Modelling winter operational strategies of a hydropower system

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Abstract

The ice conditions in regulated rivers can be very complicated due to both intake and release of water to and from hydropower plants. The optimal operational strategies for the hydropower system must involve ice management in the river basin and finding a balance can be a challenge for the hydropower operator. Issues with ice occur during both freezeup and breakup, and at certain conditions both situations can occur in a basin at nearly the same time. In this study, a series of modelling tools have been used to investigate the consequences of a forced shutdown of a power plant in the Orkla river. The associated impacts on the stability of the ice cover in a downstream bypass reach and the ice and ecological conditions in the reaches upstream of the power plant have been explored. The reason for this is restrictions on upstream water releases during the shutdown period given in the regulation permit to prevent ice breakup in the downstream bypass reach and subsequent flooding problems downstream. The study demonstrates a wide application of numerical tools for environmental impact assessment, providing knowledge for better decision-making and for optimal operational strategies for hydropower systems during winter.

In summary, the analysis shows that a shutdown period shorter than the travel time of water from the upstream hydropower plants to the bypassed reach does not guarantee a reduction of the ice problems in the bypass reach. Since the intake pond is too small to store already released water from the upstream power plants, spill and ice breakup will occur. It is rather found that a shutdown of the upstream power plants can induce environmental problems due to the rapid dewatering of the river, and an ice breakup during the restart of the upstream power plants.

1. Introduction

The interaction between hydropower generation and river-ice is a complex process which is determined by climatic conditions, river morphology and hydropower operational strategies. In regulated catchments, changes of the flow regime, the thermal regime and the river ice regime are often observed (Tesaker, 1990; Gebre et al., 2013). Downstream of power plant outlets, warm water release from reservoirs leads to long reaches of open water which are ice covered under natural conditions (Timalsina et al., 2013). On the contrary, bypassed reaches often have a small environmental flow and freezeup completely and form a stable ice cover during winter. Open river reaches and openings in the ice covers are sources of increased frazil ice generation during cold periods. Thus, frazil formation episodes are increased downstream of hydropower outlets in regulated rivers compared to a natural case (Stickler and Alfredsen, 2009; Timalsina et al., 2013). As reported by Wigle et al., (1990) and

Gebre et al. (2013), a number of problems related to ice might occur for the operation of hydropower systems from freeze-up to break-up. Furthermore, formation of ice and changes in the ice regime can influence the river ecology (Morse and Hicks, 2005; Prowse et al., 2011), the utilization of the river and it can also be a threat for structures in and along the river (Beltaos, 1995). Therefore, most regulated rivers have operational constraints during winter to prevent excessive ice effects in the river (Wigle et al., 1990; Asvall, 2008; Gebre et al., 2013). However, such constraints could have impacts on other parts of the river system and a balance of operational strategies and corresponding effects must be assessed to take care of all objectives and to optimize the outcome for all stakeholders.

The Orkla river in middle Norway (Figure 1) has a history of ice production which was important for the planning of the hydropower system (Kanavin, 1974). After the regulation the ice regime downstream of the hydropower outlets show a marked change, and the combination of outlets and bypass reaches makes this a complex ice environment. Of particular interest is the reach from the Brattset outlet down to the Svorkmo outlet that is both important for hydropower production and important as habitat for Atlantic salmon.

The regulation permit states that if the Svorkmo power plant is shut down suddenly due to an operational failure, the upstream power plants at Brattset and Grana should reduce or stop their production immediately to prevent water from spilling the Bjørset dam and into the reach below. The main reason for this constraint is to prevent an ice breakup and the formation of ice jams in the bypassed reach downstream of Bjørset dam due to the sudden flow increase from spilled water. Once Svorkmo is restarted, the upstream power plants can also be started again. Most of the documented shutdown events at Svorkmo show a duration of less than two hours (Hiller et al., 2010), which is shorter than the travel time of water from the plant outlets at Brattset/Grana down to the Bjorset dam. Therefore, a shutdown of the upstream power plants as a response on a production stop in Svorkmo may not prevent an ice breakup and a possible ice jam flooding in the bypass reach since water already released from the upper plants at the time of Svorkmo shutdown will inevitably spill the dam. Moreover, the reach upstream of Svorkmo intake will experience a sudden drop in water level inducing rapid dewatering and drying of living areas for fish and invertebrates. Further, in cold periods with low residual flow a freezeup and subsequently breakup at the restart of the upper power plant can be a consequence of the production stop. As the water takes time to reach the Bjørset dam from the upstream hydropower outlets after a restart, a delayed restart of Svorkmo power plant will result in revenue loss. The current requirement given in the operational permit is based on a theoretical assessment with the aim at avoiding unfavorable ice conditions in the bypass reach downstream of the Bjørset dam. However, no scientific assessment of the effects of this operational constraint on the upstream river reach has been made.

With this background, a quantitative evaluation of the consequences due to the sudden stop/start of the power plants has been assessed. This paper illustrates the balancing act between power production, ice management and the mitigation of ecological impacts in the regulated river Orkla during winter. The presented assessment strategies and methods to evaluate the impacts on both ice and winter ecology can be extended and applied to similar problems in different rivers.

2. Materials and Methods

2.1 Study site

The Orkla hydropower system was put into operation in 1983 and consists of five hydropower plants with a total installed capacity of 320 MW. The water storage and transfer system also consists of three large reservoirs and several brook intakes, which have a considerable impact on the hydrological, thermal and ice regime of the river. The catchment has an area of 3,053 km2 and an average annual discharge of 70 m^3s^{-1}. The river is designated as a national salmon river and the protection of the Atlantic salmon stock is a priority for the river management.

This study focuses on the reach from Brattset outlet to Bjørset dam where the Svorkmo intake is located, and on the bypassed reach downstream of Bjørset dam. The Brattset-Bjørset reach is strongly dominated by production flows in the range of 20 - 60 m^3s^{-1} released from the Grana (20 m^3s^{-1}) and Brattset (40 m^3s^{-1}) power plants. As result of the warm production water coming from the reservoirs, the reach has a variable ice regime during winter. The bypassed reach has a stable ice regime and a minimum flow release of 4 m^3s^{-1} during the winter period.

2.2 Design of the flow scenarios

The investigated flow scenarios used in this study were developed based on the winter hydropower operational constraints outlined in the regulation permit, which is described by Hiller et al. (2010). Their study considered the period 1985-2010. During this period the power plants stopped 36 times, of which 29 times the duration of the shutdown was between one and two hours. Using this information, the scenarios to be investigated were developed based on a set of shutdown durations of the Svorkmo power plant and the compulsory shutdown of the upstream power plants Brattset and Grana. The considered shutdown durations for Svorkmo were 2, 5, 10, 15 and 24 hours. The current minimum flow requirement in the reach downstream of the Brattset outlet is 10 m^3s^{-1}, but since the regulation permit does not clearly define if the minimum flow should be released in the case of a shutdown in Svorkmo, both scenarios with a full stop and thereby a residual discharge of 0.5 m^3s^{-1} (SC_A) and scenarios with a minimum flow release of 10 m^3s^{-1} (SC_B) were developed.

2.3 Ice breakup and flooding potential

During the illustrated shutdown scenarios in Table 1, water spills the Bjørset dam when Svorkmo power plant is shut down. The spilled water flow into the bypassed reach during these events is considerably larger than the minimum flow of 4 m^3s^{-1}. Therefore, the potential for ice breakup and the flooding potential in the bypass reach must be assessed. The breakup is evaluated based on the empirical method developed by Beltaos (1997). The flooding potential due to a formation of ice jams in the case of breakup was assessed using the HEC-RAS hydraulic model (Beltaos et al., 2012).

2.3.1 Ice breakup evaluation

In the literature, the onset of ice breakup has been tested using empirical and semi-empirical methods with an aim to generalize the involved processes and to make parameters transferable to other sites. In this study, the empirical method described by Beltaos (1997) has been used to assess the possibilities for breakup. This method has been previously tested and applied in a small stream in Norway (Heggen and Alfredsen, 2013). The empirical method by Beltaos (1997) states that:

$$H_B - H_F = Kh_{i0} - F(S_5) \qquad (1)$$

Where H_B is the water level at which the ice cover starts to move; H_F is the freeze-up water level, K is a dimensionless site-specific coefficient, h_{i0} is the ice cover thickness prior to the start of the breakup and the function F is a site specific function. F has the dimension of length and by definition F(0) = 0 (Beltaos, 1997). S_5 is an index of accumulated heat input to the ice cover, defined at a base air temperature of -5^{0}C.

Measurements of ice thickness downstream of the Bjørset dam are missing, therefore a wide range of thicknesses have been used to compute a range of resisting factors. These thicknesses are compared to measurements taken in nearby streams during the winter of 2012/2013 that are within a realistic range. Since it is difficult to validate the parameters due to a lack of observations in the reach, the second term of the right hand side of the equation is neglected. By doing so the method gives a higher resisting factor which will be compensated by a lower value of K. Based on the water levels at a freeze-up and break-up event in February of 2007 recorded at the Storsteinhølen gauge located just downstream of Bjørset dam, a value for K was determined and calibrated. The air temperature measured in the field on the day of breakup was -2.9^{0}C and accumulated degree-day factor was 60^{0}C-days. The thickness of the ice was estimated based on the Stefan formula (Comfort and Abdelnour, 2013). An ice growth coefficient of 2.7

$mm^{0}C^{-1/2}day^{-1/2}$ has been taken from a previous study conducted in nearby streams (Heggen and Alfredsen, 2013), which yielded a thickness of ~21 cm.

2.3.2 Flood potential due to breakup jams

During the observed shutdowns of Svorkmo power plant, ice jams have been observed in the bypass reach, particularly at Svorkmo (Hiller et al., 2010). Based on the damage potential of an ice jam flooding, the ice jams directly upstream of Svorkmo outlet were selected for modelling. A comparatively milder slope in this area, low flow velocity and an accumulation of incoming ice discharge reduces the ice transport capacity and creates ice jams at this location. There are two types of ice jams reported in the literature, the narrow and the wide river ice jams. However the distinction between these two is unclear (Beltaos, 1995). Therefore both types of ice jams have been considered for the analysis.

A 1D HEC-RAS model was set up for the Svorkmo area for ice jam modelling. The cross sections were obtained from the Norwegian Water Resources and Energy Directorate (NVE) and originally used for flood map calculations. The geometric data covers the reach from Svorkmo bridge (cross-section CS_46, Figure 3) to the Svorkmo power plant outlet further downstream. Ice jam measurements from a breakup and jam event that occurred after a spill event in 2007 show that the ice jam was starting just downstream of Svorkmo Bridge. Therefore, additional cross sections were added upstream of the bridge by combining field GPS measurements with the digital elevation model of the area. Extra cross-sections were interpolated with a maximum distance of 50 m from the measured data.

A static intact ice thickness of one meter has been used at a cross-section located close to Svorkmo outlet to define the downstream toe of the jam. At the head of the jam upstream, a static intact ice thickness of four meter has been used. The ice jam configuration is based on observations from the 2007 event. The applied HEC-RAS model is able to predict an ice jam level comparable to the measurements made by NVE in 2007 when running with a constant flow of 4 m^3s^{-1}. The ice jam at Svorkmo area was created during a flow of 70 m^3s^{-1}, and the sudden flow reduction to 4 m^3s^{-1} points in the direction of a grounded ice jams as discussed by (Beltaos, 1995).

Two types of scenarios for ice jam floods have been evaluated. The first scenario considered a static ice jam with a measured ice jam extent and estimated the flood potential with a flow of 70 m^3s^{-1}. The second scenario also estimated the flood potential with a flow of 70 m^3s^{-1} and a measured ice jam extent, but added an additional influx of ice from the upstream river reach. The Manning coefficient depends on the types of accumulations: Loose slush, dense slush and ice floes. For the analysis, different Manning coefficients for loose slush and dense slush have been used. The details of the parameters for the ice jam flood simulations are shown in Table 2.

2.4 Consequences for the Brattset-Bjørset reach

2.4.1 Computation of dry areas and stranding potential

To estimate the dewatering of the river reaches for the different shutdown scenarios and thereby the potential for stranding of fish, spawning sites and invertebrates, a HEC-RAS hydraulic model (Brunner, 2010) was applied. HEC-RAS was chosen due to previous experiences with using the model for stranding studies (Casas-Mulet et al., 2014). The same cross-sections as for the ice simulations and a time resolution of one hour were used. It is worth noting that the uppermost part of the river contains a long section of interpolated cross sections, which perform well for the hydraulic modelling but for a detailed assessment of dried out areas they may not be as accurate as the measured cross-sections. The model was calibrated against measured water levels for one discharge (36 m^3s^{-1}) collected in the field using a Leica RTK-GPS, and the ability to reproduce flow dynamics was calibrated against the observed discharge hydrograph from the Syrstad gauge for a period of two years. For all simulations with HEC-RAS and MIKE-Ice we used the Nash-Sutcliffe coefficient of efficiency R^2 (Nash and Sutcliffe, 1970) as a measure of goodness of fit. With few exceptions, differences between simulated and observed water level were within centimeters. The exceptions occurred at locations where interpolated cross sections were used, which mean a few cross sections must be handled with care in the further assessment. The model fit well with the observed flow hydrograph, giving a R^2 equal to 0.82. For more details see Beckers (2014). Based on the hydraulic simulations, the stranding potential was described using three metrics, the dried out width of the cross section, the dry down speed and the duration of dry areas The dried out width gives us the amount of dry areas for any given time in each cross section computed by subtracting the top width of the water surface at a certain stage from the top width at full flow. By extrapolation between cross sections we can compute the total dry area of the reach. This metric provides the magnitude of the shutdown event. The dry down speed provides the rate of reduction in water level per hour and is evaluated against a defined critical level for stranding (Harby et al., 2004). This metrics provides us with a measure of stranding risk. The duration of dry areas provides the duration of the dry period, a parameter that is particularly important in winter when frost is critical for stranded juveniles or eggs. The three parameters were computed using a script in R and Microsoft Excel (Beckers, 2014). The effect of frost on the dried out areas has been estimated using a simple energy loss assessment based on air temperature scenarios.

2.4.2 Ice conditions

The ice conditions have been simulated for both possible minimum flows (0.5 m^3s^{-1} and 10 m^3s^{-1}) using the Mike-Ice model (Thériault et al., 2010). Mike-Ice simulates the hydrodynamics, water temperature, frazil ice formation, transport of frazil and surface ice, ice cover formation from border ice progression and the juxtaposition of drifting ice and thermal ice cover retreat. The Mike-Ice model was calibrated and validated for the reach from the Grana outlet to the Svorkmo intake. The evaluation was based on observed flow at Systad gauge, water temperature measured at several locations and observed ice from field campaigns and time-lapse cameras. The discharge comparison gives a R^2 of 0.79, and water temperature shows an average R^2 of 0.81 over all locations. Furthermore, it was observed that the model managed to predict both the development of ice cover and the presence of drifting frazil ice with good accuracy. A more detailed description of the model and the Orkla setup can be found in Timalsina et al. (2013). The calibrated model has been extended up to Brattset outlet and used to study the ice conditions of the entire reach from Brattset outlet to Svorkmo intake.

The scenarios presented in the previous section are used as input hydrographs for the simulation. The water temperature input at the upstream boundary (at the Brattset outlet) was taken as 1.0^0C based on measurements at the Brattset outlet. For simulations of ice formation we have used constant air temperatures of -10^{0}C, -20^{0}C and -30^{0}C combined with the flow scenarios. A measured water level at Bjorset dam is used as the lower boundary condition.

3 Results

3.1 Ice break-up in the bypass reach

The results suggest that the driving force computed from the measured water level at Storsteinhølen is higher than the stabilizing force for the full range of possible ice thicknesses and values of K (Figure 2). Therefore, based on the measurement made during the ice jam in February 2007 it can be concluded that the full production flow of 70 m^3s^{-1} will break-up the ice in the bypass reach at all reasonable ice thicknesses.

3.2 Flood potential from ice jams

The HEC-RAS simulation both on static ice with and without influx of ice floes from upstream show that there is minimal flooding potential due to ice jams in the study area. The inundation map shows minimal flooding in the Svorkmo area with dense slush type accumulation of the ice jams (Figure 3).

3.3 Dewatering and stranding in the upper reach

Figure 4 a) and 4 b) shows the dried out width for the five shutdown scenarios for a minimum flow of 10 m^3s^{-1} and 0.5 m^3s^{-1}, respectively. A similar pattern of variation in dried out width is seen for both situations with the largest impacts in the region from Syrstad to the village Å (10 km upstream of Bjørset dam). This indicates that the areas of the river with the highest total stranding risk do not change dependent on the scenario or minimum flow. For the situation when the river is lowered to 0.5 m^3s^{-1} we see an increase of dried out width can be seen over the entire river which is most pronounced in the upper part of the river. It can also be seen that the 24 hour stop leads to a significant larger dried out width at some cross sections, particularly in the lower river at the lowest minimum flow. Figure 5 shows the dry down speed summarized for all scenarios and minimum flows, and shown for areas upstream and downstream of the Grana outlet. A critical value for the dry down speed for stranding of juvenile Atlantic salmon of 0.13 m/hour found from experiments (Harby et al. 2004) is shown on the figure as a dotted line. It is seen from this that critical dry down speeds are frequent in the river upstream of Grana outlet for both scenarios, but less evident in the reach between Grana outlet and Bjørset dam. But critical cross-sections are still found in the lower river which are critical. It is also worth noting that the duration of the stop has very little impact on the distribution of critical dry down speed.

Figure 6 a) and 6 b) shows the duration of dry areas for the two minimum flows for all the five shutdown levels, ergo for all scenarios. For the shorter duration shutdowns, longer durations of dry areas are mostly seen in the upper river for both minimum flows, so the duration of power plant shutdown has a large impact on the duration of dry area as expected.

3.4 Freeze-up in the upper reach

The simulation results from Mike-Ice shown in Figure 7 demonstrate that ice forms in the reach between Brattset outlet to Bjørset dam nearly immediately after the power plants shut down during cold conditions. The results shows that the ice cover length in the reach varies widely and that it depends on the minimum flow of the scenarios, the stoppage duration of the power plants and the surrounding air temperature. For the scenarios with a minimum flow of 0.50 m^3s^{-1}, an air temperature of -10^0C and a shut down duration of 2 hours, about 5% of the river reach is ice covered. Whereas an air temperature of -30^0C and a shut down duration of 24 hours shows that 95% of the reach is ice covered (Figure 7, SC_A scenarios). Similarly, for the scenarios with a minimum flow of 10 m^3s^{-1}, an air temperature of -10^0C and a shut down duration of 2 hours, about 2% of the river reach is ice covered. With an air temperature of -30^0C and a shut down duration of 24 hours about 42% of the reach is ice cover (Figure 7, SC_B scenarios).

In addition, the results indicate that the quick start of the Brattset and Grana power plants can induce ice breakup in the scenarios with a minimum flow of 0.5 m^3s^{-1} (Figure 7, SC_A). The breakup is most pronounced during long shut down durations and low air temperatures.

4. Discussion and Conclusion

The purpose of the current shutdown requirement of the river Orkla is to mitigate the ice problems in the bypass reach downstream of Svorkmo intake and Bjorset dam. The study reveals that this requirement does not prevent an ice breakup in the bypass reach. The findings indicate that ice breakup occurs for all tested shutdown scenarios since water from the upstream river reach is directed into the bypass reach even if a shutdown is carried out. As a result, a shutdown of the upstream hydropower plants Grana and Brattset due to an accidental shutdown of Svorkmo has no mitigating effect on the ice breakup in the bypass. It may only reduce ice problems if the duration of the stop in Svorkmo is longer than the travel time of water from the upstream hydropower plants to Bjørset dam where the intake to Svorkmo is located. The assessment of the flooding potential induced by an ice jams in the Svorkmo area shows that there is a low flooding potential when considering both wide and narrow jams. A large impact on the river occurs in the reach upstream of Bjorset dam. During a shutdown, the suddenly decreasing flow discharge induces a rapid drawdown of the water level with a potential to dry out large areas of the riverbed. This can be detrimental to Atlantic salmon in the reach due to stranding of fish and dewatering of spawning sites (Saltveit et al. 2001; Scruton et al. 2008, Casas-Mulet et al. 2015). Furthermore, during a shutdown event the ice production in the reach is increased. The formed ice can break up and move downstream when the power plants are put back to normal operation. This can cause significant dynamics in the stream with similar consequences as reported by Billfalk (1992).

In the case of shutdown periods of Svorkmo of more than 4 hours, further investigations of the ice breakup and transport of ice floes in the bypass reach using numerical modelling tools are recommended. This investigation already helps to identify the critical area of ice jams and potential flooding. Moreover, a continuous operation of the Brattset power plant while shutting down Grana power plant completely may help to minimize ice problems in the Brattset - Bjørset reach as well as in the bypass reach. The reason is that the distance from Grana outlet to Bjørset dam is comparatively shorter than from Brattset outlet to Bjørset dam and ergo the travel time of water is less. However this option is not explored in this study and detailed investigations are recommended. In addition, a sudden stop of Svorkmo can also create dynamic behaviour downstream of the Svorkmo outlet, which can induce ice formation and breakup in a similar manner as seen for the Brattset – Bjørset reach.

This study demonstrates how winter operational strategies of a hydropower system can be evaluated and designed based on a numerical modelling study of the ice processes in a river. The current practice to evaluate ice-hydropower interactions in cold regions is often based on conservative strategies and on experience. With the application of numerical models that have been developed and tested recently, the experience based assessment can be augmented with more data and provide a better what-if analysis which strengthens the decision making strategies.

The main challenge of implementing the modelling strategy is a lack of data. Hence, it is recommended to improve the collection of ice data in rivers where ice is an issue, e.g. by continuous camera surveillance of critical areas. This would greatly enhance the capability of the modelling approaches.

The conclusion of the current study is that a sudden shutdown of the upstream hydropower plants as a response on an accidental shutdown of Svorkmo power plant, does not prevent ice break-up in the bypass reach but has potentially large impacts on the environment and the ice conditions in the upstream river reach (Brattset – Bjørset). For shutdowns of more than 4 hours, the impacts in the bypass can be mitigated but the problems and impacts in the upstream reach (Brattset – Bjørset) remain and even increase.

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Table 1: Different flow scenarios based on Svorkmo shutdown durations and minimum flow releases from Brattset outlet.

Flow Scenario	Svorkmo shutdown durations [hours]	Grana and Brattset shutdown	Minimum flow downstream of Brattset outlet $[m^3s^{-1}]$	
			SC_A	SC_B
1	2	Yes	0.5	10
2	5	Yes	0.5	10
3	10	Yes	0.5	10
4	15	Yes	0.5	10
5	24	Yes	0.5	10

Table 2: Selected and calibrated parameters for ice jam modelling at the Svorkmo site. Notes: [*]Model generated as function of ice jam, [**]Loose slush/Dense slush, [***]Sui and Karney (2005), [****]Simulated only for the static ice jams

HEC-RAS parameter	Scenario 1		Scenario 2	
Discharge [m^3s^{-1}]	4	70	4	70
Simulation purpose	Calibration	Flooding	Calibration	Flooding
Inflow boundary condition (normal flow depth, NFD)	NFD	NFD	NFD	NFD
Manning coefficient river bed	0.035 - 0.030	0.035 - 0.030	0.035 - 0.030	0.035 - 0.030
Manning coefficient ice sheet	-	-	0.02	0.02
Manning coefficient below ice jam	0.04	0.04/0.07[**]	Model[*]	0.04/0.07[**]
Thickness of intact ice sheet at cross section #. Measured as ice sheet elevation in m.a.s.l.	44: 36.75 43: 34.25		44: 36.75 43: 34.25	
Angle of jam	45^0	45^0	45^0	45^0
Initial ice thickness [m]	-	-	0.1	0.1[***]
Porosity of rubble comprising the jam	0[****]	0[****]	0.4	0.4
Lateral to longitudinal stress (Beltaos, 2012)	0.33	0.33	0.33	0.33
Max allowable flow velocity underneath [m/s]	1.54	1.54	1.54	1.54

Figure 1. Study area in the Orkla basin.

Figure 2. Potential ice break-up study at Bjørset- Svorkmo reach, the whole horizontal line shows the driving force (H_B-H_F), the dotted horizontal line is the idealized onset of ice breakup. The arrow indicates the ice thickness estimated for the calibration case.

Figure 3. Inundation map of ice jam study; the blue transparent color stands for the flow of 70 m^3s^{-1} and type 2 accumulation. The black rectangles in the maps are building/houses in the area. The black lines show cross-sections used in the model. The hatched red region is the analyzed static ice jam extent

Figure 4. The dried out width of the river reaches from Brattset outlet to Bjørset dam. Upper panel (a) shows a minimum flow of 10 m^3s^{-1} at Brattset outlet, and the lower panel (b) shows a minimum flow of 0.5 m^3s^{-1} at Brattset outlet.

Figure 5. Dry down speed upstream and downstream of Grana power plant for all the scenarios and both minimum flow of 10 m^3s^{-1} (labeled B) and 0.5 m^3s^{-1} at Brattset outlet. A box in the plot represents dry down speed from all the cross-sections divided into two groups, upstream (US) and downstream (DS) of the Grana power plant. The horizontal dashed line represents the critical threshold value 0.13 m/hour referred from Harby et al. (2004). The boxes represent the inner quartile with median marked. Whiskers are at 1.5*inner quartile range, and the open circles show outliers.

Figure 6. Duration of dry areas at the reach between Brattset outlet and Bjørset dam. Upper panel (a) shows a minimum flow of 10 m^3s^{-1} at Brattset outlet and the lower panel (b) shows a minimum flow of 0.5 m^3s^{-1} at Brattset outlet.

Figure 7. Mike-Ice results: Percentage of river reach covered with ice, for various scenarios based on the Svorkmo shutdown duration and the remaining minimum flow in the reach downstream of Brattset and different air temperatures (Ta). The vertical dotted line displays the moment when Svorkmo power plant shuts down. The lead time is assumed to be 20 hours. The line marked Sc_0 in the figure show the ice forming process without a stop in the power plants, and the others shows ice formation during the different shutdown scenarios given in Table 1.