.5-13 %)	2 100 (7%)	1 500 (1,9%)
Stranded brown trout #	0+ no (% of pop.)	9 100 (8%, 4-17%)	7000 (1%)	10 900 (13,6%)
	1+ and larger (% of pop.)	700 (3 %, 0-6 %)	Not estimated	Not estimated
Total juvenile population	median	29 600	> 17 000	> 28 000
Salmon smolt eqv. loss	Median (min-max) no (% of pop.)	2600 (1000 - 5600) (1,5 - 2 %)	3000 (< 3 %)	4700 (11 %)

Table 4. Examples of dewatering events related to accidental shut down of turbine flow in various Norwegian rivers. Dewatered area and dewater speed are derived from grey literature, various data sources and detail level. Sources; Sægrov et al. (2014; 2020); Bernardo (2017). unpublished material in the Jølstra court case (Harby pers com).

River (km impacted)	**Date**	**Discharge (m3/s)**		**Delta Q (m3/s)**	**Dewatering speed**	**Total dewatered area - of each river down to outlet into the sea**			**Habitat assessment**
		From	**To**	**(diff)**	**cm/hr**	**(m2)**	**m2/km river**	**% all reaches**	method
Jølstra (4.5 km)	2009-06-30 (d)	54.1	17	-37.1	90	52 000	**11 556**	24 %	Transect data at various Q
	2013-01-22 (d)	18.5	7.1	-11.4	26	58 000	**12 889**	34 %	
	2014-02-21 (d)	10	4	-6	46	68 000	**15 111**	48 %	
Røssåga	2016 -11-21 (d) Worst case test	90	15	-75	38-82	17 216		10 %	Picture from motion - drone pictures at relevant Qs
Brandåa (0.15 km)	Without BPV (worst case test)	1.3	0.08	-1.22	73 - 280	330	**2 200**	38 %	HEC-RAS
Gloppen (>3 km)	2017-11-12 (d) (grid failure)	30	5	-25	5 - > 30	-	**-**	Ca 35 %	Transect data at various Q after the end design method