CGU HS Committee on River Ice Processes and the Environment
13th Workshop on the Hydraulics of Ice Covered Rivers
Hanover, NH, September15-16, 2005

Factors controlling anchor ice formation in two Norwegian rivers.

Morten Stickler[1], Knut Alfredsen[1]
[1] The Norwegian University of Science and Technology
[1] Department of hydraulic and Environmental Engineering)
[1] S.P. Andersens vei 5
Morten.stickler@ntnu.no
Knut.alfredsen@ntnu.no

Abstract

In most northern temperate climate anchor ice is common during winter time and plays a key role when considering in stream winter conditions. The underlying mechanisms that form anchor ice and the effect of anchor ice on the flow regime is not very well known for steep streams. This paper presents results from studies on anchor ice development in two Norwegian rivers with different hydraulic characteristics.

Two rivers in middle Norway have been selected as study sites. River Stavilla is a small, steep unregulated stream with coarse substrate and river Orkla is a larger river with lower gradient. River Orkla is regulated for hydro power and thereby provides an unstable ice regime with frequent anchor ice episodes during winter. In river Stavilla we found anchor ice dams as an important mechanism for ice cover formation. The anchor ice dams formed in areas with large substrate/shallow water and reduced the water velocity in the steep section which trigged ice cover formation. In river Orkla anchor ice was produced at several locations over the study reach linked to local hydraulic and topographical conditions. The overall extent of the ice was controlled by climatic conditions with large carpets forming both in riffles and runs during the coldest nights. Most of the ice was released during mid day through the entire study period. Both studies show that anchor ice can be extensive and an important factor when analyzing ice formation, ice regime and flow conditions in small and large streams and that it should be included in winter time in-stream flow analysis in rivers in cold climate.

1 Introduction

In northern countries dynamic ice formation may occur frequently during winter time with low air temperatures and supercooled water (Kanavin, 1970). Dynamic ice formation in the form of frazil and anchor ice is dependent on meteorological conditions, the river topography and local flow conditions. Normally, anchor ice occurs in turbulent, shallow rapids with rough substrates, but it can also appear in deep areas as noted by Ashton (1986) who observed anchor ice at a depth of six meters in the Niagara River and twenty meters in the Neva River. Dynamic ice formation may cause engineering difficulties (e.g. blocked water intakes, Michel (1971); blockage/damage to hydropower installations, Freysteinsson and Benediktsson (1994); decreased discharge, Arden and Wigle (1972); and increased stage, Tsang (1982) as well as environmental challenges, Prowse (1994). In the last years there has also been a significant increase on general winter studies on stream salmonids (e.g. Cunjak and Power, 1986; Cunjak, 1988; Heggenes et al., 1993), traditionally from a biological perspective. In Norwegian rivers dynamic ice production has been a topic since the early 1920's instigated by serious ice problems caused by river regulations for hydropower production.

Formation of subsurface ice is predominantly found in shallow steep rivers or river sections when the water is supercooled (Tesaker, 1994). Supercooled water has been suggested to be slight less than 0˚C (Tsang, 1982; Kempema et al., 2004) and usually not exceeding 0.1˚C (Beltaos, 1995) although very few field measurements of the water temperature in such conditions have been recorded. In steep locations rough substratum dominate due to high water velocities and cause an increase in the turbulence level. Turbulence is a crucial factor through its vertical transportation of supercooled water from the surface and down to the river bed (Tsang, 1982). In supercooled, turbulent water tiny ice particles with adhesive features are formed, by definition, active frazil ice. In a study by Hirayama (1986) frazil ice appeared when the heat loss rate was about 58.1 J/m^2/s. In the same study frazil ice was observed in large amounts when the heat loss rate was about 116.3 J/m^2/s, which was considered low compared to previous studies. As proposed by Hiryama et al. (2002) the result might be due to differences in turbulence level and thereby differences in river characteristics. In regulated river systems dynamic ice production is believed to be controlled by both the local climate and operational strategies influencing river discharge (Kanavin, 1970), while in small, steep rivers the dynamic ice regime is predominantly controlled by natural variations, although little knowledge exist in these environments.

Anchor ice is mainly formed during cold, clear nights when the heat transportation from the water surface reaches its maximum, and released during daytime due to increased short wave radiation. In the study by Kerr et al. (2002) they found initial anchor ice growth when the cumulative freezing-degree hour of the air temperature reached less than 50˚C 6 hr. In supercooled water frazil ice is brought down to the river bed where it accumulates (Ashton, 1986), although it has also been suggested that anchor ice formation is triggered by direct underwater nucleation when super cooled water comes in contact with supercooled substratum (Ashton, 1986). Tesaker (1994) suggested a critical velocity of 0.6 m/s for dynamic ice formation while Hiryama et al. (2002) refers to 0.7 – 0.9 m/s. Kerr et al. (2002) found in an experimental set up in an indoor flume a critical water velocity of 0.25 m/s. In the same study stability and shape of anchor ice was described by the non-dimensional Froude number. The results showed that when Froude number was in the interval 0.2-0.5 "scales" and "tails" were formed on the substrate while Froude number higher than 0.5 resulted in “ball” types. During this experiment anchor ice was never observed to form below 0.4 to 0.5 d_s from the top of substratum. In a similar study by Doering et al. (2001) they found in an artificial flume maximum anchor ice growth when the Froude number was 0.27.

The formation of anchor ice, particularly in natural rivers, has been scarcely described in the literature, compared to studies on frazil ice formation. One of the earliest descriptions was made by Devik, (1930) who fundamentally pointed out the recognition of the relationship between supercooling and the formation of frazil ice in rapid flow, including a discussion of the formation of anchor ice and its consequences for the ice conditions in rapids. Traditionally, research on dynamic ice formation has focused on development and production of frazil ice in super cooled water (Carstens, 1970; Day and Anderson, 1976; Tsang, 1982; Ashton, 1986; Shen, 1998) and very little has been done on anchor ice formation (Tesaker, 1994). However, a few studies have been conducted, mainly as experimental set ups in laboratories (Kerr et al., 2002; Doering et al., 2001; Doering and Morris, 2003), but also as field experiments (Ke et al., 2000; Doering and Morris, 2003). As noted by several authors (Prowse, 2001; Shen, 2003; Kempema et al., 2004; Morse and Hicks, 2005) more knowledge on dynamic ice formation, especially on anchor ice formation, is needed. In order to understand the processes behind anchor ice formation field experiments will provide important knowledge. In the present field study anchor ice formation and its trigging factors have been investigated in two different river characteristics during winter 2003 and 2004. Findings and observations from one large regulated river and one small, steep river are discussed and presented.

2 Methods and study sites

In the present study observations from three field experiments have been collected from two different rivers; River Orkla and River Stavilla, both located in middle part of Norway (Figure 1). In River Orkla two experiments was carried out during winter 2003 and 2005 where data on meso scale (10 -100 m) and micro scale (0-10 m), respectively, was collected. In River Stavilla one experiment during winter 2003/2004 was conducted where data on meso and micro scale was collected.

Table 1: Table of physical features for River Orkla (regulated) and River Stavilla (unregulated, small, steep river).

Physical feature	**River Orkla**	**River Stavilla**
Mean annual flow	71 m^3s^{-1}	4.4 m^3s^{-1}
Average wetted width	45 m	9.15 m
Slope	0.5 %	1.6 %
Surface area of the reach	11622 m^2 (11 m^3s^{-1})	756 m^2 (1.8 m^3s^{-1})
Substratum, roughness (ks)	5.21 cm ± 4 SD	17 ± 7 SD

Study sites

River Orkla

River Orkla (63° 17’ N, 9° 50’ E) is a regulated river with a catchment’s area of about 3053 km^2 and an annual average runoff of 71 m^3s^{-1}. It was first regulated in 1981, and today, five large hydro power plants operate in the river system. The study site was located in the middle portion of the river system approximately 10 km downstream of nearest power plant outlet. The site was 250 meter long and ranged from 30 to 60 m in wetted width. The selected reach is predominantly run, pool and riffle with cobbles (mean roughness ± SD defined as effective height; 5.21 cm ± 4.0 SD) covering the bed and boulders located along the margins.

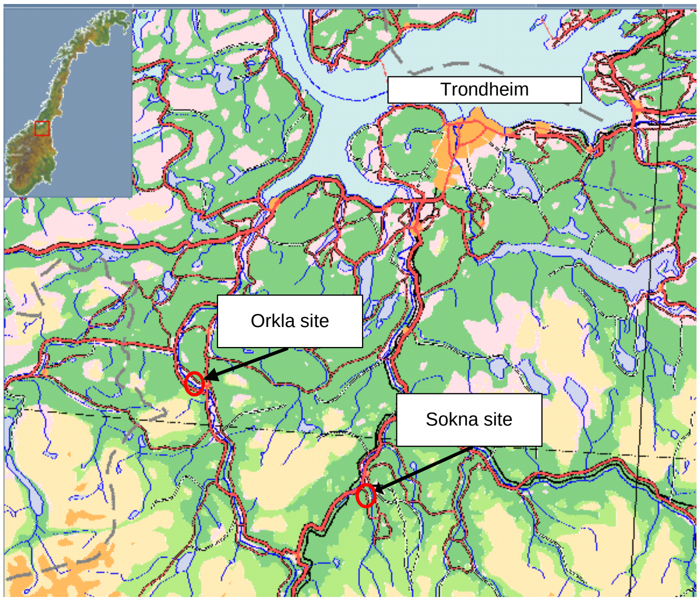

Figure 1: Orkla and Sokna study sites

Data collection and physical conditions

During a twelve day study period from 19th of February to 2nd of March winter 2003 data on topography, ice distribution, hydraulic and meteorological conditions was collected. A climate station (Campbell Scientific) was located on the study site recording net long and short wave radiation, humidity, temperature and wind speed and direction. Based on this the open water energy balance was computed using measured net radiation values and estimated sensible and latent heat fluxes by the Russian Winter Equation and Bowens Ratio as outlined by Ashton (1986). Contribution of heat from friction and ground conduction was neglected (Beltaos, 1995). No precipitation occurred during the study period thereby eliminating the precipitation component of the energy balance. Six thermographs (Vemco model Minilog TR, accuracy ± 0.1˚C) were placed upstream, in the middle and in the downstream riffle section recording water temperatures in the surface and on the bottom. In addition three Lakeland thermistors (accuracy ± 0.1˚C) chains were placed out on same locations giving three transverse temperature profiles for the reach. Discharge was monitored at the Syrstad gauging station located approximately 1 km upstream. Data on substrate and bathymetry were collected using a total station (Leica TC 307). Distribution of surface and anchor ice was mapped three times during the study period using the total station. Additionally, visual observations were conducted every 6th hours related to 20 transects evenly spaced every 15 m along the river reach.

Water discharge (Figure 2) was stable high (mean ± SD, 21.1 m^3s^{-1} ± 1.7 SD) during the first three days of the experiment, then decreased to low flow conditions (11.1 m^3s^{-1} ± 1.7 SD) reducing the wetted area by 30 %. The discharge level was then maintained low throughout the entire period except one day when water was released to prevent permanent ice build up (February 28th). Maximum depth was 2 m (mean ± SD, 0.51 m ± 0.39 SD) on low flow and 2.4 m (mean ± SD, 0.75 ± 0.53 SD) on high flow. Water temperature ranged from -0.125 to 0.65˚C (mean ± SD, 0.07˚C ± 0.15 SD) while air temperature ranged from 2.2˚C to -14.0˚C (mean ± SD, -5.3˚C ± 3.5 SD) (Figure 3).

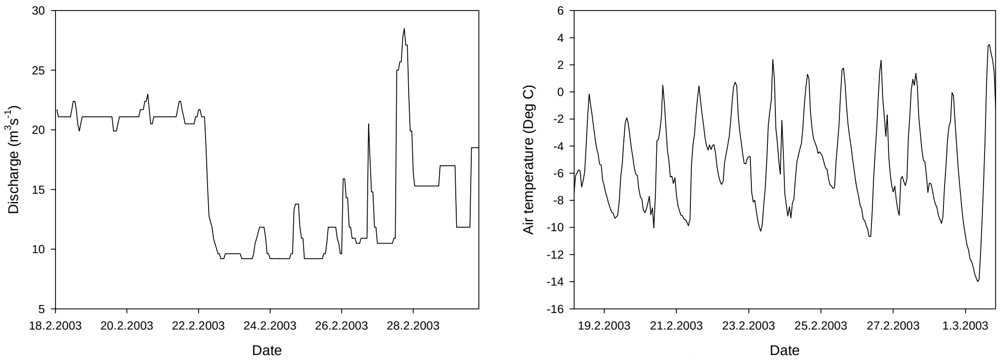

Figure 2: Discharge (m^3s^{-1}) and air temperature during the study period 18th of February to 1st of March 2003.

During winter 2005 data on micro scale was collected using high accuracy equipment in three predefined squares located in three different river sections; one in smooth glide section and two in riffle section (Table 2). Ice formation (thickness and distribution) and substratum size (longest and shortest axis) was collected using differential GPS (± 0.01 m). Effective roughness defined as vertical distance (height) from substratum bottom to substratum surface was measured using a similar technique as a slide caliper. Water temperature was measured using a high accuracy (± 0.002˚C) water temperature logger (SBE39, ITAS Instrumentation). Meteorological data was obtained from the local power company (KVO) from a gauging station 1 km upstream. Measurements of turbulence (measured as velocity fluctuations) were obtained using a Sontek ADV (10 MHz, velocity range 250 m/s, measurement period 2 minutes) on three different water depths; surface (defined as 10 cm below surface), middle (defined as 50 % of total depth) and bottom (defined as 10 cm above the bed). The axis of measurement was aligned for each measurement using fixed shore markers. Discharge was kept stable on 50 m^3s^{-1} during all measurements. Signal to Noise Ratio (SNR) for the measurements was 20.2 ± 7.7 SD. Data was filtered using the Phase-Space algorithm (Goring and Nikora, 2002) implemented in the WinADV program (Wahl, 2003), and velocity variables were calculated for each location. In the lower riffle section vibrations in the instrument during measurements was observed and the measurements were cancelled.

River Stavilla

The river Stavilla is located in central Norway (62° 55’ N 10° 15’ E) with a catchment area of 172.4 km^2 and mean annual discharge of 4.4 m^3s^{-1}. The study site is located in the lower part of the river where it meets tributary Igla form the Stavilla river. The site is 90 meters long with an average wetted width of 6.8 – 11.5 meters. The average gradient is 1.6 %. The site is composed of two different sections; a steep rapid section upstream (gradient 2.4%) and a gentler run downstream (average gradient 0.5%). Bottom substrate has a mean size of 25 cm ± 15 SD and mean roughness of 17 ± 7 SD. In addition several emergent boulders are found particularly in the upper section.

The site was mapped by total station (LEICA TC307) during the autumn of 2003 and ice measurements were carried out in the following winter. The water surface elevation was measured along the entire reach to quantify the effect of ice formation on the water level in the reach. Anchor ice was mapped for both location and thickness of the ice accumulation. The border ice along the reach was mapped during the initial ice formation, and the ice cover development was mapped several times during the winter. Air and water temperature data was collected using Vemco temperature loggers.

Statistical analysis was conducted using Minitab v. 14.1 and SPSS v. 13.0 for Windows. Assumptions of normality and homogeneity of variance were tested and, when these conditions were violated, non parametric tests were used. Results were considered significant at the $p = 0.05$ α level and mean values are shown with their associated standard deviation (± SD).

3 Results

River Orkla; ice formation winter 2003:

Frazil ice production and anchor ice growth had a diurnal cycle; growth during night time and cessation at daytime. Anchor ice formed every night except night 22nd of February where an artificial ice break up occurred due to a decrease in water discharge from 22 to 11 m^3s^{-1}. Here, no anchor ice formation was observed. During nights 27th and 28th of February and night 1st of March extensive ice formation occurred (Figure 3) covering 93.3 % of both riffle and pool section. Ice thickness up to 50 cm was observed. Air temperature dropped significantly during the nights, with lowest temperature on night 1st of March (-14.0 ˚C). Supercooling occurred every night (mean ± SD; -0.10 ± 0.02 SD) with minimum value of -0.125 ˚C on night 22nd of February. Net heat flux reached its minimum during night time (mean ± SD; -107.8 W/m^2 ± 20.5, min net heat flux = -144.3 W/m^2) and maximum during day time (mean ± SD; 55.11 W/m^2 ± 141.6 SD, max net heat flux = 362.1 W/m^2) (Figure 3). Cessation of anchor ice was observed to occur between 10 a.m. and 13 a.m. Formation of anchor ice was observed from 9 p.m. Here, the net heat flux ranged from -78.9 to -130.0 W/m^2. Statistical tests showed a significant difference (Mann-Whitney U-test, $p = 0.000$) between net heat flux during low and high degree (defined as ice covered area on the bed) of anchor ice formation with lowest median net heat flux (-132.6 W/m^2) during high degree of anchor ice formation. Test on difference between degree of anchor ice formation during high and low flow level showed no significant difference (Mann-Whitney U-test, $p = 0.18$).

During the experimental period one small anchor ice dam (50 cm high, 3 m wide) was established at the upstream edge of the riffle part causing local alterations of the water flow. In a deep pool (approximately 4 m deep, 40 m wide) at the downstream end of the study reach a hanging dam was established increasing the water depth of 30 cm 150 m upstream and thereby influencing the velocity field in the upstream riffle. In the riffle section anchor ice was observed to form between the substratum and down into the bed, filling the space between boulders.

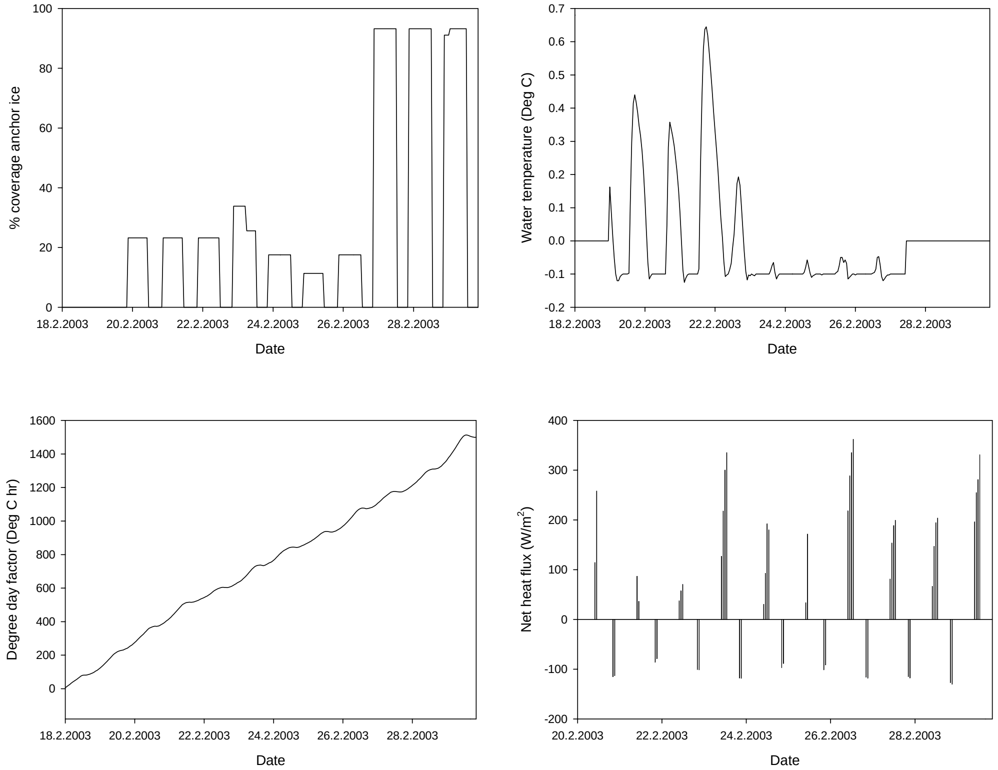

Figure 3: Graphs on anchor ice coverage, water temperature and degree day factor (1 h) during the study period winter 2003. In addition graph of net heat flux during cessation (positive values) and formation (negative values) of anchor ice.

River Orkla; ice formation winter 2005

Mean roughness (mean ± SD) defined as effective height of the substrate in the two experimental squares in the lower and upper riffle section was 10.0 cm ± 5.7 SD and 5.8 cm ± 5.1 SD, respectively. Glide section had a mean roughness (mean ± SD) of 5.7 cm ± 3.2 SD. Average mean depth in glide section was 38.5 cm ± 10.5 SD and 48.3 cm ±13.1 SD and 38.8 cm ± 9.2 SD, lower and upper riffle, respectively. Mean velocity was 24.2 cm/s (glide) and 55.0 cm/s (upper riffle). No values were recorded for the lower riffle section due to vibrations in the tripod carrying the velocity meter (visual observation). Turbulence level (represented by RMS [V']) was measured as 9.9 cm/s and 37.2 cm/s for glide and riffle part, respectively (Figure 4). Froude number was calculated as 0.11 for the glide and 0.30 for the riffle. As observed during the 2003 experiment anchor ice formed between the substrate and not only as a top layer. A high accuracy temperature logger (± 0.002) showed supercooling during anchor ice formation (9 – 10 p.m.) ranging from -0.004 to -0.08˚C (Figure 4).

Test on difference between the three experimental sites showed no significant difference in substratum composition (Kruskal-Wallis test, d.f. = 2, p = 0.76), but a significant difference in median depth (Kruskal-Wallis test, p = 0.001). Significant (Kruskal-Wallis test, p = 0.005) higher degree of anchor ice formation (defined as thickness) were found in the three experimental squares located in the riffle section and in the glide section. In the glide section anchor ice distribution was only scattered on the bottom substrate (estimated 0.5 % of total area ice covered) while in the riffle section had a uniform coverage of 97.2 and 99.2 %, respectively.

Table 2: Hydraulic features of the three experimental squares in River Orkla, winter 2005. Turbulence values are based on surface measurements while velocity is from 50 % of depth.

Hydraulic parameter	Smooth glide (upstream)	Riffle I (mid section)	Riffle II (downstream)
Area (m^2)	8.7	14.3	11.9
Substratum roughness (k_s)	5.7 cm ± 3.2 SD	5.8 cm ± 5.1 SD	10.0 cm ± 5.7 SD
Depth (Y_{av})	48.4 ± 13.12 SD	38.8 cm ± 9.2 SD	48.3 cm ±13.1 SD
Velocity (U_{av})	24.2 cm/s	57.7 cm/s	-
Turbulence (RMS [V'])	9.9 cm/s	37.2 cm/s	-
Froude number (Fr)	0.11	0.30	-

Anchor ice data			
Coverage (%)	0.5	97.2	99.2
Average ice thickness (cm)	3.6	10.9	3.9
Max ice thickness (cm)	12	20	7
Min ice thickness (cm)	0	0	0

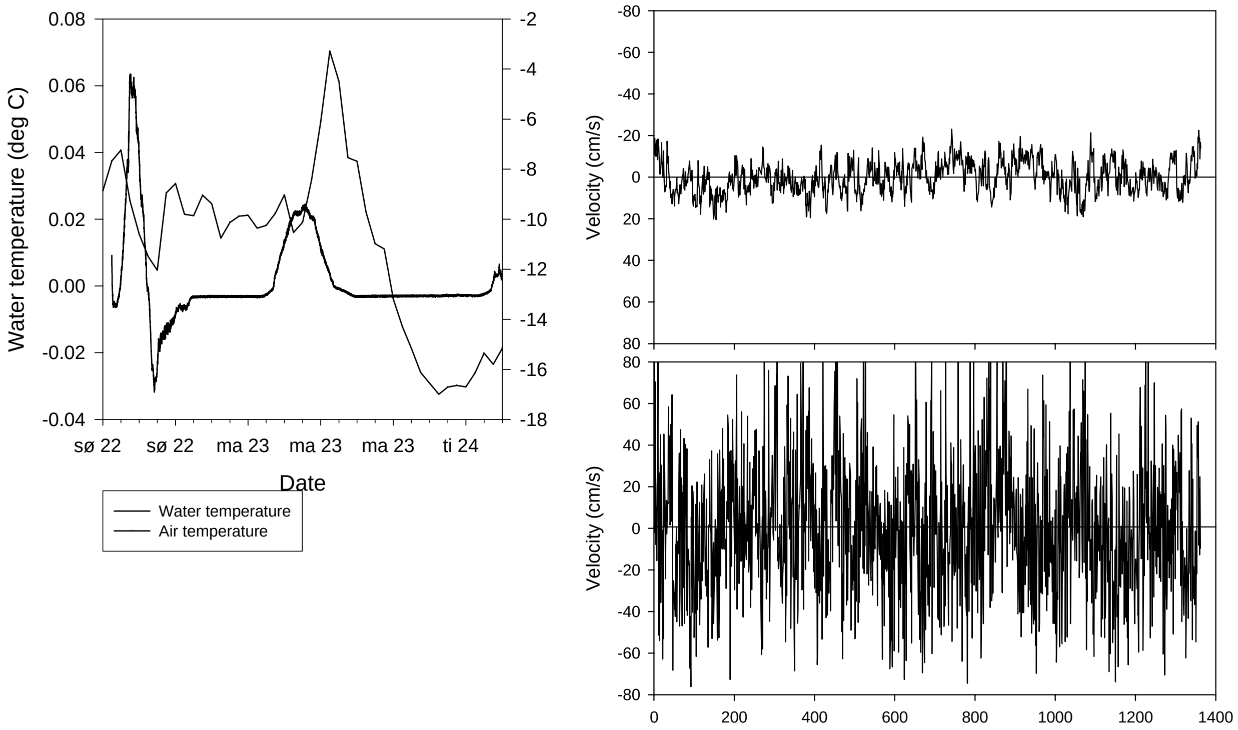

Figure 4: Water and air temperature for Orkla study site during ice measurements in 2005 (left). Velocity fluctuations around mean in upper section (upper right graph, average velocity 55 cm/s) and middle section (lower right graph, average velocity 78 cm/s).

River Stavilla, ice formation

The first ice formation appeared in late October when border ice formed along the banks. Following the first real cold period, five anchor ice dams formed in the reach (Figure 5 and Figure 6). Further, smaller anchor ice aggregations occurred on larger substrate in the upper part of the reach, and carpets of anchor ice covered the bottom in the lower part of the reach. The anchor ice dams reached a thickness of 58 cm (mean 22 cm ± 13 SD).The formation of anchor ice dams lead to a rise in water level at each location, with the most pronounced rise at the most downstream area of the study site (Figure 5). The discharge at the time of ice formation was 1.8 m^3s^{-1}. A continuous ice cover formed on the pool upstream of the lower anchor ice dam while the dams upstream eventually were drained. The edges of the upstream anchor ice dams froze and formed permanent constrictions to the river channel that increased the border ice cover and formed further anchor ice dams in the river. The narrowing of the river reach altered the flow pattern and the velocity distribution within the channel

The initial formation of anchor ice occurred in areas with large bottom substrate/emergent boulders and/or in areas with shallow water. Typically were areas where the river was narrower and where substrate formed underwater sills in the river

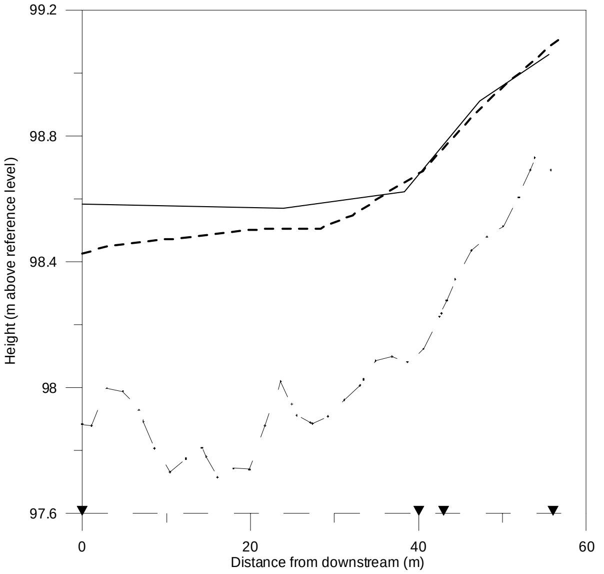

Figure 5: Change of water surf ace elevation in River Stavilla before (small, dashed line) and after (solid line) anchor ice formation. Elevation of river bed is given as large, dashed line (lower line).Triangles shows position of the anchor ice dams from downstream end.

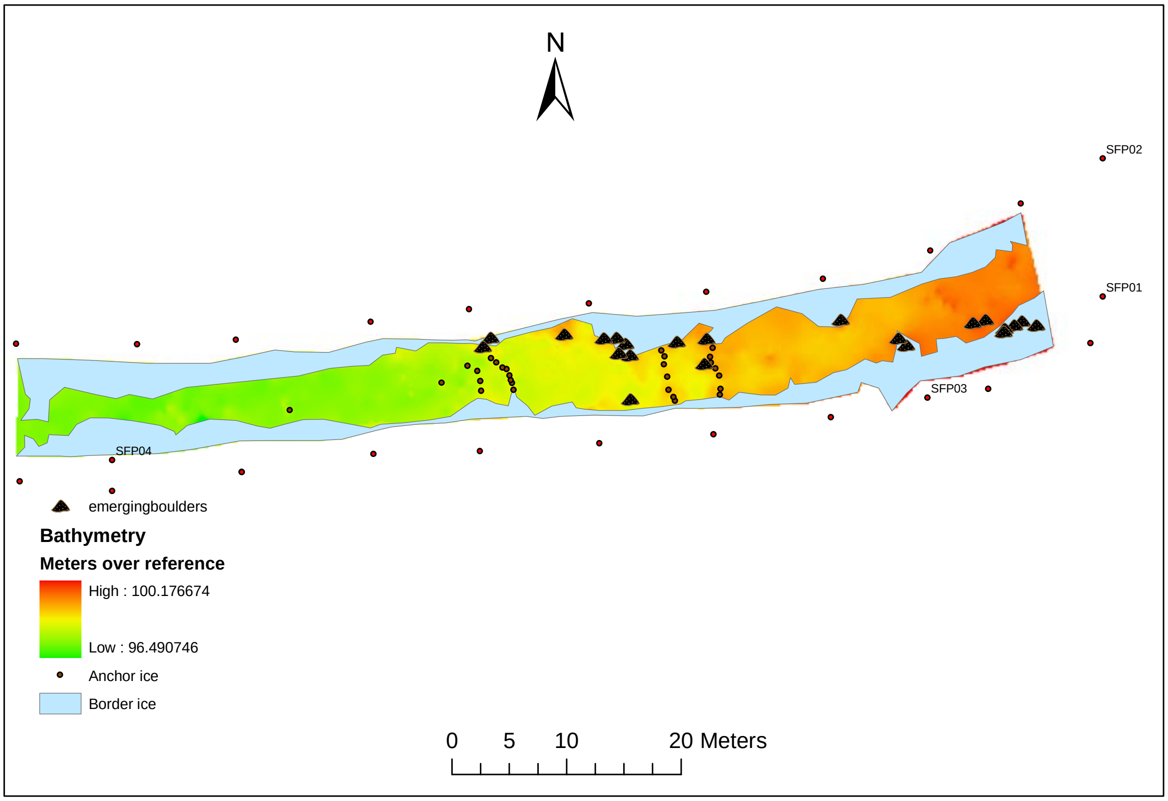

Figure 6: Position of anchor ice dams and border ice in Stavilla during initial freeze over.

4 Discussion

According literature anchor ice formation has been related to predominantly occur during supercooled water in locations with sufficient level of turbulence, i.e. rapids and riffles (e.g. Carstens, 1970; Tesaker, 1971; Ashton, 1986). In the present study anchor ice formation in two different river types, one regulated and one small, steep river has been studied. Results show that the dynamic ice process itself varies dependent on the river characteristics.

The study reach in River Orkla are less steep (0.5 %) compared to River Stavilla (1.6 %), and has a gentler flow pattern with a combination of riffle and pool areas. The pool areas will freeze over and for the parts of the river that are not affected by the hydropower system a fixed cover may form. The river Sokna is mostly composed of rapids and riffles with few areas where velocity conditions permit a fixed ice cover. Therefore the ice formation regime is different from the river Orkla using border ice and anchor ice dams to form the ice cover.

In River Orkla anchor ice followed a diurnal pattern with growth during night time and cessation during daytime. In addition large quantities of frazil accumulated downstream in a deep pool causing a hanging dam that frequently raised and lowered (due to drainage) the water level. Only one, small (relative compared to the size of the study area) anchor ice dam was established, but this had no effect on the ice formation in the reach. In River Stavilla anchor ice did not loosen during daytime and several anchor ice dams were formed, predominantly upstream larger boulders and on shallow underwater sills in the rapid section. Observations indicate that formation of such dams is a crucial factor for further ice cover formation in small, steep rivers, which corresponds with previous literature and observations (Kanavin, 1970; Tesaker, 1994). Formation of an ice cover in a steep river must follow a different process than in a gentle sloping river due to velocities above the limit for ice accumulation. The most common process is a combination of border ice formation in shallow and slower flowing areas and anchor ice dams that raises the water level and reduces the velocity so that an ice cover can form. These processes were evident in the study reach in Stavilla, and the ice cover that eventually formed was to a high degree controlled by the formation of anchor ice dams. Similar formation processes were also seen in the river downstream of our study site where anchor dams of more than 1.5 meters in height was observed. This process was repeated over several cold periods until a stable cover formed. In a discussion on ecological effects of winter the increased variability in flow pattern may be of important since anchor ice dams completely alter the upstream flow conditions and that repeated drainage of the dams may create an unstable flow regime in the reach.

As noted by Kanavin (1970) dynamic ice production may increase in regulated rivers. In River Orkla extensive anchor ice formation occurred during night time both in riffle and pool section. In our study this occurred after a decrease in water discharge covering up to 99.2 % of the bed with a maximum ice thickness of 50 cm. The decrease in water discharge seemed to stabilize the water temperature at a lower level thereby increasing the cooling effect and may have contributed to the extensive ice formation. However, no significant difference was found between water flows and high and low degree of anchor ice formation, indicating that other parameters may be more important.

Most previous research (Michel, 1971; Arden and Wigle, 1972; Tsang, 1982; Daly, 1991) indicates that anchor ice formation starts hours after sunset. In a study by Kempema et al. (2004) these assumptions were made in which midnight was assumed to be the starting time for growth. In the present study in River Orkla anchor ice formation was observed initiated 2-3 hours after sunset (8 to 9 p.m.). Here, net heat flux ranged from -78.9 to -130.0 W/m^2 which is similar compared to Hirayama (1986) who observed that a large amount of frazil appeared when the net heat flux was -116.3. Anchor ice is also suggested to only remain attached to the river bed during supercooled water and released when the sun is warming the water (e.g. Arden and Wigle, 1972; Tsang, 1982). In River Orkla the anchor ice were not released until mid day (from 10 to 13 a.m.). Although our observations during winter 2003 experiment showed that the water stayed supercooled the accuracy of the temperature loggers have to be considered (± 0.1˚C). In River Stavilla the ice was not released from the river bed during the whole day. Here, it has to be considered that River Stavilla study site has only one and a half hour with sunlight during day time due to its position in a steep forested valley. On the other hand small, steep rivers seem to have a more extensive dynamic ice formation and higher degree of ice accumulation, relative to its size. Also, when the established anchor ice dams in this river drained the remaining ice borders froze and provided grounds for further ice development.

General discussions on anchor ice formation have been concerned with loose bindings and formation on the upper part of the substrate. Kerr et al. (2002) made observations of anchor ice laying on top of substrate, and similar observations were made by Roussel et al. (2004) in a study on Atlantic salmon (*Salmo salar*). In the laboratory experiment by Kerr et al. (2002) they found that anchor ice never formed lower than 0.4 to 0.5 d_s of top of the gravel. In contrast, the observations in both Stavilla and Orkla show that the ice may completely encapsulate the bottom substrate and remove interstitial space. In River Stavilla it was also observed frozen ice on the river bottom after a prolonged period with cold weather. Substrate size has also been discussed in relation to anchor ice formation. Tsang (1982) states that anchor ice normally form on boulders and gravel, but usually not on sand, silt or finer material. In River Orkla anchor ice growth seemed not to be affected by the substrate size in the area, i.e. ice formation was observed both on pebbles and cobbles. However, locations with sand or silt were never observed with anchor ice which corresponds well with previous studies. In the experiment during winter 2005 no significant difference on substrate size between the experimental sites was found, but it was found a significant difference in anchor ice distribution. Further, a significant difference in depth distribution was found and measurements of turbulence level near surface were different between the riffle and the smooth, glide section. Mean velocity was also found to be different between the sections. Earlier findings (Tesaker, 1994; Hiryama et al., 2002) have suggested a critical velocity value of 0.6 to 0.9 m/s for initiation of dynamic ice formation. In our study anchor ice formed in both low velocity (0.24 m/s) and in high velocity (0.58 m/s) fields, although the amount of ice formed in the low velocity area was small. The results indicate that anchor ice formation may not be determined by velocity or substrate alone, but is dependent on the amount of vertical mixing (turbulence), which seems to be a general statement in the literature. This could again be attributed to slope, depth and bed roughness in the river reach for a simple relationship between anchor ice formation and physical parameters in the river.

5 Acknowledgments

The project is partly funded by the Norwegian Research Council under the “Wild salmon research program” and partly by the Faculty of Engineering Science and Technology by a PhD scholarship to Morten Stickler. The authors wish to thank Åsta Gurandsrud and Ingerid Pegg for field work and data analysis.

6 References

Arden, R. S. and T. E. Wigle, 1972. Dynamics of ice formation in the Upper Niagara River. The role of snow and ice in hydrology, IAHS-UNESCO-WMO, Banff.

Ashton, G. D., 1986. River and lake ice engineering, Water resources publications. ISBN 0-918334-59-4

Beltaos, S., 1995. River ice jams. Water Resources Publications, LLC. ISBN 0-918334-87-X.

Carstens, T., 1970. Heat exchanges and frazil formation. Proceedings of the symposium on ice and action on hydraulic structures, Reykjavik, Island.

Cunjak, R. A., 1988. Behavior and microhabitat of young Atlantic Salmo (Salmo Salar) during winter. Can. J. Fish. Aquati. Sci. 45: 2156-2160.

Cunjak, R. A. and G. Power, 1986. Winter habitat utilization by stream resident brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*). Can. J. Fish. Aquati. 43: 1970-1981.

Daly, S. F., 1991. Frazil ice blockage of intake trash racks. C. R. T. Digest**:** 12p.

Day, T. J. and J. C. Anderson, 1976. Observations on river ice, Thomson River, Banks Island, District of Franklin. Canadian Geological Survey Paper 76-1B.

Devik, O., 1930. Thermal and dynamic conditions for ice formation in watercourses (in Germany), Geof. Publ.

Doering, J. C., L. E. Bekeris, M. P. Morris, K. E. Dow and W. C. Girling, 2001. Laboratorie study of anchor ice growth. Journal of Cold Regions Engineering 15: 60 - 66.

Doering, J. C. and M. P. Morris, 2003. A digital image processing system to characterize frazil ice. Canadian Journal of Civil Engineering 30: 1-10.

Freysteinsson, S. and A. Benediktsson (1994). Operation of hydro power plants under diverse ice conditions. Proceedings of the 12th Symposium on ice. Trondheim, Norway, August 23-26, Vol 1. pp. 118-128.

Goring, D.G. and V. I. Nikora (2002). Despiking Acoustic Doppler Velocimeter Data. Journal of Hydraulic Engineering vol 128, no 1, pp 117-126.

Hammar, L. and Shen, H.T. (1995) Anchor Ice Growth in Channels. 8th Workshop on hydraulics of ice covered rivers. pp. 77-88

Heggenes, J., O. M. W. Krog, O. R. Lindås, J. G. Dokk and T. Bremnes, 1993. Homeostatic behavioural responses in a changing environment: brown trout (Salmo trutta) become nocturnal during winter. Journal of Animal Ecology 62: 295-308.

Hirayama, K., 1986. Growth of ice cover in steep and small rivers. International Association of Hydraulics and Research Ice Symposium, Iowa City.

Hiryama, K., M. Yamazaki and H. T. Shen, 2002. Aspects of river ice hydrology in Japan. Hydrological processes 16.

Kanavin, E. V., 1970. Ice cover formation in lakes and rivers. Oslo, Norwegian Electric Company (NVE)**:** 34.

Ke, S., G. Lu and Z. Ren, 2000. Study on mechanisms of ice jam formation in Bayangaole of Yellow river. Shuiili Xuebao/Journal of Hydraulic Engineering 7: 66-69.

Kempema, E., E. Reimnitz and P. Barnes, W., 2004. Anchor-ice formation and ice rafting in Southwestern Lake Michigan, U.S.A. Journal of Sedimentary Research 71: 346-354.

Kerr, D. J., H. T. Shen and S. F. Daly, 2002. Evolution and hydraulic resistance of anchor ice on gravel bed. Cold regions science amd technology 35: 101-114.

Michel, A. B., 1971. Winter regime of rivers and lakes.

Morse, B. and F. Hicks, 2005. Advances in river ice hydrology, 1999-2003. Hydrological processes 19: 247-263.

Prowse, T. D., 1994. Environmental significance of ice to streamflow in cold regions. Freshwater Biology 32: 241-259.

Prowse, T. D., 2001. River ice ecology. I:Hydrologic, Geomorphic, and Water-Quality Aspects. Cold Regions Engineering.

Shen, H. T., 1998. Ice in surface waters. Proceedings of the 14th international symposium on ice, Balkema, Rotterdam.

Shen, H. T., 2003. Research on river ice processes: Progress and missing links. Journal of Cold Regions Engineering: 135-142.

Tesaker, E., 1971. Hydraulic conditions in ice covered rivers, The Norwegian Electric company (NVE).

Tesaker, E., 1994. Ice formation in steep rivers. Proceedings international ice symposium, IAHR, Trondheim, Norway.

Tsang, G., 1982. Frazil and anchor ice, a monograph. Ottawa, National research counscil of Canada, Subcommitee on hydraulics of ice-covered rivers.

Wahl, T.L. (2003). Discusson of " Despiking Acoustic Doppler Velocimeter Data". Journal of Hydraulic Engineering, vol 129, no. 6, pp. 484 - 487

Williams, G. P., 1959. An emperical method of estimating total heat losses from open-water surface. Proceedings of the VIII International Association of Hydraulics Research Congress, Montreal.