Modelling ice effects on head loss at hydropower intakes

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Ice induced head loss or blocking of intakes is a problem for hydropower production in cold climate. The problem spans frazil accumulation on trash racks to accumulation of broke ice on intakes, and happens both on small and large hydropower installations. This can be a costly problem for the operator causing lost production and a need for mitigation measures during the winter period. In this paper the head loss at the Svorkmo intake in river Orkla is evaluated based on observed and modelled ice and climate variables. Head loss events are evaluated to find the driving factors, and a generalized linear modelling approach is used to identify the significant factors governing the ice blocking of the trash rack. At the Svorkmo intake it is observed that significant head loss is not only related to typical cold periods with high frazil production, but also warmer periods without super cooled water conditions can have significant head loss. This can be due to drifting ice in the form of released anchor ice or frazil flocs reaching the intake or a lag in the removal of ice deposited during the cold period. The results from the statistical analysis show that there are no simple linkages between the variables available for the site and the observed head loss, and that accumulated effects has the strongest influence on the head loss. The prediction provides reasonable results, but they vary over the different head loss generating periods which indicate that other factors than the ones available for this study is needed. This work has identified the need to detail the data for the intake site to be able to understand the details in the ice formation.
1. Introduction

Ice creates problems for hydropower operation in cold climate (Gebre et al. 2013), and one of the more severe issues is clogging of intakes. This can be caused by clogging at break-up or from release of anchor ice, and by aggregation of frazil ice on trash racks in super cooled conditions. Aggregated ice on the intake can lead to total blockage and loss of both water and energy production, but also to increased head loss at the intake site and thereby lowered production from the hydro power plant. Vaskinn (2013) reported that ice caused the majority of reported problems at Norwegian small hydro plants, and of these blockages due to ice runs in the intake channel or at the trash rack accounted for around 60%, and frazil formation at the intake for 25%.

The accumulation of frazil on trash racks is one of the major sources of head loss on hydropower plants and occurs when frazil particles in super cooled flows adhere to the trash rack rods and eventually builds up a partial or full ice cover over the trash rack. Several studies exist in literature on the build up of frazil on intakes racks and analysis of driving factors behind intake clogging. Daly (1991) describes the process of frazil buildup on trash rack bars, and presents laboratory data on the relationship between head loss and time after the initiation of the freeze-up event. He also suggests mitigation measures to avoid clogging problems. Daly and Ettema (2006) presents blocking events at intakes in the Great Lakes, and shows how frazil events occurs in a lake environment and penetrates to the depths of the intake driven by cold temperatures and wind. They show the time pattern of head loss with a gradual buildup followed by a rapid increase as the trash rack is being blocked by ice. Andersson and Andersson (1992) report on results from a field experiment to record the ice accumulation on the trash racks of several Swedish hydro power plants. They combined underwater video to observe frazil with climate and flow data to find the conditions that cause trash rack clogging. They also looked at the effect of bar materials on the ice build-up. They observed frazil formation and adherence to the bars at a temperature of -4°C during a snowfall. Richards and Morse (2008) studied a drinking water intake in the St. Lawrence River by deploying an ice profiler on the river bottom and combining this with measurements and modelling data for climatic and hydraulic variables. They found that frazil blockage happened over a range of temperatures depending on other factors like tide and surface energy loss. With low tide and clear skies at night only a small negative temperature (-2.3°C) was required. They also found that super cooled conditions could last for a long time, thereby increasing the potential for blocking, and also that an increased amount of surface ice might not remove the super cooling of the water. Another issue that can create problems for intakes ice floes or other drifting ice like released anchor ice. Lokna (2006) describes the blocking of a mountainous hydropower intake due to ice runs, and estimated a cost of NOK 750,000,- for each day the intake is blocked. Similarly, Derrien (2005) describes the repeated blocking of a brook intake due to accumulation of drifting ice floes when ice break, an event that for this particular intake also happens mid-winter. For such intakes, remote locations and difficult monitoring and mitigation conditions during winter can lead to significant losses of water.

In this paper a series of measured head loss data from the intake of the Svorkmo power plant in river Orkla is analyzed against a combination of observed and modelled ice and climatic conditions in the river upstream of the intake to try to find relations that can be used to predict
head loss due to ice aggregation at the intake. Further, the mechanisms behind the blocking events observed at the intake are evaluated to differentiate the approach to estimate the head loss.

2. Materials and Methods

Study site
The Orkla river is located south of Trondheim in Norway (63°17’N, 9°5’E) and is regulated by a high head hydropower system comprising five power plants and three large reservoirs located in the mountains. The last power plant in the system, Svorkmo, has an intake in the main river and a total head of 99 meters (Figure 1). Svorkmo power plant operates on production discharge from the Grana (20 m³s⁻¹) and Brattset (40 m³s⁻¹) power plants upstream, and in winter the hydropower releases totally dominates the flow in this reach. The Svorkmo intake has a trash rack that is 33 m long and 3 m high with an opening between bars of 50 mm. The sections of the trash racks are 1 m wide and there are 10 openings pr. meter. In front of the intake there is a concrete skirt wall that has a primary objective of preventing salmon smolts from entering the intake.

The release of water from the Grana and Brattset outlet creates ice-free conditions, and when the water cool on the way to the Svorkmo intake, heavy formation of frazil and anchor ice in the reach upstream of the intake is experienced (Stickler and Alfredsen 2009). The intake has a history of problems related to ice formation (Carstens et al. 1992), and both mechanical removal of ice and operational constraints to create an ice cover on the intake pond have been employed to minimize the effect of ice formation.

Ice model
To simulate the ice formation MIKE-ICE (Theriault et al. 2010) was used for the reach from Grana outlet to the Svorkmo intake. MIKE-ICE is a process based 1-dimensional ice model integrated in the MIKE11 hydraulic model. Measured discharge and temperature at the outlet of the Grana power plant was used to drive the model, and the model was tested against discharge measured at Syrstad, water temperature from three different locations and ice observations mainly made using time lapse cameras and from field campaigns. For more details see (Timalsina et al. 2013).

Data
The head loss was computed from measured water pressure in the intake pond and in the tunnel just inside the intake collected by the operator Trønderenergi. Hourly continuous measurements were used to create a time series of head loss over the trash rack. The power company also records the production discharge for the turbines, which were used to compute the base head loss over the trash rack using the Kirschmer formula:

\[ h_f = K_1 \cdot K_2 \cdot \sin \alpha \left( \frac{b}{a} \right)^{3/4} \cdot \frac{v^2}{2g} \]

Where \( K_1 \) is a loss factor due to angled current, \( K_2 \) is a loss factor due to the bar shape, \( a \) is the angle of the rack, \( b/a \) is the ratio between the bar width and the opening between bars, \( v \) is the velocity through the gate and \( g \) is the acceleration of the gravity.

In addition to the simulated ice cover and frazil transport data data on ice cover formation at the Svorkmo intake pond were derived from a time-lapse camera setup (Moultrie Game Spy I-65S) a
few hundred meters upstream of the intake. Further, a similar camera was used at an open water section upstream to record days with frazil and drifting ice.

Climate data were collected from stations nearby, and the total and bypass discharge were collected from the Syrstad and Storstøinhølen gauges respectively. Water temperature was measured by using a Vemco minilog II. During the study period, detailed temperature data at a resolution that captures super cooling was not done, but previous measurements at a site located about a kilometer upstream of the intake site show frequent super cooling during winter in Orkla (Stickler and Alfredsen, 2009).

Analysis
Data collected from the season 2011-12 was used to try to establish linkages between river ice parameters and observed head loss at the Svorkmo intake. This period overlaps a time period where data on frazil transport at Hårræya further upstream and ice cover at the intake basin is collected, and when we have simulation results from MIKE-Ice for the river reach down to the Svorkmo intake (Timalsina et al. 2013).

The relationship between head loss and ice conditions in the river was modelled using generalized linear models (GLM, Zuur et al. 2009) to try to establish links between flow, climate and ice variables and the observed head loss. The general model will be on the following form:

$$y_i = n_i + x_i^T \beta$$

Where \( y \) is the head loss on day \( i \), \( n \) is an optional offset, \( x \) is a vector of climate, ice and hydraulic variables and \( \beta \) is a vector of model coefficients determined in the model fitting process. Potential significant variables were identified, and various models evaluated using both the Aikake Information Criteria (AIC) and measures of goodness of fit between observed and modelled results.

All analysis was done in R (R-DevelopmentCoreTeam 2011)

3. Results and discussion
Figure 2 shows the distribution of measured head loss over the hydrological year 2011-12 at Svorkmo and the corresponding discharge through the hydropower plant. A number of episodes with high head loss are seen during the cold weather period. The episodes observed in September, October and May is most likely caused by accumulation of debris at the intake. This is further seen on Figure 3, which shows that the head loss is particularly large in the cold months of the year, and in winter there is also a significantly number of situations with large head loss for discharges less than the full capacity of the turbine. Compared to the computed theoretical head loss for the trash rack, the observations are higher for most of the winter period.

Previous studies shows that frazil formation in Orkla has a diurnal pattern with the main growth during night (Stickler and Alfredsen, 2009), but a similar pattern is not seen in the head loss data shown in Figure 4. From these data we see a nearly even distribution of head loss over the day, and that episodes of high loss due to ice accumulation on the trash rack can happen at any time.

Figure 5 shows the time evolution of central variables measured and observed at the Svorkmo intake over the months January and February of 2012. The frazil amount and surface ice is
modelled with MIKE-ICE, and data is taken from the cross section closest to the intake pond. There is an uncertainty in the frazil amount since it is not verified against observations. The variable is used more as a measure of when frazil is produced in the river, which the model was able to predict with good accuracy, rather than a specific volume. The surface ice variable indicates if the cross section is covered with ice or not, and is also verified against observations with good result. But the cross section is located two hundred meters upstream of the intake, and it could be that the ice cover at the intake is intact when the cross section is ice-free. The variable $Q_{\text{prod}}$ shows the production flow in the power plant, which here is the water passing through the intake, and $Q_{\text{bypass}}$ is the water that passes over the dam. In winter the reach downstream of the Svorkmo intake has a constant flow of 4 m$^3$s$^{-1}$, so some short spill episodes are observed over the period. Some of these are related to ice formation on the trash racks where blockage causes the water to spill over the dam and into the bypass reach.

During the studied period the ice cover at the upstream end of the intake pond was broken several times, typically following milder weather and changes in discharge. The power company tries to maintain an ice cover on the intake to possibly reduce the amount of frazil that reaches the intake. Several times a large hanging dam has been observed at the upstream end of the intake pond, but this was not observed during the study period. The relatively unstable cover could contribute to this observation. Further, a shortened ice cover possibly increases the time when super cooled water that can reach the trash rack.

From the data in Figure 4 it seems evident that high head loss is not only related to cold weather and frazil formation, but blocking also occur in warmer periods without super cooled water. Other types of drifting ice like anchor ice released from the bottom, frazil flocs or broken surface ice, could cause this. From the same figure, it is seen that the increase in head loss is in many cases very fast, when it reaches a specific level it rises rapidly to the peak level. This is similar to laboratory observations by Daly (1991) and field observations by Richards and Morse (2008). One thing that is also seen in the data is that in most cases a high head loss episode can last for a long period with a fluctuating peak level. As will be shown later, reproducing this fluctuation by combining climate, ice or large-scale hydraulic variables is difficult. The reason could be that small-scale hydraulics of releases and changes in the ice formation, or due to mechanical removal of the ice from the trash rack. Data on the latter are unfortunately not available.

Looking at the head loss graph in Figure 4 different episodes can be identified. From the 31st of January and onward to the 5th of February there is a period with low temperature ($T_a = -11.7 \, ^\circ\text{C}$). With the exception of a small bypass incident, this period has rather similar discharge conditions (Figure 6B). The simulation results show that frazil is produced through this period. The head loss has a mean value of 2 meters, with frequent fluctuations between roughly 1.5 to 2.5 meters. After this period the temperature rises fast to positive, but the period with high head loss lasts for four more days at the same high level before it recedes. During the cold period the entire intake pond is ice covered and this also show that super cooled conditions must extend all the way to the intake, which is in line with theoretical computations.

From about the 8th of January a cold period ends and air temperature shows a rapid increase from around $-10 \, ^\circ\text{C}$ to positive values (Figure 6B). At the same time, the production discharge is increased to maximum. During the cold period only a single head loss peak is observed, and the
intake pond is covered with ice. Frazil is also produced during this period. But the observed head loss increases to more than two meters, which is far above what could be attributed to the discharge increase alone. A likely explanation could be that the discharge increase increases transport of ice accumulated in the river upstream during the period with lower flow and that this is accumulated at the intake.

From the 22nd to the 27th of January there is a prolonged head loss incident that starts with cold temperature and the formation of a full ice cover on the pond. During the period the temperature increases to positive value and modelled frazil production ceases, but the increased head loss continues for several days after the cooling period is over. Like the other periods, a significant fluctuation of head loss is also seen here.

To find the relationship between the observed head loss and possible driving factors, a generalized linear model was fitted to the data. Since the initial analysis show that different mechanisms are working at different times, models of shorter durations were fitted first. Since there are interactions and various mechanisms as seen in Figure 4, some derived variables were added. The accumulated temperature was computed as an alternative to the instantaneous temperature measured at the site since this gives a smoother variation, and similarly accumulated flow in m$^3$ was also used in the model. Changes in flow with different time lags were computed, and the velocity over the trash rack was also computed following the Kirschmer formula. Lastly, the head loss on the previous day was used in the model as a measure of the evolution of blockage on the trash rack. An offset equal to the computed base head loss was also evaluated.

Table 1 shows the initial model parameters and three steps of the selection process carried out towards the final result. In the parameter selection process, only the variables measuring accumulated or rate of change were left at the end, and the in the final model the accumulated flow is left out even if it was significant in the previous step. This reduces the parameter numbers and makes the model more parsimonious and explainable. The model fit is shown in figure 7. The NSE is 0.711.

Figure 8 shows modelled and observed head loss for the early January period (Figure 6B) using the same parameters for the as in table 1. The NSE is 0.46. Doing a second round of fitting for this specific period improves the NSE to 0.48, but the pattern is similar. This indicates that effects not defined in the model may be important here.

Compared to previous findings of frazil ice formation and blocking of intakes similar features are also observed at Svorkmo. Like Andreasson and Andreasson (1992) observed for river intakes and Richards and Morse (2008) observed for a lake intake, frazil blocking on relatively high negative temperature also occurs at the Svorkmo intake.

4. Conclusion and further work

The ice accumulation at the intake to Svorkmo power plant is a complex process in which ice blocking appears to be controlled by not only frazil in super cooled water but also by transport of ice after the cooling period ceases. For the period studied here, the ice cover of the intake pond is not able to stop frazil events. The statistical approach to evaluating significant variables shows that the accumulated environmental variables and antecedent conditions are important for the
result. The model reproduces the head loss reasonably, but more interaction and more detailed knowledge of processes at the intake site are necessary to improve the prediction.

Further work on this involve using a SWIPS instrument to better measure the frazil transport at the intake site. Further, a camera and temperature sensor will be mounted at the intake to understand the transport of ice and super-cooled water at the trash rack. A better geometry of the intake pond will be generated with the purpose of modelling flow in the pond and in more detail at the intake.

Acknowledgements
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References
Theriault, I., J. Saucet and W. Taha (2010). Validation of the Mike-Ice model simulating river flows in presence of ice and forecast of changes to the ice regime of the Romaine river due to hydroelectric project. 20th IAHR International Symposium on Ice.
Figure 1 The Orkla hydropower system and the Svorkmo intake

Figure 2 The distribution of head loss (panel a) and production discharge (panel b) over the hydrological year 2011-2012. The box represent the 25% - 75% percentile with median marked, the whiskers are 1.5*the inner quartile range. Dots represent outliers.
Figure 3 hourly head loss distributed on month of the year. The line indicates the computed head loss for the trash rack using Kirschmers formula.

Figure 4 Diurnal distribution of head loss in meters for the months January and February.
Figure 5 Observed and simulated variables at the Svorkmo intake.

- Air temp (C)
- Ice cover
- Q bypass (m^3/s)
- Frasdr
- Precip (mm)
- Head loss (m)
Figure 6. Periods of head loss. Panel A shows a cold period with frazil production and head loss, Panel B shows a period where the main head loss event lags the cold period.
Table 1 Output of GLM analysis. For the variables: I - intercept in model, Qpr - production discharge, Ta - air temperature, dQ - change in discharge, lag 1, AccT - accumulated temperature, AccQ - accumulated inflow, Fra - frazil from model, v - velocity at trash rack, RR - precipitation and pHf - head loss the day before. For the significance (Sig column): 0 **** 0.001 *** 0.01 ** 0.05 * 0.1 ' 1

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Figure 7 Modelled and measured head loss over a continuous cold period in February. The Nash-Sutcliffe R² is 0.711.
Figure 8 Modelled and observed head loss for a period in early January when the peak head losses appeared after a milder period. Parameters are the same as for the previous case, NSE = 0.46.