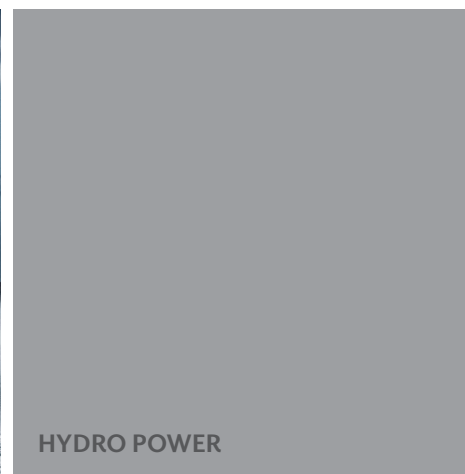


RECENT RIVER ICE RESEARCH AND RIVER ICE MANAGEMENT IN SCANDINAVIA

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Recent river ice research and river ice management in Scandinavia

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Foreword

Hydropower operation in Scandinavia is occasionally obstructed by formation of frazil ice and/or slush. Local knowledge about how to mitigate the problems exists, but documentation is very sparse. This study summarize established and new knowledge regarding ice problems related to hydropower and the practical experiences regarding how to mitigate these with focus on Scandinavian conditions.

The report was prepared by Johan Casselgren, Gunnar Hellström and Angela Lundberg for the benefit of HUVA - Energiforsk's working group for hydrological development. HUVA incorporates R&D-projects, surveys, education, seminars and standardization. The following are delegates in the HUVA-group:

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Stockholm, November 2015



Cristian Andersson

Energiforsk

Sammanfattning

Isproblem inom vattenkraften ser olika ut på olika platser i Sverige.

Klimatförändringar och förändrad drift kan förvärra problemen.

Lokala kunskaper om hur man kan hantera problemen finns, men dokumentationen är begränsad. En insats för att öka kunskaperna i Sverige gjordes i början av 90-talet men omfattningen på forskning inom området har sedan dess varit begränsad medan endel studier genomförts i Norge.

I rapporten summeras etablerad och ny kunskap om isproblem inom vattenkraftområdet samt praktiska erfarenheter om hur de kan åtgärdas med fokus på skandinaviska förhållanden. Studien baseras på litteratur samt intervjuer med personal på flera vattenkraftföretag.

Instrumentering för att detektera förhållanden som kan leda till issörja och kravis nyttjas sällan eller aldrig. I rapporten ges en introduktion till mättekniker som kan användas för att detektera is inkluderande nya metoder och angreppssätt för att identifiera förutsättningar för kravning. Forskningsbehov och ett antal förslag till fortsatta studier presenteras.

Summary

Hydropower operation in Scandinavia is occasionally obstructed by formation of frazil ice and/or slush, requiring heating of gates or forcing the operators to spill water. Predictions of climate warming and altered operation practices (larger flux variations) tend to worsen these problems.

Local knowledge about how to mitigate the problems exists, but documentation is very sparse. An effort to increase the Swedish knowledge regarding frazil ice was made at the beginning of the 90's but later research efforts in Sweden has been minor (an ecology study with focus on river regulation impact on shore vegetation) while several studies have been made in Norway. The objective with this study is to summarize established and new knowledge regarding ice problems related to hydropower and the practical experiences regarding how to mitigate these with focus on Scandinavian conditions. The study is based on literature and interviews of personal at hydropower plants from several companies.

Instrumentation to detect conditions preceding slush and frazil ice formations is sparse or non-existing. The report gives an introduction to measurement techniques used to detect ice (thickness of ice sheets, frazil ice concentrations etc.) including novel approaches to identify conditions favoring frazil ice formation. Research gaps are identified and a few suggestions for new studies are presented.

List of content

1	Introduction	7
2	Hydropower systems	9
2.1	River stretches	11
2.2	Reservoirs and dam structures	11
2.3	Spillways	12
2.4	Water intakes with trash gate	12
2.5	Pressurized water: convey systems (penstocks, siphons, tunnels, etc.)	12
2.6	Riprap and riparian areas	13
3	Mitigation measures	14
3.1	Ice problems and how they are solved –results from interviews	14
3.1.1	Ångermanälven	14
3.1.2	Luleälven	16
3.1.3	Skellefteälven	17
3.1.4	Barduelva, Norway	19
3.1.5	Alta, Norway	19
3.1.6	Concluding remarks	19
3.2	Measurements to MITIGATE problems and enhance knowledge	20
4	Ice modeling for hydropower applications	21
5	Ice detection and forecasting	23
6	Research gaps and suggested new studies	26
6.1	Frazil ice formation	26
6.2	Modelling	26
6.3	Ice loads	26
6.4	Suggested new studies	26
6.4.1	Use of existing data:	26
6.4.2	Development and testing of techniques for detection of frazil ice and piling ice:	27
6.4.3	Study outline	27
7	References	28

1 Introduction

Hydropower production accounts for about 99% and 47% of the total electricity production in Norway and Sweden respectively (Gebre et al., 2013; Elåret, 2014). As the largest need of electricity is during the winter it is important that electricity production doesn't get reduced during this period of the year. A problem that is general for hydropower in cold climate is ice. Ice problems in hydropower systems is a wide area, some examples are underwater dams, ice jams and blockage of water intakes. When and under which conditions the ice problems appear are often quite specific for each hydropower plant, as they depend of the river formation when regarding depth, water flow (speed), width, surroundings etc. Ice problems for Canadian hydropower plants seem to be largest during freeze up (60%), smaller during the ice-covered period (25%) and smallest during break up (15%) according to Wigle et al., (1990). Similar conditions prevail in Scandinavia, but with the assumed climate warming the freeze up period gets longer which increase the period with largest problems. Examples of estimated costs due to ice related problems could be found in Gebre et al. (2013).

In Scandinavia hydropower is the largest renewable energy source, offering large potential for reduction of carbon emissions. With an ongoing shift to renewable energy sources, there is a large need for balancing solar and wind energy sources. Hydropower enables this feature by hydro peaking, however, one negative effect of peaking is that it will be more difficult to ensure ice cover that prevents the most common ice problems. To meet winter demand in cold region hydropower systems, storage schemes are to a large extent, implemented in tandem with run-of-river schemes.

The assumed climate change have potential to influenced river ice regime (and hydropower operation) and can be expected to further influence ice formation, ice cover duration, frequency of intermittent ice cover and breakup processes (Timalsina et al., 2013; Gebre et al., 2014a; 2014b). The positive effects on hydropower operation, from the assumed climate change, are expected from shorter ice season and reduced static ice load, but unstable winters might increase the number of freeze-thaw periods (Gebre et al., 2014b) with risk for more frazil ice formation.

The objective with this study is to summarize established and new knowledge regarding ice problems related to hydropower and the practical experiences regarding how to mitigate these with focus on Scandinavian conditions. The study is based on literature and interviews of personal at hydropower plants from several companies. Theories regarding processes and modeling are only treated passingly.

In section 2 we shortly describe a hydropower plant and where ice problems arise. In section 3 we describe how these problems are handled today and how they can be mitigated based on the literature and interviews. Section 4 presents a survey regarding river ice modelling. Section 5 regards measurement techniques used to detect ice (thickness of ice sheets, frazil ice concentrations etc.) then follows

including novel approaches. Finally research gaps are identified and a few suggestions for new studies are presented.

2 Hydropower systems

A hydropower system usually consists of a reservoir and a dam with spillways, water intakes, waterways (penstocks, headrace channels, tailraces) and different types of outlets (in rivers, lakes or reservoirs) (Figure 1). Along the river and the reservoirs are riparian areas and erosion exposed sections that often are armored with rip rap.

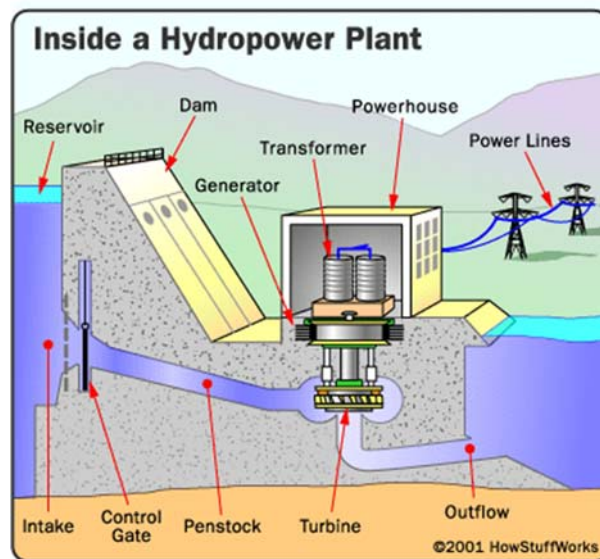


Figure 1. A schematic hydro-plant, courtesy of HowStuffWorks.

Possible problem areas are first briefly described below and later discussed more in detail.

1. **River stretches:** Ice jams or underwater dams that block the river water may occur upstream in the river, so less water reaches the hydropower plant. These problems can be caused by different icing event.
2. **Reservoir and dam structure:** Thermal expansion of ice sheets ice jams and may exert large pressure on reservoir sides and dam structures (Figure 2). One situation that may be particularly problematic is a combination of ice, fluctuating water levels and wind. Riprap (shot rock, rock armor, rubble) used to armor shorelines of reservoirs against erosion, may also be influenced by ice actions.
3. **Spillway:** The spillways might freeze up.
4. **Water intakes with trash racks:** During special circumstances the intakes can be partially or completely blocked by ice, preventing water to reach the turbine.
5. **Penstock and turbine:** During exceptional situations there can be icing in the penstock and on the turbine, decreasing the efficiency of the hydropower plant and causing severe problems.

6. **Pressurized water:** When frigid water in a conduit first is exposed to a pressure decrease and then a pressure increase frazil ice might be formed in pressurized conveys.
7. **Riprap and riparian areas:** Both reservoirs and river stretches have riparian areas along the sides which are effected by ice action.
8. **Dry river beds:** Water release into dry riverbeds might cause aufice formation

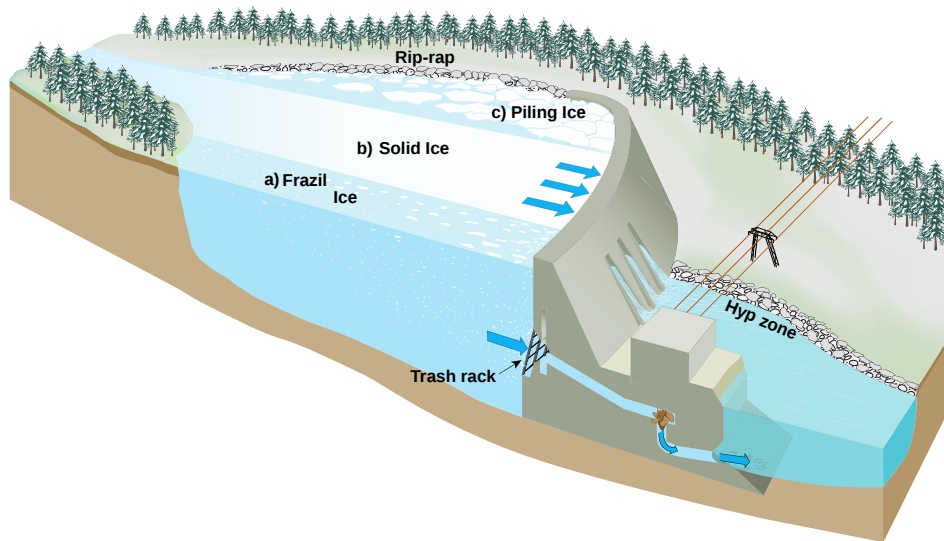


Figure 2. A conceptual illustration of possible ice impact on reservoir sides and dam structures during different ice phases. a) frazil ice formation and accretion on intake gates, b) pressure by solid ice sheet on the dam-structure and the riprap at the reservoir shore, c) pressure by large piling ice sheets on the dam-structure and the riprap at the reservoir shore.

Ice problems can be divided into the following kinds of ice:

- a) **Frazil ice** that is small fish scales of ice or ice needles that are very aggressive and attach to all kinds of materials. Frazil ice is formed in subfreezing waters with high water velocities and intense turbulence preventing formation of a solid ice cover. Fast cooling of the air often allows super cooling of the water so the water temperature decreases below 0°C .
- b) **Solid ice covers** that covers the reservoirs or river or will put pressure on reservoir sides and dam structures. Formation of an ice cover often needs water surface velocities below $<0.6 \text{ m/s}$ and temperatures under 0°C during a period of time.
- c) **Piling ice** forms when an ice cover breaks up and consists of large ice sheets that can block the intakes, exert pressure on dam structures and create ice dams in narrow passages of rivers.

In the following subsection the different ice problems are discussed for each part of a hydropower plants as described in section 2.

2.1 RIVER STRETCHES

River stretches with regulated minimum flux or runoff-river regulation can be exposed to frazil ice formation, ice dams and aufis, especially when the discharge varies abruptly as during peak operations or load balancing.

A rough estimate of how far downstream (Δx , m) from an outlet a river stretch remains ice free can according to Carstens, (1986) be calculated based on the specific heat of water, (C_p , 4,200 J/kg, °C), the density of water ($\rho = 1,000 \text{ kg/m}^3$), the surface width of the river (B , m) the river flow (Q , m³/s), the net heat loss (Q_h , Watt/m²) and the temperature of the released water (T_{outlet} , °C) by:

$$\Delta x \approx C_p \rho T_{\text{outlet}} Q / (B Q_h)$$

For a period with large heat loss (500 W/m²), which corresponds to a wind speed of about 10 m/s and an air temp of about -20°C (Gebre et al. 2013), and with a water flux of 1 (m³/s, m), the ice free distance (Δx) then becomes $8,400 \cdot T$, so for a water temperature of 0.5°C the river stretch would remain ice free for 4.2 km. In the study by Lind et al. (2014) on small water courses, the ice conditions (aufice, frazil ice dams) was related to hydrological and hydraulic indices: altitude, distance to upstream lakes, water temperature, cumulated negative degree-days, flux, water velocity, wet perimeter, slope, stream power, contribution from groundwater, number of days after passage zero isotherm and the fraction of the river bed covered with large stones, wood and gravel.

The ice covers on river stretches (and reservoirs) which normally are strong enough to allow recreation and transport activities might also be disturbed when the discharge varies abruptly, making it difficult or impossible to these activities.

Water intakes can be located at different depths in the reservoirs and for deep intakes the thermal stratification of reservoir water might cause release of distinctly warmer water than the surface water. When this water during cold weather is released downstream into a steep water cause, frazil ice formation might occur (see also comment below regarding pressurized flow).

2.2 RESERVOIRS AND DAM STRUCTURES

Pure ice pressure: The maximum force an ice sheet can impinge on a structure is the force required to break the ice, which is a function the geometry of the structure, the ice thickness and its compressive strength. Two meta studies aiming at estimating the thermal ice pressures on dam structures for a 0.5 m ice cover both showed huge scatter in estimated maximum pressures. The pressures, in the empirically based study by Kjeldegaard and Carstens (1980), ranged between 14 to 210 kN m⁻¹. In the study by ICOLD (1996), where the ice load was expressed as linear functions of the ice thickness the pressures ranged from 45 to 150 kN m⁻¹.

These values can be compared to the expression proposed by Carter et al., (1998): $\text{Pressure} = 2.53 h^{1.5}$, where h is ice thickness (m). This expression gives a maximum ice pressure for $h = 0.5$ of 90 kN m^{-1} .

Combinations of ice pressure, fluctuating water levels and wind: Much higher loads than due to only static pressure can be expected when combined with changing water levels. For example, Morse et al. (2011) found that combinations of ice pressure and rapid water level changes produced around twice as large pressures as estimated by the static pressure model (Carter et al., 1998) and Stander (2006) reported pressures from 200 to 250 kN m^{-1} for a combination of 0.75 m thick ice and water level variations. Blazevic (2011) report ice loads three to ten times larger with water level variations than without.

Recent research thus indicates that ice pressure on reservoir sides and dam structures thus may be considerably larger than previously assumed.

2.3 SPILLWAYS

Spillways can be regarded as part of the dam structure and ICOLD (1987) offer thorough descriptions of different designs with advantages and disadvantages with diverse types of spillways. Gated, un-gated and combination spillways exist and in Norway, un-gated spillways are preferred even if also gated spillways exist there according to Lia (1998). Ice problems with gated spillways are usually caused by direct freezing of water on the gates hampering their operability and causing safety issues if they cannot be operated properly (e.g. Billfalk, 1992). In Norway spillways tunnels are common, and during winter cold air entering the tunnels cools these, and if water leakage from groundwater or from the reservoir freezes and the tunnels might be blocked (Lia, 1997). Gebre et al. (2013) illustrated how ice blocked about 75 % of a Norwegian outlet tunnel.

2.4 WATER INTAKES WITH TRASH GATE

A major problem for some hydropower plants is frazil ice accumulation on the trash gates that causes reduction in flux and sometimes total blockage of the gate (Andersson 1997, Andersson and Andersson, 1992). Andersson (1997) estimated the Swedish annual loss to 1-2 million SEK due to frazil ice on intakes. Sundqvist (1991) investigated ice related problems in Swedish hydropower plants and concluded that ice jams and frazil ice were the largest problems and often in combination. She also noted that problems were observed in 45 different Swedish watercourses. Frazil ice on trash racks, and flow reductions to encourage solid ice formation causes most problems during freeze-up along with head losses (increased friction) due to ice cover formation and raising tail water levels (Gebre et al. 2013).

2.5 PRESSURIZED WATER: CONVEY SYSTEMS (PENSTOCKS, SIPHONS, TUNNELS, ETC.)

Frazil ice is often an underestimated problem for many water conveyance systems and especially in mountain terrains with a combination of low air temperatures, rapid flows and limited accessibility (Ettema et al. 2009). Most problems arise

when frigid water in a conduit first is exposed to a pressure decrease and then followed by a pressure increase (e.g. inverted siphon or in turbine and its outlet (for illustrations see Ettema et al. 2009). Possible ice in incoming water is then first melted (during decreased pressure) and when the pressure increases again frazil ice is formed. Pressure changes of the magnitude 0 to 2 MPa are common in pumps, penstocks and siphons (an elevation difference of 100 m causes a pressure difference of 1MPa). The relationship between water temperature, water pressure and freezing temperature can be described by Clapeyron equation (Ettema et al. 2009) and an increase in pressure of 1 MPa, decreases the freezing temperature by about 0.0074°C. Depression of the freezing temperature can thus result in frazil ice formation with corresponding risk of blockage.

2.6 RIPRAP AND RIPARIAN AREAS

Riprap (shot rock, rock armor, rubble) used to armor shorelines of reservoirs and downstream outlets against erosion, may also be influenced by ice actions. Ice sheets and ice piles in combination with fluctuating water stages or thermal expansion of ice sheets may all deteriorate the riprap.

Both reservoirs and river stretches have riparian areas along the sides. Frazil ice formation of ice dams has been shown to have large (positive) impact on riparian ecology of small streams by removing common hardy species and increasing the diversity of species when the sides of the streams are flooded and covered by ice (Lind et al. 2014).

3 Mitigation measures

The aim with the mitigation measures is to ensure continuous operation of electricity generating facilities without detrimental impacts on the downstream river. They can be classified as below following (Gebre et al. 2013). A few examples of measures are listed here and a detailed summary of mitigation measures with references to relevant studies is found in Gebre et al. (2013).

- **Design guidelines** for all parts of the plant (intakes trash racks, outlets, sluices, channels etc.). Intake velocities should be kept <0.6 m/s to facilitate formation of ice cover formation.
- **Operational guidelines for discharge (Q) and water stage (ΔH)**. Avoid rapid changes in Q and ΔH to avoid unwanted breakup and jamming and reduce Q during freeze-up to encourage ice sheet formation. Avoid release of water into dry riverbeds to prevent aufice formation. Combine water outtake from different depths when needed. Remove frazil ice from water conveys.
- **Structural ice control**. Facilitate ice cover formation by reducing the water surface velocity using different types of floating devices (jetties, ice-booms, nets) and canal constructions to reduce the open water surface area. Levees and dams can be built to prevent flooding and riverbeds can be armored to prevent erosion and scour. Production losses in the Swedish hydro-power station Stornorrfor were reduced when net and ice booms were used to facilitate formation of solid ice in front of the station to prevent frazil ice accumulation (Sahlberg 1993).
- **Thermal measures**. Heating of trash racks and gates and covering of intakes to reduce energy loss due to long wave heat radiation can be used and air bubbles can be used to raise deeper (warmer) water to the surface.

3.1 ICE PROBLEMS AND HOW THEY ARE SOLVED –RESULTS FROM INTERVIEWS

In this section the interviews regarding ice problems and the mitigation taken to prevent the problem are summarized. Each specific hydropower plant, Swedish river by river, and two Norwegian rivers are first reported separately followed by some concluding remarks.

3.1.1 Ångermanälven

Hjälta

At Hjälta hydropower plant there has been problems with frazil ice almost complete blocking the water intakes, see Figure 3. The intakes gates are at water level so only part of the gates is water covered allowing chilled air cooling down the gates causing ice problems. By covering the space around the gates with plastic strips the air space becomes isolated reducing the ice problems. At Hjälta they also used to utilize booms attached to a wire hanging over the river to lower the speed of the surface water. However, these booms have not been used lately since when

the ice cover was broken by the booms, piling ice along with accumulated frazil ice tended to regulate the river.



Figure 3. Frazil ice blockage of a water intake at Hjäлта hydro power plant.

Edsele

At Edsele there were no problems with frazil ice instead they had problems with freezing of the spillways. The freezing of the spillways was solved by infrared heaters on the mechanisms of the gate and the use of air bubbles in front of the gates.

Sollefteå

At Sollefteå there was few ice problems recorded. What was interesting at Sollefteå was the scrape used for trash, as it was equipped with teeth (Figure 4). Scrapes are often used to remove frazil ice from trash gates, when this is done the scrape with teeth gives the best results. The scrape without teethes are more or less useless for ice removal.



Figure 4. Scrape for removing trash and ice from the intake gates.

3.1.2 Luleälven

Vittjärv/Boden

Historically, there have been repeated problems on the stretch between Vittjärv and Boden hydropower stations. In the 80's there was a lot of innovative ideas tested some examples were dredging and testing of various types of booms; solid and operable. Another innovative solution was to break solid ice into ice floe and transport it to the problem area to build a solid ice cover, like a puzzle. This was connected to high risks.

In 1986 the Boden water magazine was dammed up by 0.5 m, which affected the icing positive (greater area lower water speed). Continued there were shallower areas that created problems but nowhere near the same extent as before the dredging. In 1992 nets was mounted on a wire across the river at a shallow part that was critical for icing, the idea was to lower the speed of the surface water to create an ice cover. The net gave a good result.



Figure 5. Ice booms with mounts for nets.

In 2010 there was an ice jam that created big problems. After 2010 the net and wire construction was improved with a boom and net construction as shown in Figure 5. In addition, more water temperature and water level gauges were placed along the river enabling a better tool to monitoring the ice progress. Since then it hasn't been any problems with ice jams at the Boden hydropower plant.

Also notable is that upstream Vittjärvs hydropower plant booms without net are mounted to facilitate an ice cover.

3.1.3 Skellefteälven

In 1988 there were a large ice jam between the Kvistforsen power plant and Bergsbyn. After that ice nets have been mounted over the river just up-stream of the place where the ice jam arose in order to reduce the speed of the surface water so a stable ice cover can form.

In the beginning the ice nets were mounted by boat, but in the winter 2012/2013 the system shown in Figure 6 was used enabling a simpler way of distributing the ice nets over the river.

During the two last winters (2013/2014 and 2014/2015) no nets have been deployed, as the water reservoirs and the regulation rate have been low enabling ice cover formation.

To accomplish a solid ice cover along the river the following conditions are needed:

- the flux need to be low (80-110 m³) during 3-7 days.
- the air temperature has to be below -7° C

- the water temperature (measured at the plant Kvistforsen) has to be around $+0,1^{\circ}\text{C}$.

Bergsbyn

There are only spillways and no hydro power plant at Bergsbyn since the dam structure is designed to keep a water reservoir (water mirror) in the river independent of the regulation of the hydropower plants upstream.



Figure 6. To the left, machinery for winding of the cable for mounting of the net. To the right, the location under a bridge where the ice nets were mounted.

Finnfors and Kvistforsen

At the hydro power plants Finnforsen and Kvistforsen there have been occasional problems with frazil ice. However, recent years the problems have decreased since ice nets have been used to reduce the surface water velocities, enabling formation of ice covers upstream of the plants. At Kvistforsen the water intakes are similar to Hjäлта with an air gap (Figure 7) so some kind of insulation could be of interest to reduce problems with frazil ice, if they should reemerge.



Figure 7. The water intake gates at Kvistfossen.

3.1.4 Barduelva, Norway

Regarding the Bardu River there has been some problems with piling ice as well as ice drift. The experience from Statkraft in these incidents is that the possibility to regulate the river with a higher amplitude and frequency is there, when an ice cover is created. However, Statkraft would like to investigate the possibility to use the river in such way that the regulating freedom would increase, but still keeping the ice load in an acceptable level.

3.1.5 Alta, Norway

At Alta River the main question is considering ice drift and how to control it in such a way that the effects, both on the surrounding as well as the production, is as low as possible. For the Alta power plant this is mainly controlled through utilizing the two alternative intakes available. The two intakes, situated at different levels in the reservoir, make it possible to control the temperature of the water in the river in order to mimic natural conditions as much as possible. Hence, the flow situation can be created in such a way that the ice cover can be controlled, both upstream as well as downstream the Alta power plant through planning the production.

3.1.6 Concluding remarks

Scrapes: At some hydropower plants they had scrapes without teeth and these were considered more or less useless, when applied to icing problems at the water intake gates. Purchase of scrapes with teeth can be recommended.

Heating: The heating had been removed at some places because of the environmental risk of oil spill from old generators. But it is still a method to prohibit the frazil ice particles to attach to the intake gates and is used at other sites.

Insulation: Problems with ice blocking of unshielded gates at surface water level could be reduced if the access to cold air to the gates is reduced by some type of insulations (e.g. by hanging plastic stripes).

River regulation: The Norwegian experience emphasized the importance of using river regulation schemes with stable, low flow conditions which allowed formation of ice sheets, and requested more information which would allow them more freedom in hydro power regulation.

3.2 MEASUREMENTS TO MITIGATE PROBLEMS AND ENHANCE KNOWLEDGE

As ice formation of all kinds is dependent of weather, i.e. water temperature, air temperature, wind, cooling, cloud coverage etc. are interesting parameters to record. Other useful hydrological and hydraulic parameters are: altitude, distance to upstream lakes, cumulated negative degree-days, water flux, water velocity, wet perimeter, river slope, stream power, contribution from groundwater, number of days after passage zero isotherm and the fraction of the river bed covered with large stones, wood and gravel as described in Lind et al. (2014).

Established techniques to measure relevant parameters

Today there are simple and cheap sensors available to measure several of these parameters, the sensors often have connections so the data can be stored or sent to a server so analysis can be done over a longer periods making it possible to get a better understanding of different icing events. As the sensors are cheap, several sensors could be deployed along a river to get spatial variations as well.

Within this project several interviews with the personal at different hydropower plants were conducted. The results are presented earlier in this section 3.1. One of the impressions of the interviews was that lot of knowledge about ice problems are concentrated to the personal working at the specific hydropower plant. This knowledge has been gathered during a long period of practical experience. Therefore measurements to get a general understanding of the factors that are affecting different icing event would be of interest.

Tested innovations

Notable is that there also was some innovations that have been tested at some of the hydropower plants for a specific problem and this problem might be the same for another company. But this knowledge is not spread. Here is a gap much of the knowledge about ice problems is situated to the people working at the hydropower plants and this is not that documented. This in the next step implies that the knowledge get lost when the persons retire or leave for another work assignment

4 Ice modeling for hydropower applications

There exist several public domain models of ice jams, such as ICEJAM, RIVJAM, HEC-RAS, RIVICE etc. Some of them also have the capability to capture features of the frazil ice, such as HEC-RAS. They are mainly based on similar differential equations (steady-state one-dimensional flow; stability of ice rubble, which is considered a granular medium). However, they utilize different solution methods and assumptions concerning the key conditions at the toe (downstream end of the jam). One of the models, the HEC-RAS model provides a platform for computations under any type of hydraulic condition, such as open-water flow, sheet-ice cover, ice jam, and any combination of these within the study reach. Although, it requires in addition to bathymetric information, input on different parameters such as: river discharge, water level or normal flow depth, locations of toe, limits of open-water and sheet-ice cover reaches, Manning coefficients, thickness of sheet ice cover, ice porosity, internal friction angle, maximum allowable flow velocity etc.

Lindenschmidt et al. (2012) used the RIVICE ice jam model to simulate the Red River and the ice jam flooding scenario there. Their main findings were that rivers flowing through low-lying areas such as river delta pose particular challenges for ice jam modelling. A solution using main channel abstraction to represent bank overspill into a floodplain and leakage into side channels proved successful.

Gebre et al. (2014a) studied the sensitivity to climate change of the thermal structure and ice cover regime of three hydropower reservoirs in Norway. They used a one-dimensional deterministic approach through MyLake, with some modifications to handle reservoir outflows. Gebre et al. found that, dependent on the climate scenario, a reduction in ice cover duration ranging between 15 and 81 days. In Gebre et al. (2014b) the same group used the MyLake approach to examine the effects of climate change on lake ice phenology and lake ice thickness in the Nordic and Baltic regions. A one-dimensional, process-based model of lake water temperature, ice cover growth and ablation (MyLake) was used to simulate lake ice phenology and ice thickness on a spatial grid of 25 km. Based on a comparison of the mean predictions in the future 30-year periods with the control (1961–1990) period, ice cover durations in the region is expected to be shortened by 1 to 11 weeks in 2041–2070, and 3 to 14 weeks in 2071–2100. Annual maximum lake ice thickness will be reduced by a margin of up to 60 cm by 2041–2070 and up to 70 cm by 2071–2100.

A one-dimensional river-ice simulation model RICEN based on an unsteady flow model for a channel network with ice; and a thermal and ice condition simulation model. The model simulates the water-temperature variation along the river, including supercooling; frazil-ice concentration distribution; anchor-ice growth, decay, and release; surface ice transport; ice-cover progression; undercover ice transport, deposition, and erosion; thermal growth and decay of ice covers; and ice-cover stability, Wasantha Lai and Hung Tao Shen (1991) and Hung Tao Shen, De Sheng Wang and Wasantha Lai, (1995).

Shuang Ming Wang and Doering, (2005) developed a mathematical model to simulate the supercooling process and frazil ice evolution is developed from previous models. It incorporates improvements for the physical process of initial seeding, ice particle growth, secondary nucleation, flocculation/breakup, and gravitational removal. A variable Nusselt number related to the flow turbulence is used. It has been found that two calibrated parameters, initial seeding, and a parameter that limits the secondary nucleation are correlated to the turbulence intensity, which is useful for the practical application of the model developed in this paper. Furthermore sensitivity analysis is carried out for these two parameters. The simulations results show good agreements with experimental data.

Matsumura and Ohshima, (2015) developed a new modelling framework using Lagrangian particle tracking has been developed to assess dynamic and thermodynamic effects of underwater frazil ice. This frazil-ice model treats a Lagrangian particle as a bulk cluster of many frazil crystals, and calculates the thermodynamic growth of each particle and the corresponding budget of latent heat and fresh water. The effective density and viscosity of sea water depend on the mass fraction of underwater frazil ice, and hence affect ocean convection. An idealized experiment using our model successfully reproduces the formation of underwater frazil ice and its transition to grease ice at the surface. Because underwater frazil ice does not reduce the atmosphere/ocean heat exchange, surface heat flux and net sea-ice production in the experiment with frazil ice are relatively high compared with the experiment where surface cooling directly leads to columnar growth of a solid ice cover which effectively insulates the heat flux. These results suggest that large-scale sea-ice models which do not take account of the effects of frazil ice might underestimate atmosphere/ocean heat exchange, particularly at times of active new ice formation.

She et al. (2012) report and simulate an interesting consolidation event prompted by the combination of I) a quick doubling in river flow (from ~900 to ~1800 m³/s) (a 5 day hydro peaking response to increased energy demands) and II) a rapid upstream ice cover development under a period of very cold weather in year 1982. They conclude that hydro-peaking seems to have played a minor role while the quick progression of the ice front during the period of extremely low temperatures was the primarily effect of the formation of a long and thick ice jam downstream. They also state that, even if the current practice with voluntary flow control (steady flow of 1600 m³/s) during freeze-up had been practiced then, a similar severe event might still have arisen (if a following warm period delayed strengthening of fresh surface ice accumulation) and that more research is needed to investigate the initiating mechanisms for freeze-up consolidation events (She et al. 2012).

As there are little data from the different hydropower plants it is difficult to validate different models for predicting ice problems. Hence, doing more measurement could enable better modeling of the ice problems.

5 Ice detection and forecasting

As a result of the assumed climate changes ice problems are likely to increase as the air temperatures will oscillate more around 0 degrees which will cause difficulties to create ice covers to prevent ice problems. This coupled with the generation shift of the workforce and new hydropower management schemes with larger variations in water fluxes means that there are challenges in hydropower applicable regarding ice problems.

One conclusion from the interviews of hydropower staff was that there is very little data logged when ice problems occurs since ice problems not occur very often. However when they do, they sometimes cause major problems. Another conclusion is that much knowledge about ice problems is among the staff at the various stations. This is a problem when staff is replaced then the knowledge might be lost.

To deal with these problems modeling of the ice problems would give a better understanding of ice accretion. A model would also enable better forecast to mitigate the problems. To develop a model of different icing events data should be collected over a longer period of time. The data should include parameters as:

- Weather parameters (temperature, humidity, wind speed, wind direction, radiation, cloud coverage)
- Water parameters (speed, fluid dynamics)
- Channel parameters (depth, width of the channel)
- Ice parameters (ice cover, frazil ice, ice pressure)

Weather parameters are quite easy to measure, today there are good weather stations available within an acceptable price range. These weather stations also have some kind of logging functions to a server or a cloud. Water parameters could also be measured and the dynamics could be simulated based on channel parameters.

The different ice parameters require various measurement techniques.



Figure 8. Ice cover the 25 of mars 2015, Luleå river. In the middle there is open water with ice at the edges. The weather is clear with just some high cloud so the outlet of radiation will be high.

For ice cover measurements the most widely used technique is camera surveillance. This has been successfully used by Hydro-Quebec to get an early warning of ice cover break up. Today there are advance Near InfraRed (NIR) cameras that uses the differences in absorption for water and ice to make road condition classifications. Such a camera could be used together with image processing to detect changes in the ice cover. The advantage with NIR light is that it is invisible to the human eye so the illumination doesn't disturb animals and humans. Another advantage compared to ordinary cameras is that the detection becomes more sufficient using NIR techniques. The disadvantage is that they are still quite expensive. So if a larger part of the river needs to be covered ordinary cameras would be a good option as they are much less expensive and they already have solutions to be remotely connected.

For frazil ice measurement cameras are also an alternative. In Doering et al. (2003) and Casselgren (2005) camera solutions was used to detect frazil ice particles in the water. Both methods use image processing to detect the ice particles. Today the camera technologies have become much better and less expensive so development of these methods would be beneficial.

In Morse et al. (2009) and Marko et al. (2010) Ice Profiling Sonar was used to detect frazil ice particles, however, this technique is more for research purpose and not suited for day to day operations.

To place a chain in the water is a method used for a long time at various hydropower plants to detect frazil ice. The frazil ice will attach to the chain and make it detectable. The disadvantage with this method is that during the years the detection of the frazil ice accumulation is been done manually. However, this method could be significantly improved in several ways:

- Instead of manual inspection a camera could be used for detection.
- Strain gauges could be mounted on the chain to measure strain in the chain that is caused by an increased weight of frazil ice attachment. These sensors could be connected to a cloud or a server for remote monitoring.
- An untested new method that could make frazil ice detection possible is the use of optical fibers. Research has shown that by using three different wavelengths of NIR light Casselgren (2007) it is possible to distinguish different road conditions. These wavelengths of light are also used in optical fibers. By manufacturing a special fiber and measuring how the light propagates in the fiber it could be possible to distinguish water and ice on the fiber. Making possible to detect frazil ice attaching on the fiber. If this method would work the fiber could be mounted on almost any material for ice detection.

The problem of ice pressure was never discussed during the interviews. So no focus has been put on that question, as it seems as a smaller problem then the other ice problems.

6 Research gaps and suggested new studies

Research gaps regarding frazil ice formation and modeling, and regarding ice loads were identified but the problems associated with the frazil ice were much larger, based on the interviews. All interviewed companies had problems but the problems were not frequent. This makes the urge to solve the problems quite small, therefore it would be good to have an organization as HUVA where most of the companies are represented to fund the research.

6.1 FRAZIL ICE FORMATION

The knowledge regarding the controlling factors for forming of frazil and anchor ice (water depths, turbulence, Reynolds number etc.) is still limited (Stickler et al. 2010; Stickler and Alfredsen, 2009). E.g. Stickler and Alfredsen, (2009) found that frazil ice can be formed in both turbulent (riffles) and less turbulent water (shallow and slow flowing). Stickler et al. (2010) question the current paradigm, stressing the role of runoff in steep streams as the main controller of stream heterogeneity in boreal environment.

6.2 MODELLING

River ice is a common feature in most cold climate rivers and hydropower operation is in some cases adversely affected by river ice. Commonly seen effects are reduced ice cover and increased frazil formation. Hydropeaking will further influence the ice formation and type of ice formed, Gebre et al. (2013). To assess the impact on ice, modelling studies of ice formation combined with field and laboratory studies to get accurate data on frazil formation and frazil concentrations using a frazil profiler, e.g. (Ghobrial et al. 2013). As mentioned in section 6.1 there is a limited knowledge regarding the controlling factors for forming of frazil ice and anchor ice, (Stickler et al. 2010; Stickler and Alfredsen, 2009). Routines and strategies for optimal operation of hydro power stations regarding ice formation and break-up would also be beneficial to be further developed and linked to innovative monitoring of physical conditions of the river.

6.3 ICE LOADS

General models for estimation of ice loads are, according to Gebre et al. (2013), still not fully verified and accepted, and they request development and testing of thermodynamic numerical ice load models.

6.4 SUGGESTED NEW STUDIES

6.4.1 Use of existing data:

The study of ice conditions in 25 small boreal Swedish streams during two years by Lind (2015) focused on average winter ice conditions and how these influence stream bank vegetation. This is rather unique dataset which could also be used to assess when and during what conditions frazil ice and ice dams are formed and we

have a preliminary promise to use this data set. Some of the knowledge from small streams can be transferred to larger rivers but additional measurement will be needed in regulated rivers. We have also had contact with Torbjörn Strömslid, Statkraft, Norway and they are interested in cooperation, so we can also use their data on frazil ice formation.

6.4.2 Development and testing of techniques for detection of frazil ice and piling ice:

For the first two studies a river locations where frazil ice formation is common will be identified and for the last study a location having problems with piling during ice brake up is already identified.

Frazil ice

- A. *Underwater camera:* To identify a camera and a light source suited for work underwater and test the system for frazil ice detection.
- B. *Strain gauges:* Attach strain gauges to the ends of a chain strained across the river and test if the system can be used to detect frazil ice.

When combined with a weather station these measurements could also be used to increase knowledge about weather conditions favoring frazil ice formation and for modeling of frazil ice.

- C. *Fiber optics:* Develop a new method based on a new optical fiber. The project would be based on cooperation between LTU and Swedish ICT Accreo where Accreo would manufacture the fiber and LTU would carry out laboratory tests to ensure the functionality of the new method.

Ice Cover

- D. Camera and image analysis of piling ice cover.
- E. Weather and hydrological measures
- F. Weather and hydrological measures to validate suitable models for predicting and modeling of ice problems.

6.4.3 Study outline

These studies could preferably be made as a combination of one/two PhD-studies (further analysis of existing frazil ice data and modeling) and senior research study (developing and testing of new measurement techniques).

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RECENT RIVER ICE RESEARCH AND RIVER ICE MANAGEMENT IN SCANDINAVIA

Hydropower operation in Scandinavia is occasionally obstructed by formation of frazil ice and/or slush. Local knowledge about how to mitigate the problems exists, but documentation is very sparse. This study summarizes established and new knowledge regarding ice problems related to hydropower and the practical experiences regarding how to mitigate these with focus on Scandinavian conditions.

The report gives an introduction to measurement techniques used to detect ice including novel approaches to identify conditions favoring frazil ice formation. Research gaps are identified and a few suggestions for new studies are presented.

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