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Ice breakup in small Norwegian streams

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MASTEROPPGÅVE I VASSDRAGSTEKNIKK

Kandidat: **Siv Heggen**

Tema: **Isgang i små vassdrag**

1. Bakgrunn

Isgangar i små og store vassdrag fører regelmessig til skader både på infrastruktur som bruer og vegar og på sjølve elva gjennom erosjon av bredder og vegetasjon. I tillegg kan isen og oppstuving av vatn føre til problem med kommunikasjon og blokkering av inntak av vatn. Hovudtyngda av forskning på isgangar er gjort i store elver i Nord Amerika, og lite analyser er gjort i Norge. Målet med denne oppgåva er å utforske drivkrefter bak isgangar i norske elver og korleis vi kan føresjå isgangar gjennom tilpassing av modellar for isgang. Bakgrunn og teoretisk grunnlag for oppgåva bygger på prosjektarbeid hausten 2012.

2. Arbeidsoppgåver

Oppgåva vil ha følgjande hovuddelar:

1. Følge opp målekampanjer i Sokna og Ingdalselva med tanke på å kunne analysere isgangar i desse elvene med metodikken frå 4) når elvene mest sannsynleg er isfrie i løpet av slutten av mars og starten av april. Ein viktig del av oppgåva er å følgje med på utviklinga, foreslå måleopplegg og i tilfelle det lar seg gjere å observere og dokumentere

sjølve isgangen. Det skal og samlast inn data slik at vi kan vurdere isvekst denne vinteren.

2. Vurdere og prøve ut ei metode for å modellere isvekst i Sokna og Ingdalselva med tanke på å estimere tjukkelsen på isen ved start av isgangen. Dette er viktig både med tanke på data frå i år, men og for å kunne utnytte data frå eldre observerte isgangar. Data frå 1) skal brukast for å teste metoda.

3. Analyse eksisterande data for kjende isgangar (t.d. Sokna 2005/6 eller Ingdalselva kan vere alternativ) for å undersøke kva drivkreftene bak isgangen er. Vurdering av eksisterande måledata og innhenting og utrekning av andre data dersom dette er naudsynt, evt bruke data frå litteraturen.

4. Prøve ut modellar for isgangar som vart samla inn i løpet av prosjektoppgåva for å sjå korleis desse passar til data funne i 1). Vurdere kva som fungerer og kva som eventuelt må oppgraderast for å tilpasse desse modellane til norske tilhøve. Tilpasse modell og teste ut denne.

5. Basert på funn i oppgåva foreslå prosedyrer for vidare forskning om isgangar. Dette kan dreie seg om målekampanjer, analyse av historiske data, felt/labstudier av is og modellutvikling.

3. Rettleiing, data og informasjon

Faglærar vert professor Knut Alfredsen ved institutt for vann- og miljøteknikk, NTNU. Stipendiatane Netra P. Timalsina og Solomon B. Gebre kan vere aktuelle for diskusjonar rundt is og ismodellering. Kandidaten er elles ansvarleg for innsamling, kontroll og bruk av data. Hjelp frå dei ovanfor nemnde personane eller andre må refererast i rapporten.

4. Rapport

Hovuddelen av den skriftlege rapporten av oppgåva er ein konferanseartikkel til Committee on River Ice Processes and the Environment (CRIPE) 2013 i Edmonton, Canda. Resultata skal og presenterast ved denne konferansa.

Sidan ein artikkel typisk inneheld ei oppsummering av resultata frå prosjektet skal rapporten og innehalde tilleggsinformasjon om arbeidet utforma som "supplementary information" til artikkelen. Dette kan vere meir detaljert skildring av metoder, resultat som ikkje er brukte i artikkelen, utdjuping av resultat og data og ytterlegare diskusjon av resultat. Resultat frå del 5) i oppgåva må og dokumenterast i rapporten.

Data som er samla inn skal dokumeterast og leverast på digital form.

Denne oppgåveteksta skal vere inkludert i rapporten.

Formatet på rapporten skal følgje standarden ved NTNU. Alle figurar, kart og bilete som er inkludert i rapporten skal vere av god kvalitet.

Kandidaten skal inkludere ei signert fråsegn som seier at arbeidet som er presentert er eins eige, og at alle bidrag frå andre kjelder er identifiserte gjennom referanser eller på andre måtar.

Frist for innlevering er 10. juni 2013.

Insitutt for vann og miljøteknikk, NTNU

Knut Alfredsen

Professor

PREFACE

This report is the product of the Master`s thesis which is conducted in the 10th semester of the Civil and Environmental Engineering program at Norwegian University of Science and Technology (NTNU). The assignment is conducted at the department of Hydraulic and Environmental Engineering and is included in the project HydroPeak WP8 “Ice problems in rivers”. HydroPeak WP8 is funded by the Centre for Environmentally Designed Renewable Energy (CEDREN).

I would like to thank my supervisor, Knut Alfredsen, for many good suggestions and discussions. I appreciate the great commitment throughout the semester and all the help provided at short notices. Thanks to Spyros Beltaos, Rheannon Brooks and Jennifer Nafziger for help on varying issues during the progress of work. I was met with very welcoming, interested and helpful responses. Special thanks to PhD student Netra P. Timalsina for assistance in field and great motivation to work at my best.

Finally I want to thank my fellow students at “Verkstedloftet” for a great atmosphere and enjoyable days even when the stress was at its worst.

The presented work is my own and contributions from other sources are identified through references or other means. In addition to this report it is attached a CD with full documentation of data and results.

Siv Heggen

Siv Heggen

Trondheim 10.06.13

ABSTRACT

River ice is present parts of the year in cold region environments and is an important component of the flow regime. The river ice is known to produce many extremes and potential floods far exceed those possible under open-water conditions. Thus, predicting the time of a river ice breakup is essential as it concerns environmental impact, emergency flood warning and hydropower production.

The available predictive methods are developed and tested only for moderate-gradient medium and large rivers. Their utility for high-gradient small streams is not known. As a first step toward development of a criterion for ice breakups in small streams one of the existing criteria for large rivers is tested. The ice cover thickness is an important parameter considering the river ice breakup, thus a simulation of the ice cover growth is included in the analysis. Extensive data are retrieved from field studies and analysis regarding ice cover growth and ice breakup is conducted.

The Stefan formula is proven to give good results for the ice cover growth in the observation sites. The method provides reliable values of the ice thicknesses which then are used as input parameter to the Empirical criterion for onset of breakup. The Empirical criterion has some inconsistency in its simulations of the river ice breakups. However, the criterion was able to simulate three of five ice breakups in small streams. This is evaluated as a promising result and the criterion can thereby be used as a foundation for further research and development.

SAMANDRAG

Is er tilstades delar av året for elvar i kalde regionar og er ein viktig komponent for strøymningsbiletet. Isen i elvane er kjent for å skape mange ekstreme hendingar og potensielle flaumar overgår dei som er aktuelle for situasjonar med ope vasspegl. Det er dermed avgjerande å kunne forutsjå tidspunktet for ein isgang sidan det påverkar både miljø, flomvarsling og kraftproduksjon.

Dei tilgjengelige metodane er utvikla og testa berre for middels og store elvar med moderat helning. Bruksområde for bratte små elvar er ikkje kjent. Som eit første steg mot utvikling av eit kriterie for isgangar i små elvar er eit av dei eksisterande kriteria for store elvar testa. Tjukkelsen på isdekket er ein viktig parameter for isgangar og det er dermed inkludert ei simulering av isveksten i analysa. Frå feltstudiar er det samla inn omfattande data og det er gjennomført analysar både for isvekst og isgang.

Stefan formel viser å gi gode resultat for isveksten på observasjon stadane. Metoden gir pålitelege verdiar for istjukkelsane som vidare er brukt som input parameter til det Empiriske kriteriet for initiering av ein isgang. Det Empiriske kriteriet har ikkje fullstendig samsvar i simuleringane av isgangane. Kriteriet var likevel i stand til å simulere tre av fem isgangar i små elvar. Dette er evaluert som eit lovande resultat og kriteriet kan dermed brukast for vidare forskning og utvikling.

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GLOSSARY

Expression	Definition
High-gradient small stream compared to moderate-gradient large river	Inclination limit around 0.3-0.6 % while small and large must be seen as relative terms
Ice cover formation	Progress from open-water conditions to a full ice cover
Frazil ice	Small ice crystals formed in supercooled water
Anchor ice	Build up of frazil ice around cold surfaces
Full ice cover	A stable ice cover which runs over the river width
River ice breakup	River ice is broken up and transported with the flow
Onset of river ice breakup	First sustained movement of the winter ice cover
Ice jam	Congestion of ice rubble and blocks
Jave	Steep-wave initiated by a jam release
Mechanical breakup	Fracture and dislodgment of a still competent ice cover
Thermal breakup	Ice breakup initiated by a significant ice strength and thickness reduction
AFDD	Accumulated freezing degree-days
ATDD	Accumulated thawing degree-days
Empirical criterion	Used as a specific name on the empirical criterion which have been tested
Infiltration capacity	The soils ability to absorb the water which arrives at the soil surface
Gauge station	Field instrument for climate data measurements such as temperature, wind and air humidity
Pressure sensor	Field instrument for water level measurements
masl	Meter above sea level
GPS	Global Positioning System

1. INTRODUCTION

1.1. Background

River ice is present parts of the year in cold region environments. The ice cover makes an important component of the flow regime and it is known to produce many extremes. Potential floods far exceed those possible under open-water conditions (Prowse, 2001). Other impacts may be low winter flows and interference with energy production (Prowse, et al., 2002). Ice jam floods introduce most socioeconomic effects, in which both loss of property and human life may be experienced. The consequences emphasizes the importance of understanding the river ice processes, but still the research is at an early phase of development and many of the processes are only partially understood (Beltaos, 2012).

Considering ice breakups in moderate-gradient medium and large rivers several studies have been conducted over the last decades and a good knowledge base exists in literature. However, significant local damages from ice breakups in Norwegian high-gradient small streams are also observed (Alfredsen, pers.com). Nevertheless, not much work has been done to understand the mechanisms behind these events. Another problem is that very little or no data on ice breakup is available in Norway (Gebre, et al., 2011). Norwegian rivers are of moderate size and fairly steep compared to rivers often referred to in ice studies, such as Canadian and Russian rivers. Even the largest rivers in Norway appear to be small in such a scale (Asvall, 1994).

1.2. Objectives and scope of work

The purpose of this Master`s thesis is to get a better understanding of the mechanisms behind river ice breakups in small steep streams. An exact definition of a small steep stream does not exist. However, a limit of 0.3-0.6 % in inclination is used in some contexts regarding anchor ice formation (Tesaker, 1994). 0.3.-0.6 % inclination can be seen as the limit between gentle and steep slopes for this study. Regarding the size a definition is not made. Small and large must rather be seen as relative terms.

Ice breakups can appear as both mechanical and thermal events, of which the mechanical breakups lead to the most severe consequences. Mechanical breakups are therefore the ones focused upon. Measuring work are implemented and used to document the river ice during the winter season 2012/13 for two streams in the middle part of Norway; Ingdalselva and Sokna. In addition data from two ice breakups in Sokna during 2005/06 are analyzed. One of the criteria developed for high-gradient medium and large rivers are tested on the known ice breakups.

It has been decided to exclude the process of ice formation and rather concentrate on the ice cover development after the ice has formed as a full cover. This way the focus is centered on the river ice breakup processes. The ice cover thickness is important in determining the stability of the ice cover and later on its breakup. Thus, the mechanical breakup models initiate a field study of the ice cover thickness.

The dynamic river ice processes, which follow a mechanical breakup, are excluded. These are very complex and would have required an independent study.

This report is structured around a conference article for the Committee on River Ice Processes and the Environment (CRIPE) 2013 in Edmonton, Canada. Chapter 3 consists of the article in its totality. The additional chapters are added to give a more detailed description of the background literature as well as supplementary information on the methodology and further discussion.

2. LITERATURE REVIEW

Most of the literature presented is retrieved from the project work conducted fall 2012 by the author. The project work was led out as a literature study for the Master`s thesis and Chapter 2 is therefore a composition of the main theory from that work. For further information it is referred to the project work (Heggen, 2012).

2.1. River ice processes; Brief description

Ice forms in rivers after sufficient heat has been removed from the water to the surrounding air, resulting in a lowering of the water temperature to 0°C (Ashton, 1978). In slow flowing turbulent water bodies the initial ice formation is due to frazil ice. Frazil ice is small ice crystals that are formed in supercooled water. The suspended ice crystals increase both in size and number, freeze together and form a cover (Svensson, et al., 1993).

In fast flowing rivers conditions are not present for a floating frazil ice formation. Instead frazil ice builds up on accessible cold surfaces such as large boulders. After sufficient growth anchor ice dams form. Upstream of each dam the water level increase, velocity decrease and formation of a surface ice cover can take place (Turcotte, et al., 2011).

The freezeup period, characterized by formation, growth and accumulation of ice, changes the hydraulic conditions of the river. The increased wetted perimeter and boundary roughness reduces the flow conveyance, leading to flooding for smaller discharges than for the open-water condition (Beltaos, 2008).

The ice cover is not necessarily intact throughout the winter, and mid-winter breakups can occur if the driving forces acting on the cover exceed the resisting forces. Rain-on-snow events cause the most rapid runoff in general, especially when the ground is frozen and has a low infiltration capacity. The climatic conditions that characterize freezeup are reversed at breakup. Greater solar insolation and rising air temperatures result in a positive heat flux to the ice cover, which initiate a thermal decay. The spring runoff also affects the breakup by increased discharges, flow velocities and shear stresses that are applied on the ice cover. These factors reduce the structural integrity of the cover (Beltaos, 2008).

2.2. Thermal and mechanical breakup events

Generally for all rivers the most important factors that resist ice cover dislodgment are the thickness, strength and areal extent of the ice. Examples of driving factors are hydrodynamic forces and water surface width. Considering a stable ice cover the resisting factors (R) are larger than the driving factors (D). However, as the breakup period advance, a point is reached when the driving factors equals the resisting factors. The development up to this point determines the type of breakup event that occurs. The different types of breakup events are described in Table 1 (Beltaos, 2008).

Table 1: Breakup events (Beltaos, 2008)

Breakup event	Description	Figure 1
Normal event	The point D=R is reached due to a decrease of the resisting force at the same time as the driving force increase	A
Premature breakup event	The resisting force remains constant while the driving force increase. D=R will happen after a longer time than for the normal event.	B
Thermal breakup event	The driving force remains constant while the resisting force decrease. D=R will happen after a longer time than for the normal event.	C

Shortly after the situation for D=R the driving factors exceeds the resisting factors and the ice cover is dislodged and set in motion. The development of the different breakup events can be shown in Figure 1. D and R are here termed as “forces” but should be understood to incorporate a variety of effects (Beltaos, 2008).

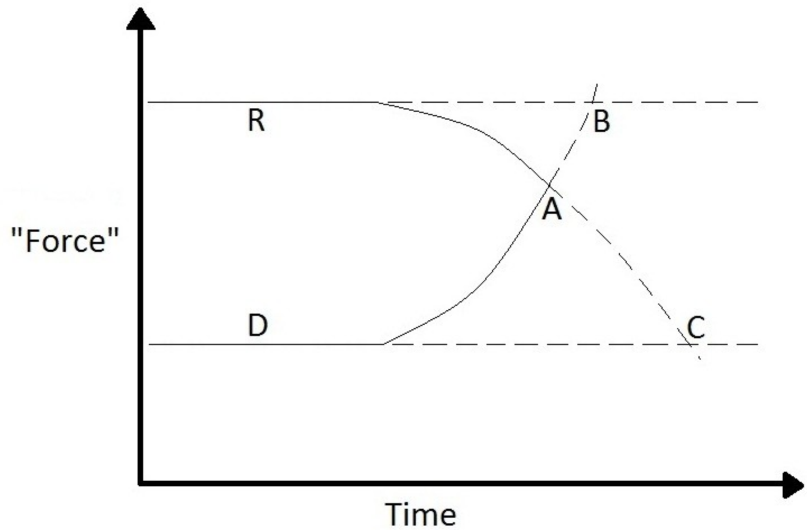

Figure 1: Illustration of different types of breakup events (Beltaos, 2008)

A thermal breakup, event C in Figure 1, takes place when the strength and thickness of the ice cover are reduced to the point where it disintegrates in place. The opposite form of breakup is called a mechanical breakup, characterized by the fracture and dislodgment of a still competent ice cover. Both event A and B in Figure 1 belongs under the definition of mechanical breakups (Beltaos, 2008).

A mechanical breakup is much more severe than a thermal breakup and can lead to extreme ice-jam flood events (Beltaos, 2003). When a jam releases, the water that has been stored moves down the river in form of a steep wave, called a *jave*. Downstream sites experience a rapid rise in water levels and preexisting ice cover may be broken up and set in motion by the jave. If the downstream ice cover is sufficiently strong it may cause another ice jam (Beltaos, 2008).

By contrast, thermal breakups can only produce insignificant, if any, jamming. Under thermal breakups most of the ice is melted before it is set in motion (Beltaos, 2003).

2.3. Mechanisms behind mechanical breakups

There is a complex interaction between hydrometeorological influences and ice mechanical properties which are decisive when it comes to the size of the forces acting on a river ice cover (Washanta Lal, et al., 1993). Solar insolation penetrating into the cover can cause internal melting and loss of structural integrity even before the air temperature rises above freezing. This reduction of ice cover strength and the increase in basin runoff and river discharge are important factors in the initiation of ice cover breakups (Shen, 2009).

The mechanisms presented here are developed for moderate-gradient large and medium rivers. The validity of the mechanisms for high-gradient small streams is not known.

2.3.1. Driving forces

The main forces acting on a river ice cover are the flow shear stress and the weight of the cover, both working in the downslope direction. The flow shear stress, τ_i, is applied on the bottom surface of the ice cover, and is estimated as (Beltaos, 2008):

$$\tau_i = \rho g R_i S_f = \frac{n_i}{8} \rho U^2 \qquad \text{(Eq. 1)}$$

Table 2: Overview of parameters in flow shear stress formula (Beltaos, 2008)

Parameter	Description	Unit
ρ	Density of water	[kg m^{-3}]
g	Gravitational acceleration	[m s^{-2}]
R_i	Hydraulic radius of the ice cover	[m]
S_f	Energy slope	-
n_i	Friction factor	-
U	Flow velocity	[m s^{-1}]

While the downslope component of the weight of the cover, w_i, is expressed by (Beltaos, 2008):

$$w_i = \rho g s_i \eta S_w + 0.96 \rho g \eta_p S_w \qquad \text{(Eq. 2)}$$

Table 3: Overview of parameters in formula for weight of the ice cover (Beltaos, 2008)

Parameter	Description	Unit
ρ	Density of water	[kg m^{-3}]
g	Gravitational acceleration	[m s^{-2}]
s_i	Specific gravity of ice (≈0.92 for freshwater applications)	-
η	Ice cover thickness	[m]
S_w	Water surface slope	-
η_p	thickness of the porous accumulation under the solid ice sheet	[m]

The flow shear stress and the weight of the cover are quantities which have the units of stress. Nevertheless, it should be understood that the component from the weight of the cover is not a genuine stress, but arise from a force taken over a unit surface area (Beltaos, 2008).

2.3.2. Crack development

When an ice covered river is subject to increasing discharge at the same time as thermal effects are insignificant, a formation of longitudinal fractures appears.

The longitudinal fractures are known as hinge cracks, and are developed due to the increased water pressure making the centre portion of the channel to lift. The situation of hinge crack formation is illustrated in Figure 2 (Beltaos, 2008).

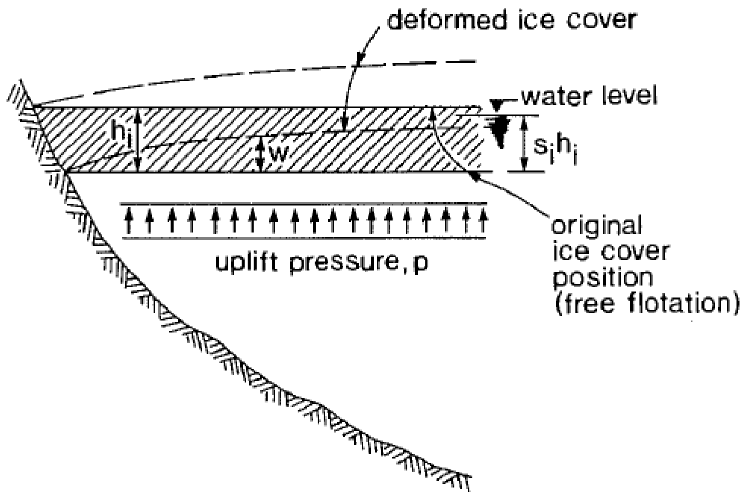

Figure 2: River section with an ice cover subjected to an uplift pressure (Beltaos, 1990)

The hinge cracks forms parallel to the river banks. However, in narrow rivers with thick ice covers, these may be replaced by a single crack in the middle of the channel. By assuming the floating ice to respond as an elastic beam, applicable equations exist as to calculate the distance from the edge of the river to the location of the hinge crack (Beltaos, 2008).

Once the hinge cracks have formed the water level rises and the border ice becomes submerged. The relief of excess pressure head causes this effect. The middle ice strip is still intact, but no longer supported laterally (Beltaos, 2008). While hinge cracks form due to bending in the vertical plane, transverse cracks may form if bending occurs in the horizontal plane (Guo, 2002). The accumulated effects of the flow shear stress and the downslope component of the weight of the cover cause this effect. The mechanism is illustrated in Figure

3. Bending moments are present in a meandering river and if the bending stress exceeds the flexural strength of the ice transverse cracks can occur. In a straight river only compressive stresses can develop by these forces (Beltaos, 1990).

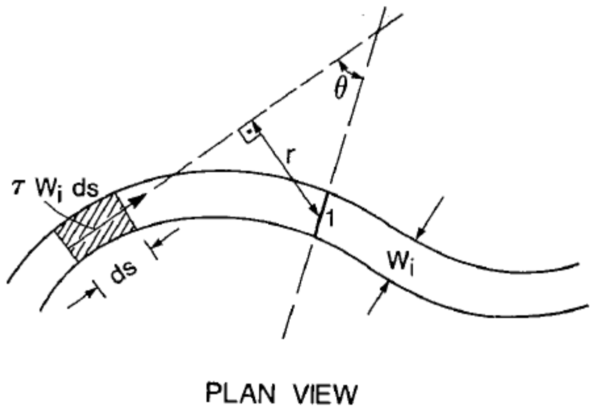

Figure 3: Generation of stresses in section 1 leading to transverse cracks (Beltaos, 1990)

The discussed crack development does not necessarily lead to the onset of breakup. If no further changes considering the river conditions encounters, the ice sheets can remain stationary (Beltaos, 1990). However, once such ice sheets are set in motion, they quickly break down into small pieces by impacts at channel banks or against each other (Guo, 2002).

2.4. Mechanical breakup models

Mechanical breakups often lead to severe ice runs and ice jams. These can be destructive to hydraulic structures and shoreline properties. Because of its consequences it is useful to understand the processes and the mechanisms behind the initiation. The modeling approach is still very limited and in many cases site-specific empirical methods have been the only option (Shen, 2009).

General criteria which can be applied to any river site are desirable. A first step in this direction was taken by Beltaos (1997), where the literature was scanned for semi-empirical hypotheses and formulas that have the potential for transferability. Five such criteria developed in accordance with the actual mechanism of the initiation of breakup were found. The criteria do not entirely describe all of the complex phenomena at hand, but they have a basis on physical reasoning while requiring empirical evaluation of one or more parameters (Beltaos, 1997).

The five criteria are evaluated against dataset considering the breakup for five sites on Canadian rivers (Beltaos, 1997). It must be emphasized that the criteria are tested on moderate-gradient medium and large rivers which form relatively continuous and stationary floating ice covers over the winter (Task Force, 1993). The criteria are not tested for high-gradient small streams. Two of these criteria are described in the two following subchapters.

2.4.1. Empirical criterion

Empirical predictions of the breakup have relied on local records. Formulations have been made by Shulyakovskii in 1966, Galbraith in 1981, Murakami in 1972 and Beltaos in 1987, using variables such as air temperature, degree-days of thaw, ice thickness and water level. The following type of equation appears to give the most consistent results (Beltaos, 1997):

$$H_B - H_F \approx K\eta_0 - F(S_5) \quad \text{(Eq. 3)}$$

Table 4: Overview of parameters in the Empirical criterion (Beltaos, 1997)

Parameter	Description	Unit
H_B	Water level at which the ice cover starts to move	[m]
H_F	Water level at which the ice cover is formed	[m]
K	Site-specific coefficient (often close to 3)	-
η_0	Ice cover thickness prior to the start of melt	[m]
S_5	Index of the accumulated heat input to the ice cover	[°C]
F	Site-specific function	[m]

S_5 is often defined simply as the accumulated thawing degree-days referred to a base air temperature of -5°C. F has the dimension of length and by definition F(0) = 0 (Beltaos, 1997).

The basis for Equation 3 is an assumption having a trapezoidal section where the channel width increases linearly with stage. This is assumed at least in the range of freezeup and breakup levels. The equation represents mechanical breakup events which are initiated when the water level rises above the freezeup stage by an amount proportional to the ice thickness (Beltaos, 2008).

2.4.2. Boundary constraint criterion

The earliest study concerning the initiation of mechanical breakups is found in the former Soviet Union. In 1972 Shulyakovskii presented the theory about transverse cracks being the initiating factor. Beltaos worked further with this theory, but argued that transverse cracks could not be the reason alone. He found that river ice breakups are also dependent upon the river geometry. The geometry has to be in such a form to allow movement of the ice sheets that are separated. A Boundary constraint criterion was developed based on the assumption that transverse cracks are formed (Beltaos, 2008):

$$\frac{W_B - W_i}{\eta_0} = \frac{(m - 0.50)\beta\sigma_f\eta}{8m^2\varpi_i\eta_0} \qquad \text{(Eq. 4)}$$

Table 5: Overview of parameters in the Boundary constraint criterion (Beltaos, 2008)

Parameter	Description	Unit
W_B	Water surface width at the time of breakup initiation	[m]
W_i	Width of the ice sheet (distance between hinge cracks)	[m]
m	Radius of curvature divided by the river width	-
β	Coefficient between 0.3 and 1.5	-
σ_f	Flexural ice strength prior to breakup	[Pa]
ϖ_i	Tractive stress acting on the ice cover	[Pa]

The dimensionless radius of curvature, m, expresses the shape of the river planform. This value will be larger for a straight reach compared to a sharp bend. Thus, it can be seen from Equation 4 that a sharp bend will have a higher right hand side expression and straight reaches are expected to break up first, as in accordance with experience (Beltaos, 1997). The criterion was examined by Beltaos (1997), and the five dataset considered gave a relatively small range of scatter leading to an encouraging result.

2.5. Ice cover thickness models

From the mechanical breakup models it is seen that the ice cover thickness is used as an input parameter to the models. There are different ways of modeling the ice cover thickness. All of which takes the heat exchange into consideration (Washanta Lal, et al., 1993). Most analyses of the thickening of ice covers are conducted using variations of the Stefan formulation (Ashton, 2011).

2.5.1. Stefan formula for ice cover growth

The Stefan formula, developed by Stefan in 1891, has extensively been used to predict the ice cover thickness in lakes and rivers. The ice cover thickness (η) is given as (Washanta Lal, et al., 1993):

$$\eta = \alpha_h \sqrt{S} \qquad \text{(Eq. 5)}$$

Table 6: Overview of parameters in the Stefan formula (Washanta Lal, et al., 1993)

Parameter	Description	Unit
S	Accumulated freezing degree-days	[°C]
α_h	Empirical degree-day factor	[mm $°C^{-1/2}$ $day^{-1/2}$]

The accumulated freezing degree-days (AFDD) are given as (Ashton, 2011):

$$S = \int_{t_0}^{t} (T_f - T_a)dt \xrightarrow{snow\ included} \tilde{S} = \int_{t_0}^{t} (T_f - T_s)dt \qquad \text{(Eq. 6)}$$

Table 7: Overview of parameters in formula for AFDD (Ashton, 2011)

Parameter	Description	Unit
T_f	Freezing temperature of water	[°C]
T_s	Temperature at top of the ice cover	[°C]
T_a	T_a is the air temperature	[°C]

2.5.2. Degree-day factor

Stefan formula introduces the degree-day factor. Michel defined this factor in 1971 to account for surface insulation and exposure by water body type. Typical values of α_h are shown in Table 8. The model does not account for spatial variations of climatic drivers different from air temperature (Brooks, 2010).

Table 8: Typical values of the degree-day factor, α_h (Brooks, 2010)

Ice cover condition	α_h (mm °C$^{-1/2}$ day$^{-1/2}$)
Theoretical maximum	34
Windy lake with no snow	27
Average lake with snow	17-24
Average river with snow	14-17
Sheltered small river with rapid flow	7-14

Considering the degree-day factor work is advanced by Brooks (2010), in which influences of other climatic variables are captured. The degree-day factor is spatially stratified by hydro-climatic regions and water-body type, and is empirically defined by use of a degree-day ice growth model. Brooks (2010) employs 256 river observation sites in addition to several lake and reservoir observation sites to calibrate and subsequently validate the model. The model validation achieved and R^2 of 0.44 for rivers. Data sets were retrieved from river sites in Russia, Sweden, Yukon and British Colombia. The results are shown in Figure 4 and Table 9. The world is divided in fourteen different cluster areas, in which each cluster has its own degree-day factor (Brooks, 2010).

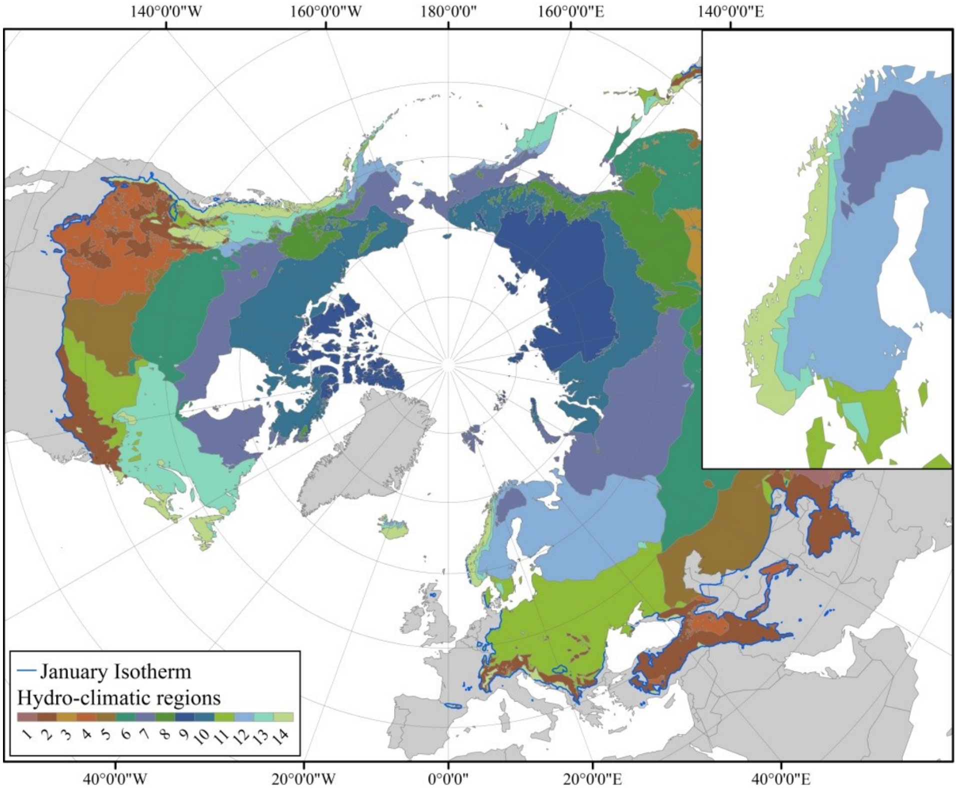

Figure 4: Cluster areas for different degree-days factors (Brooks, 2010)

The different colors used for the cluster areas are blown up in Figure 5 to easier see which color represent which cluster area.

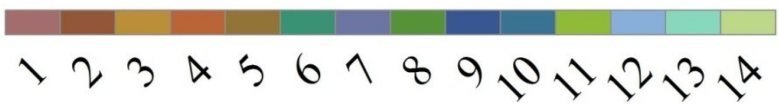

Figure 5: The fourteen cluster areas with their representative colors (Brooks, 2010)

Table 9: Cluster areas with respective degree-day factors (Brooks, 2010)

Cluster area	Mean January Precipitation Cluster mean [mm/month]	Mean January Temperature Cluster mean [°C/month]	Large Lake and Reservoir coeff.	Small to Medium Lake and Reservoir coeff.	River coeff.
1	5	-14.6	19.4*	21.2*	19.9*
2	61	-4.8	19.4*	21.2*	16.7
3	4	-21.7	19.4*	21.2*	19.9*
4	9	-7.5	19.4*	21.2*	19.9*
5	13	-7.2	9.2	21.2*	19.9*
6	17	-17.7	23.2	19.6	20.7
7	27	-21.6	19.4*	19.7	22.0
8	15	-29.8	19.4*	17.7	14.0
9	11	-37	19.4*	24.6	18.2
10	16	-30	21.7	23.7	20.7
11	41	-4.9	17.8	20.1	18.8
12	37	-12.3	20.7	21.7	20.5
13	66	-15.1	20.7	18.2	21.7
14	145	-6.1	19.4*	21.2*	27.5

* Denotes hydro-climatic regions lacking observational data, therefore employing the single optimal coefficient defined during calibration by water-body type.

2.6. Snow`s effect on an ice cover

2.6.1. Insulating effect

Snow consists of different layers, each with its own density which varies with temperature, wind conditions and age. Because of the porous composition, snow gives an insulating effect to a potential ice cover. The thermal conductivity is dependent on the snow density, in which high density snow generally has a higher thermal conductivity. A relation is found from 488 measurements (Lundberg, et al., 2009):

$$K_s = 10^{2.65\rho_s - 1.652} \quad \text{(Eq. 7)}$$

Table 10: Overview of parameters for thermal conductivity of snow (Lundberg, et al., 2009)

Parameter	Description	Unit
K_s	Thermal conductivity of snow	[W m^{-1} °C^{-1}]
ρ_s	Snow density	[kg m^{-3}]

Temperature distribution through materials

To calculate the temperature at the boundary between two materials the following formula can be used (Byggforsk, 2007):

$$T_b = T_1 + \left[(T_2 - T_1)\frac{R_1}{R_1 + R_2}\right] \quad \text{(Eq. 8)}$$

Table 11: Overview of parameters for temperature between two materials (Byggforsk, 2007)

Parameter	Description	Unit
T_b	Temperature at the boundary between two materials	[°C]
T_1	Temperature at the outer boundary for the first material	[°C]
T_2	Temperature at the outer boundary for the second material	[°C]
R_1	Thermal resistance of the first material	[W m^{-2} °C^{-1}]
R_2	Thermal resistance of the second material	[W m^{-2} °C^{-1}]

The thermal resistance of a material, R_m, is given as (Byggforsk, 2007):

$$\mathrm{R_m} = \frac{K_m}{\eta_m} \quad \text{(Eq. 9)}$$

Table 12: Overview of parameters in thermal resistance formula (Byggforsk, 2007)

Parameter	Description	Unit
K_m	Thermal conductivity of the material	[W m^{-1} °C^{-1}]
η_m	Thickness of the material	[m]

2.6.2. Penetration of solar insolation

Sahlberg (1988) modeled the amount of short wave radiation that penetrates a snow cover in three steps. First the snow albedo is considered. Second, absorption occurs in the upper 0.1 m of the snow cover and third, the remaining radiation decays exponentially. Which penetration formula is used depends on whether the snow depth is greater than 0.1 meters or not (Sahlberg, 1988).

Penetration formula for snow depths larger than 0.1 meter (Sahlberg, 1988):

$$F_i = F_s(1-\alpha_s)i_{os}e^{-K_s(\eta_s-0.1)} \quad \text{(Eq. 10)}$$

Penetration formula for snow depths less than 0.1 meter (Sahlberg, 1988):

$$F_i = F_s(1-\alpha_s)i_{os} \quad \text{(Eq. 11)}$$

Table 13: Overview of parameters for penetration of solar radiation through snow (Sahlberg, 1988)

Parameter	Description	Unit
F_i	Amount of shortwave radiation that penetrates the snow cover	[W m^{-2}]
F_s	Insolation towards the snow cover	[W m^{-2}]
α_s	Snow albedo	-
i_{os}	Penetration factor	-
K_s	Bulk extinction factor	[m^{-1}]
η_s	Snow depth	[m]

In dry and compact snow K_s is approximately 20-30 m^{-1} and in melting snow K_s is in the range 10-15 m^{-1}. Reported values of α_s, range from 0.50 for melting old snow to 0.95 for fresh dry snow. For snow depths less than 0.1 m, $i_{os} = 1-(9*\eta_s)$. Otherwise $i_{os} = 0.1$ (Sahlberg, 1988).

3. ICE BREAKUP IN SMALL NORWEGIAN STREAMS

Abstract

Predicting the time of a river ice breakup is essential as it concerns environmental impact, emergency flood warning and hydropower production. The available predictive methods are developed and tested only for moderate-gradient large rivers. Their utility for high-gradient small stream scenarios is not known. As a first step toward development of a criterion for ice breakups in small streams one of the existing criteria for large rivers is tested. The ice cover thickness is an important parameter considering the river ice breakup, thus a simulation of the ice cover growth is included in the analysis. This paper represents an initial study of ice breakups in small and steep streams. Extensive data are retrieved and analysis regarding ice cover growth and ice breakup is conducted. The Stefan formula is proven to give good results for the ice cover growth in the two study areas. Regarding river ice breakups the Empirical criterion has some inconsistency in its simulations of the test cases. Nevertheless, the results are found promising and the criterion can be used as a foundation for further research and development.

3.1. Introduction

The breakup of river ice is a brief event, but it may lead to major consequences (Beltaos, 1997). Infrastructure as bridges and roads are exposed as well as the river itself through erosion of the banks and vegetation. In addition ice and congestion of water may cause problems with communication and blockage of hydropower intakes (Lokna, 2006).

Norwegian rivers are of moderate size and fairly steep compared to rivers often referred to in ice studies, such as Canadian and Russian rivers. Even the largest rivers in Norway appear to be small in such a scale (Asvall, 1994). Despite the consequences of ice breakups in small Norwegian streams, not much work has been done to understand the mechanisms behind these events. Another problem is that very little or no data on ice breakup is available in Norway (Gebre, et al., 2011).

Considering the study of breakup processes a key question is how the event is initiated. This is essential for the progress towards forecasting and to assess the spatial variability and severity of the event. Criteria predicting the initiation of a mechanical breakup exist. However, the criteria are to a greater or lesser extent empirical and site-specific. Their utility is limited by the need for historical data (Beltaos, 1997). A second limitation arises because the criteria are developed and tested only for moderate-gradient medium and large rivers. Their applicability to high-gradient small streams is not known (Beltaos, pers.com).

A method applicable for high-gradient small streams is needed. With this study, a first step is taken in this direction. Measuring work are implemented and used to document the river ice for two streams in the middle part of Norway; Ingdalselva and Sokna. In addition data from two ice breakups in Sokna during 2005/06 are analyzed. One of the criteria developed for moderate-gradient medium and large rivers is tested on the known ice breakups. This includes a simulation of the ice cover growth, in which the Stefan formula is used. The original formula is expanded by the need for an evaluation of the insulation effect of potential snow covers. In addition, the known overprediction of thin ice covers is taken into account. The implications of the results and adjustments which are made are discussed.

3.2. Study areas and instruments

The field study was carried out in two unregulated streams: (i) Sokna (62°94'N, 10°20'E, 240 masl) and (ii) Ingdalselva (63°46'N, 9°90'E, 0 and 15 masl). Their location is shown in Figure 6. The two streams are considered small, steep and shallow. This is consistent with the physical characteristics given in Table 14. During winter the ice often form as full covers in the two rivers and mechanical breakups are likely to occur due to common mid-winter thaws and large spring runoffs.

Figure 6: Location of the two study areas within Norway (Kartverket, 2013)

Table 14: Physical characteristics of the study areas

Study site	Sokna	Ingdalselva
Study length [m]	150	200
Catchment area [km^2]	196	102
Mean flow [m^3 s^{-1}]	4.4	2.6
Meter above sea level [masl]	240	0-15
Mean gradient [%]	1.2 (2.5*)	7.0 (1.7*)
Mean wetted with [m]	8.0	20
Max depth [m]	1.0	4.0

* River mean

Considering Ingdalselva two separate parts of the study reach is evaluated. An existing pressure sensor is located at the lower part of the studied reach. Here a waterfall enters a relative deep pool as shown in Figure 7.

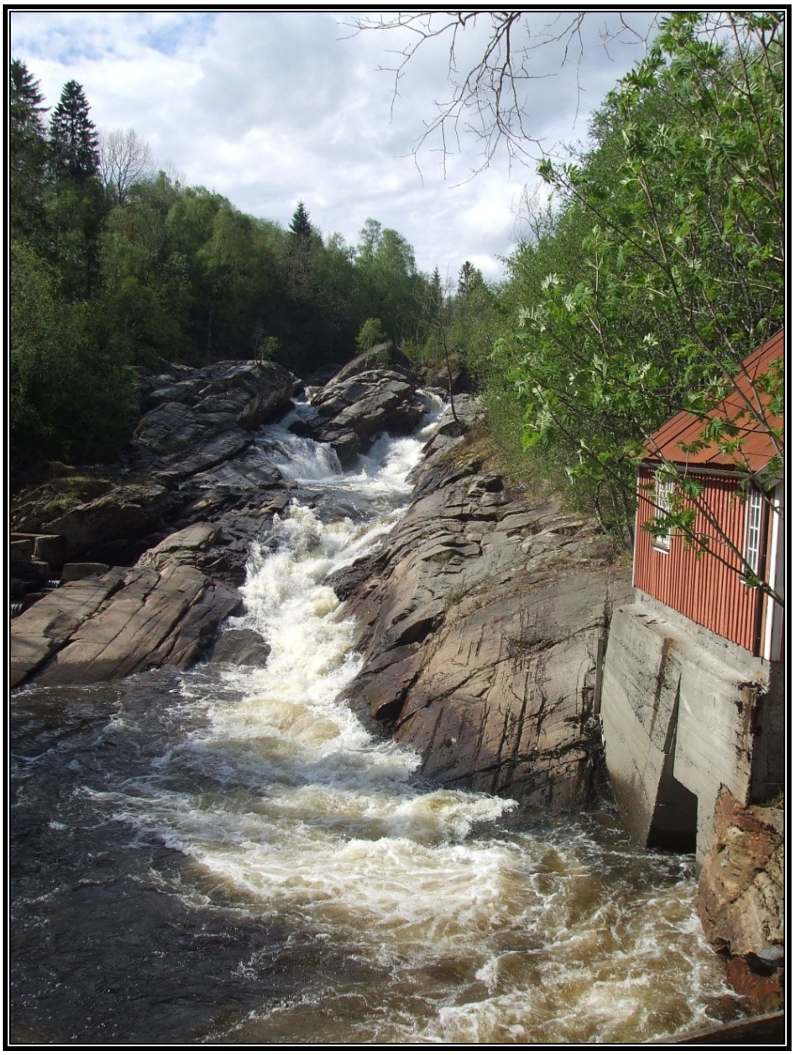

Figure 7: The lower part of the study area Ingdalselva

At the upper part of the study reach the river is more wide and shallow, shown in Figure 8 and 9.

Figure 8: The upper part of the study area Ingdalselva at low water

Figure 9: The upper part of the study area Ingdalselva at high water

A separate pressure sensor was placed at the upper observation site for three days. The correlation between the two sites is shown in Figure 10.

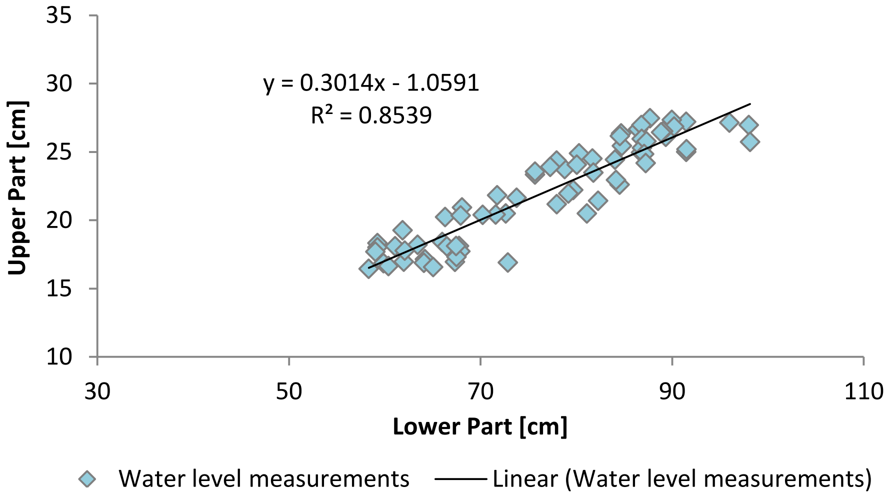

Figure 10: Correlation of water level measurements in Ingdalselva

A value of R^2 = 0.85 justifies the use of data from the lower part. The recorded water levels are converted to the upper part by use of the correlation formula:

$$H_{Upper} = 0.3014 * H_{Lower} - 1.0591 \quad \text{(Eq. 12)}$$

Equation 12 is used for water levels higher than the minimum water level recorded in the three day period. The reason for this is the discontinuity of the river profile at low water. At low water a simplified rectangular profile for the main flow is assumed and Manning formula is used to calculate the water levels (Task Force, 1993). The profile is shown in Figure 11.

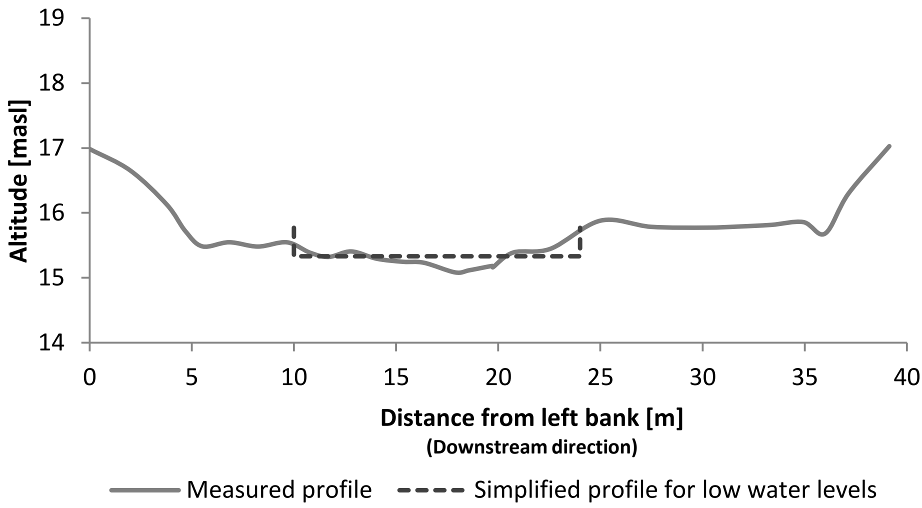

Figure 11: The river profile of the upper part of Ingdalselva

Considering the study area Sokna the nearest pressure sensor is at Hugdal Bridge, located about 8 km downstream the observation site Stavilla. In the period 2004-2006 a separate transducer was placed in Stavilla. The correlation between Hugdal and Stavilla is shown in Figure 12.

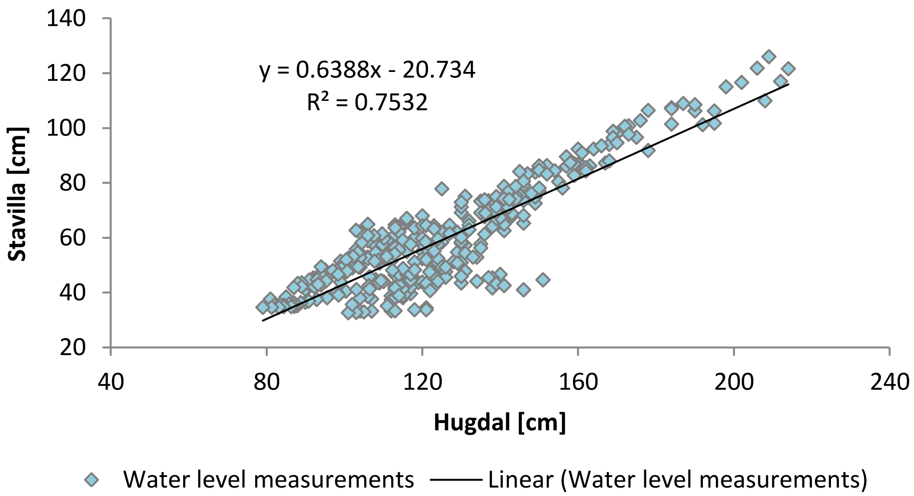

Figure 12: Correlation of water level measurements between Hugdal and Stavilla

A value of R^2 = 0.75 justifies the use of data from Hugdal for the season of 2012/13. The recorded water levels are converted to the Stavilla site by use of the correlation formula given as:

$$H_{Stavilla} = 0.6388 * H_{Hugdal} - 20.734 \quad \text{(Eq. 13)}$$

Tree-mounted cameras were installed taking photos every hour. Only day-time photos could be used (09:00-15:00 in December, 07:00-19:00 in April). The ice cover thickness was measured throughout regular field trips. Climate data records are retrieved from nearby gauging stations. The location of cameras, pressure sensors and gauge stations are showed in Figure 13 and 14. Pictures from the camera observations are shown in Appendix A.

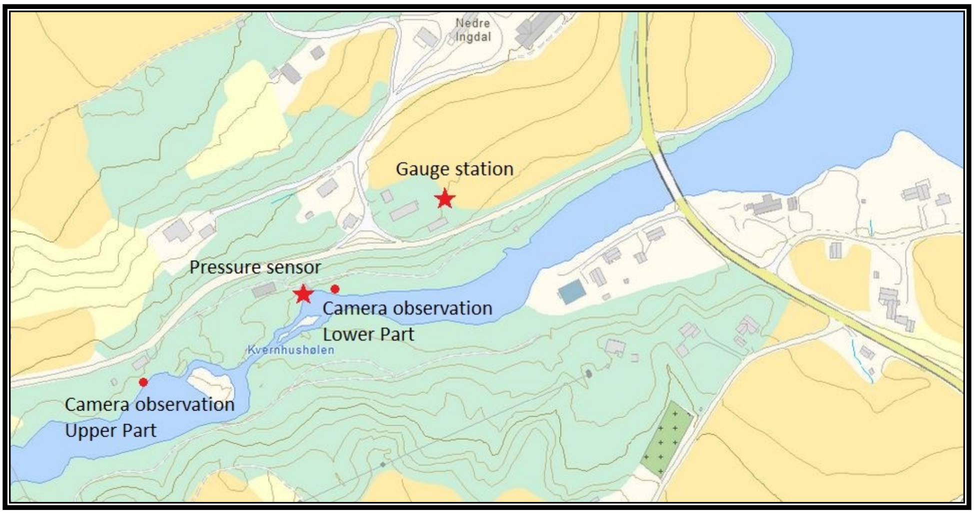

Figure 13: Field instrumentation for Ingdalselva (NVE, 2013)

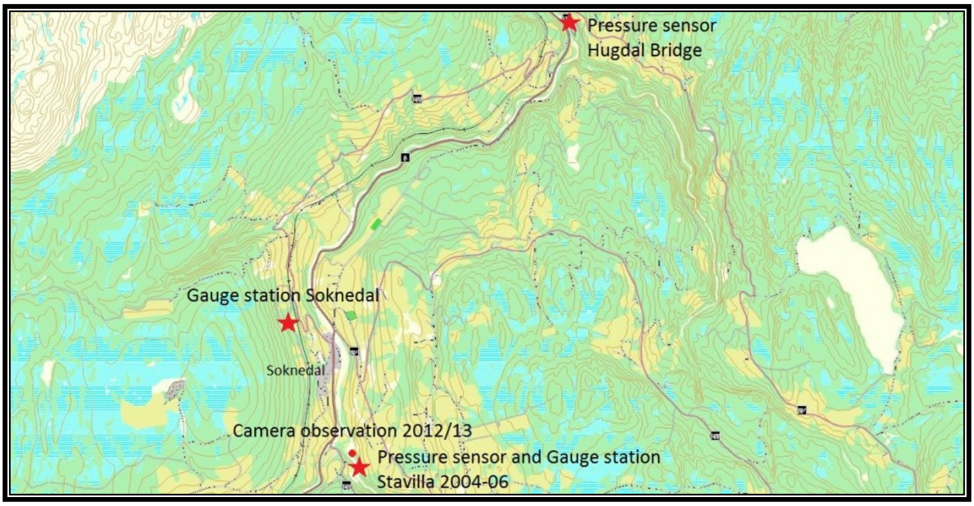

Figure 14: Field instrumentation for Sokna (NVE, 2013)

3.3. Method

3.2.1. Stefan formula

The Stefan formula is used to calculate the ice cover thickness. The simulations are calibrated based on field measurements conducted about once a month between formation and breakup. Stefan formula is given as (Washanta Lal, et al., 1993):

$$\eta = \alpha_h \sqrt{S} \quad \text{(Eq. 14)}$$

Table 15: Overview of parameters in the Stefan formula (Washanta Lal, et al., 1993)

Parameter	Description	Unit
S	Accumulation of degree-days of freezing	[°C]
α_h	Empirical degree-day factor	[mm °C$^{-1/2}$ day$^{-1/2}$]

The degree-day factor is decided based on the results from Brooks (2010). In her study Hydro-climatic regions for the northern hemisphere were used to find the degree-day factors. Maximum observed seasonal ice thickness values from 256 river observation sites across the northern hemisphere were used for validation (Brooks, 2010). The Stefan formula is known to overestimate the ice growth in the formation period and for thicknesses less than about 10 cm it is shown that the method results in too large ice thicknesses (Ashton, 1989). It is attempted to exclude this source of error by use of a lower degree-day factor in the formation period.

The Stefan formula in its most common form do not account for variations in snow depth on top of the ice cover. In this study a linear temperature method based on the thermal resistance in ice and snow is used. The temperature at top of the ice cover is calculated and replaces the air temperature in the expression of the freezing degree days when snow is present. The conductivity of ice and snow are set as constants within normal ranges, 2.03 and 0.25-0.35 W m^{-1} °C^{-1} respectively (Sturm, et al., 2002; Jasek, 2006; Byggforsk, 2007; Lundberg, et al., 2009). The Stefan formula does not simulate the formation of snow ice and is therefore also excluded from the measurements. The method in its totality with formulas used is given in Appendix B.

3.2.2. Material

The results from the simulation of the ice cover growth lead to the material component for the breakup study. The seasonal variations in temperature, snow depth and ice cover thickness is retrieved for both Ingdalselva and Sokna. The upper part of Ingdalselva experienced the winter season 2012/13 an ice cover with two layers. During a period of water on top of the first formed ice cover a second layer formed. The first layer is set with a constant thickness while the Stefan formula is used for the formation and growth of the second layer. The material component for the different study sites is shown in Figure 15, 16, 17 and 18.

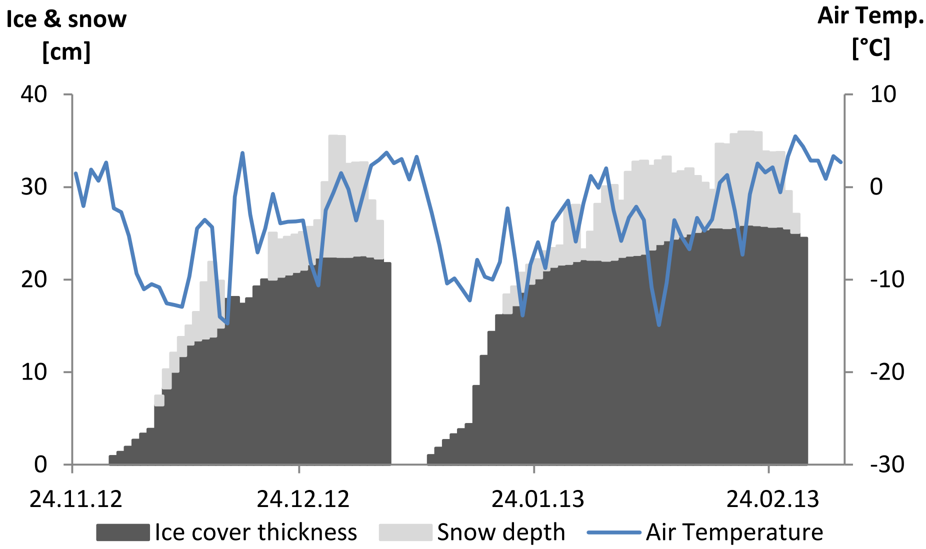

Figure 15: Ice cover simulation for the lower part of Ingdalselva

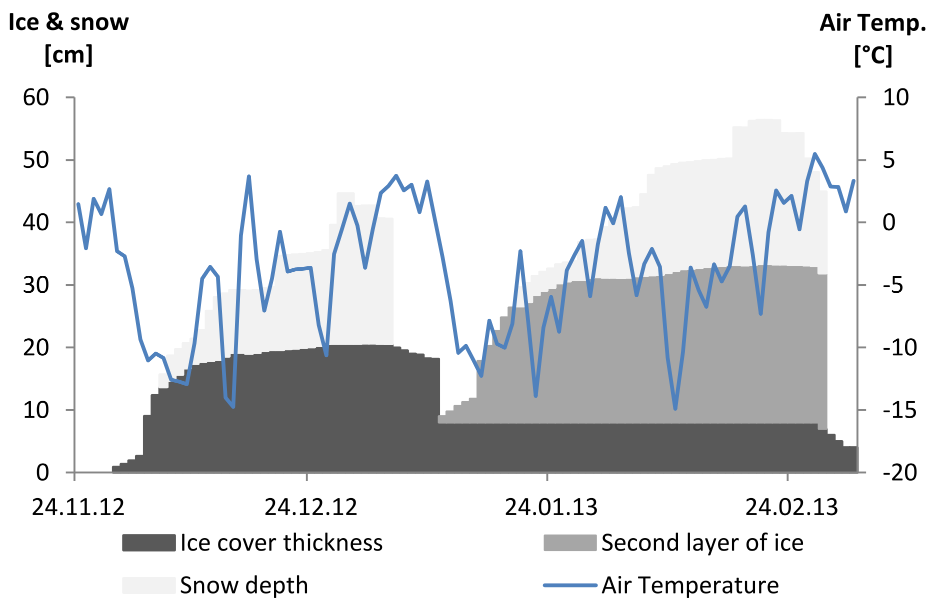

Figure 16: Ice cover simulation for the upper part of Ingdalselva

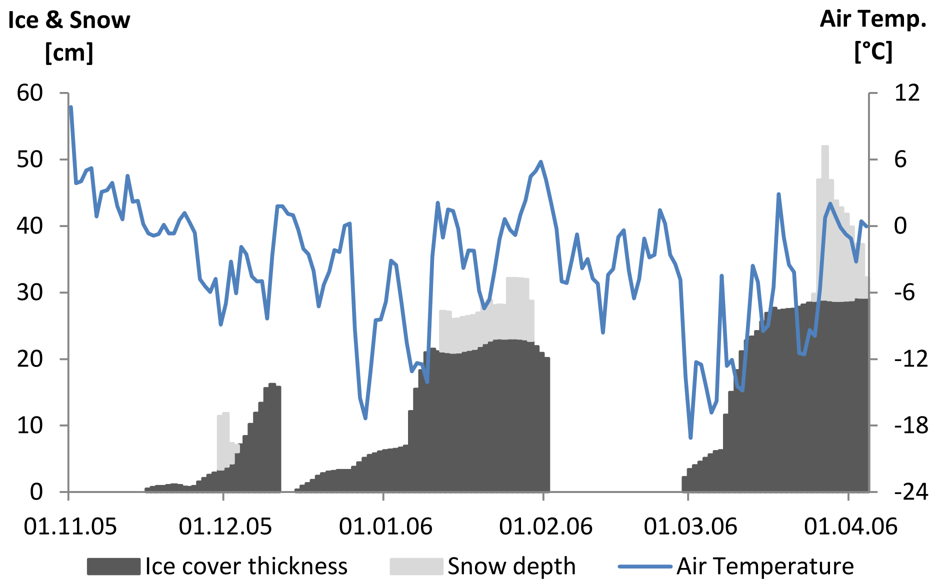

Figure 17: Ice cover simulation for Sokna 2005/06

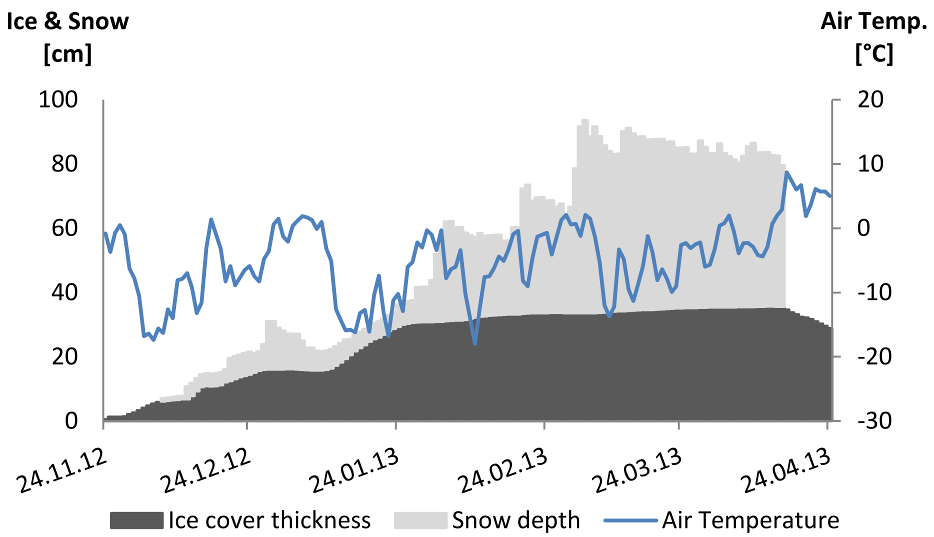

Figure 18: Ice cover simulation for Sokna 2012/13

3.2.3. Empirical criterion

The change in water level is regarded as the only driving factor held back by an amount proportional to the ice cover thickness and is shown to be representative for moderate-gradient medium and large rivers (Beltaos, 1997). Only small adjustments have been made compared to the original formula. The criterion used in this study:

$$H_B - H_F \approx K\eta - F(S_5) \qquad \text{(Eq. 15)}$$

Table 16: Overview of parameters in the Empirical criterion (Beltaos, 1997)

Parameter	Description	Unit
H_B	Water level at which the ice cover starts to move	[m]
H_F	Water level at which the ice cover is formed	[m]
K	Site-specific coefficient (often close to 3)	-
η	Current ice cover thickness	[m]
S_5	Index of the accumulated heat input to the ice cover	[°C]
F	Site-specific function	[m]

The current ice cover thickness replaces the thickness prior to the start of melt from the original formula. This is done to get a criterion which compares the driving factors to the stabilizing factors for each day. H_F is set as the average water level for the first seven days of a full ice cover, consistent with Beltaos (2008). K is set as 1.5 by calibration. $F(S_5)$ include the effect warming weather and insolation has on the ice cover strength and is usually evaluated as the accumulated thawing degree days (ATDD) with a base of -5°C. The negative base will then account for the effect of solar insolation (Beltaos, 2008). For a snow covered ice cover it is shown that the solar insolation to a small degree penetrates the snow. The penetration is dependent on the albedo, depth and bulk extinction of the snow cover (Sahlberg, 1988). Formulas described by Sahlberg (1988) are used to calculate the amount of solar insolation which reaches the ice cover. $F(S_5)$ have been neglected for all study cases.

3.4. Results

3.4.1. Stefan formula

The Stefan formula is shown to present good simulations of the ice cover thicknesses for the two study areas. Disregarding the situations with water on top of the ice the accuracy is found in the range +/- 4 cm for Ingdalselva and +/- 6 cm for Sokna 2012/13. For Sokna 2005/06 no measured values of the ice cover thickness are available and the accuracy is therefore not known. Snow ice was only observed in Sokna in March and April 2013, but is excluded from the measurements. Figures of the simulated thicknesses compared to the observed thicknesses are given in Appendix C.

3.4.2. Empirical criterion

The Empirical criterion simulated three out of five ice breakups in small steep streams. Results in numeric form are given in Appendix D.

Ingdalselva

The lower part of Ingdalselva experienced two river ice breakups during 2012/13 winter season. Only one of these situations led to an ice breakup also for the upper part. The Empirical criterion gave good results for the lower part of Ingdalselva. Both of the ice breakups which occurred were simulated by use of the Empirical criterion. For the upper part the criterion failed to simulate the ice run that occurred 28.02.13. At this date the ice consisted of two layers. The first layer was submerged while the second layer was broken up by the hydrodynamic forces. Only the second layer is evaluated in the criterion. The results are shown in Table 17, Figure 19 and 20.

Table 17: Results of the Empirical criterion tested on Ingdalselva

Date	River location	Observed	Empirical criterion
04.01.2013	Lower Part	Ice breakup	Breakup simulated
	Upper Part	No breakup, water on top of the ice	No breakup simulated
28.02.2013	Lower Part	Ice breakup	Breakup simulated
	Upper Part	Ice breakup	Breakup NOT simulated

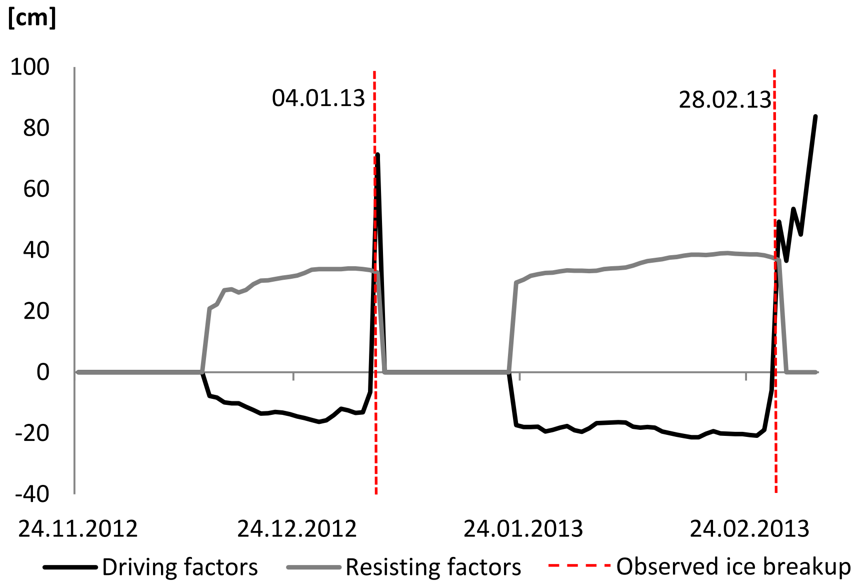

Figure 19: Empirical criterion tested for the lower part of Ingdalselva

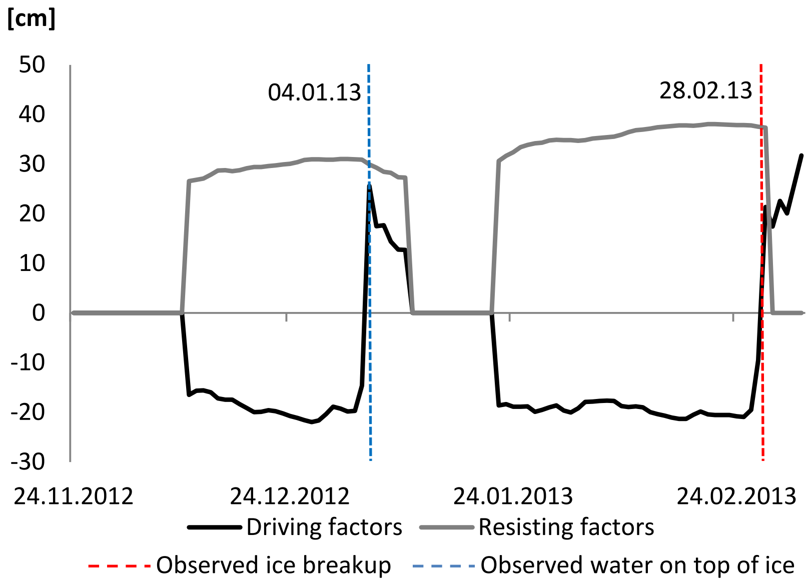

Figure 20: Empirical criterion tested for the upper part of Ingdalselva

Sokna

Sokna experienced two river ice breakups in the winter season 2005/06. In 2012/13 the water found its way on top of the ice cover during the spring runoff and dissolved after some days submerged. The Empirical criterion simulated one of the two ice breakups during the season 2005/06. The criterion was not able to simulate the ice breakup 11.12.05. Considering the season 2012/13 the Empirical criterion simulated an ice breakup 17.04.13, two days after it was observed water on top of the cover. The result is shown in Table 18, Figure 21 and 22.

Table 18: Results of the Empirical criterion tested on Sokna

Date	Observed	Empirical criterion
11.12.2005	Ice breakup	Breakup NOT simulated
01.02.2006	Ice breakup	Breakup simulated
15.04.2013	No breakup, water on top of the ice	No breakup simulated
17.04.2013	NO breakup, water on top of the ice	Breakup simulated

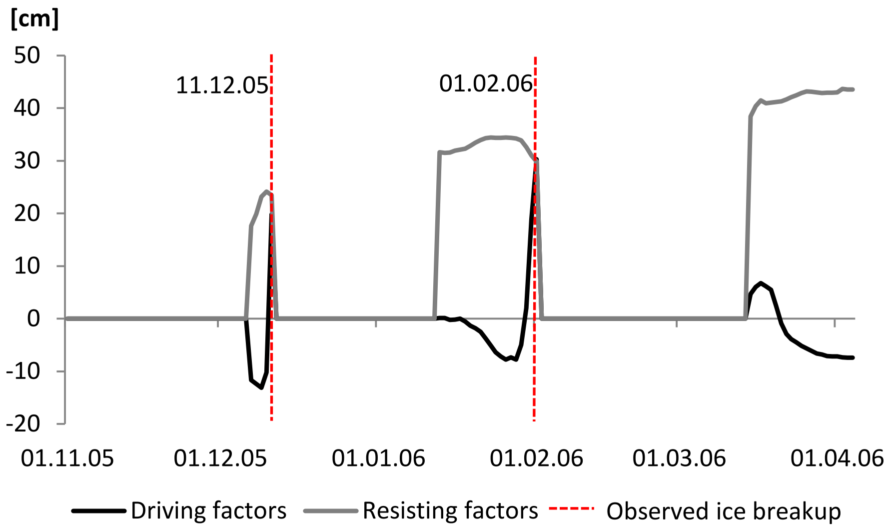

Figure 21: Empirical criterion tested for Sokna 2005/06

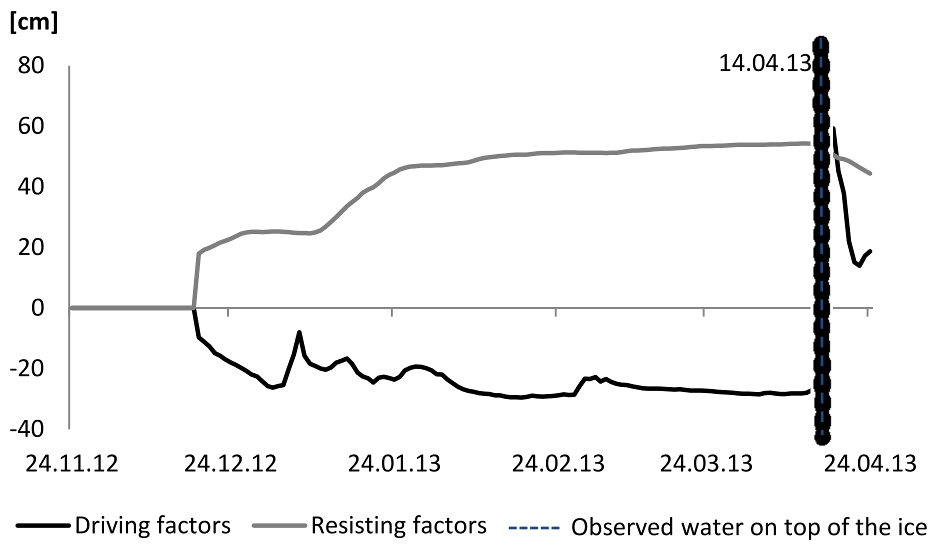

Figure 22: Empirical criterion tested for Sokna 2012/13

Reduction of the ice covers strength

Due to a more or less continuous snow cover in 2012/13 the solar insolation towards the ice is insignificant and the ice cover temperatures are close to 0°C. Considering Sokna 2005/06 the gross insolation is relative low because of the time of year of which the ice breakups occur. The results from the calculations of the amount of solar insolation towards the ice cover are shown in Figure 23, 24, 25 and 26. The ATDD in the periods before the ice breakups are given in Table 19.

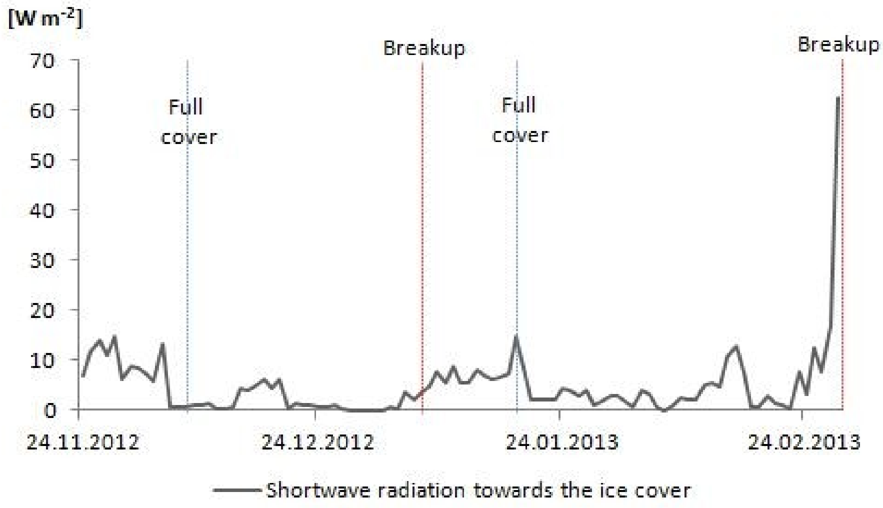

Figure 23: Solar insolation towards the ice in Ingdalselva lower part

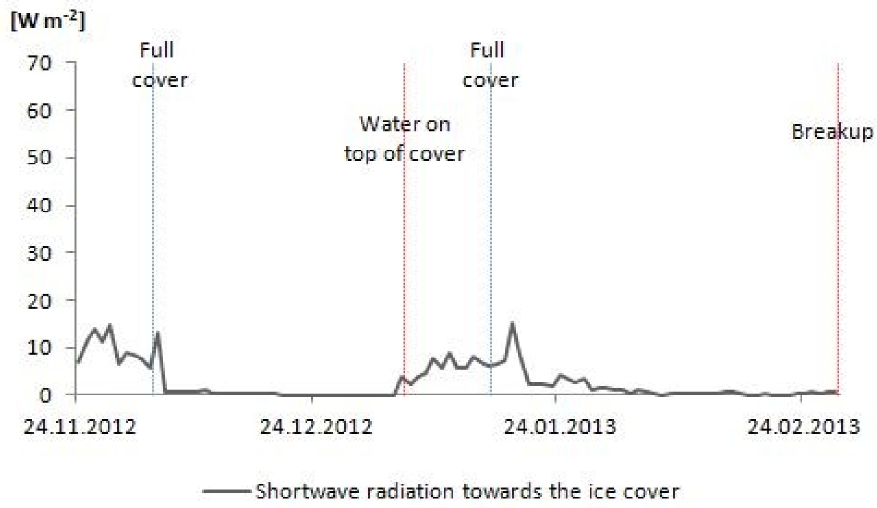

Figure 24: Solar insolation towards the ice in Ingdalselva upper part

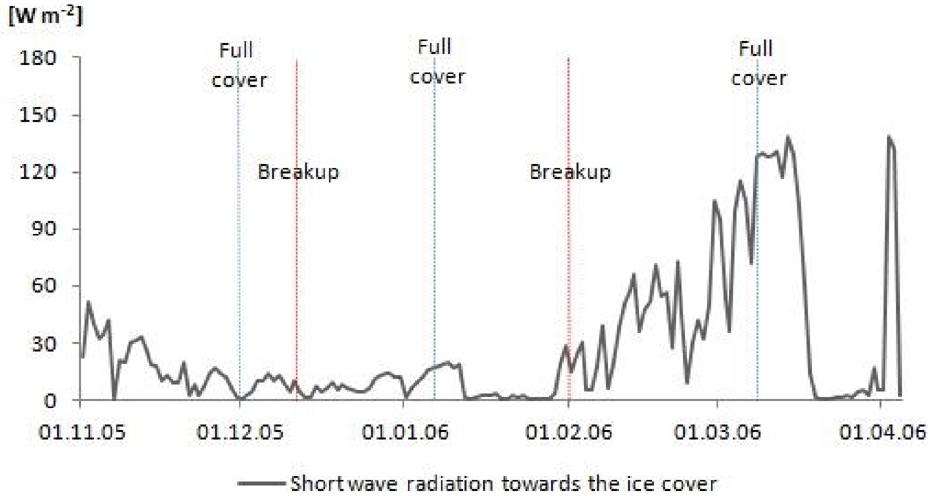

Figure 25: Solar insolation towards the ice in Sokna 2005/06

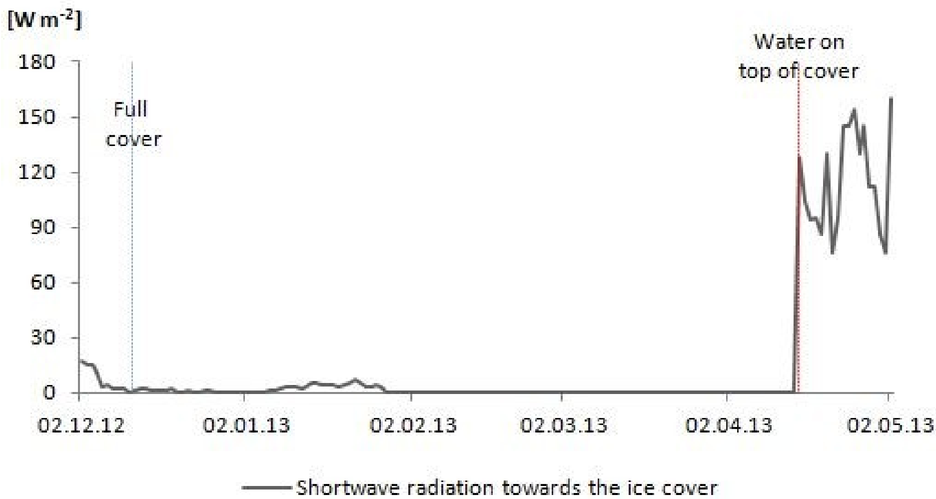

Figure 26: Solar insolation towards the ice in Sokna 2012/13

Table 19: ATDD in the periods before the ice breakups

River reach	Date	ATDD at ice cover surface [°C]
Ingdalselva lower part	29.12.2012 – 04.01.2013	6.21
Ingdalselva lower part	22.02.2013 – 28.02.2013	11.47
Ingdalselva upper part	29.12.2012 – 04.01.2013	4.26
Ingdalselva upper part	17.02.2013 – 28.02.2013	3.83
Sokna	11.12.2006	1.79
Sokna	27.01.2006 – 01.02.2006	17.19
Sokna	12.04.2013 – 15.04.2013	9.37

3.5. Discussion

3.5.1. Stefan formula

Stefan formula provides reliable values of the ice thicknesses and the accuracy level gives the possibility of combining the method with the Empirical criterion. By use of the Stefan formula only the ice cover growth is evaluated and no thinning of the ice is considered. Excluding thinning of the ice is thought sufficient since the focus of this study is mechanical breakups. Mechanical breakups is initiated before the ice has had sufficient time to melt, thus thinning of the ice cover occurs only to a small extent. This seems reasonable for the two study areas based on the observations. The few days of warm temperatures which occur between formation and breakup do not affect the ice cover in most cases due to snow cover insulation. However, incidents with water flowing on top of the ice cover reduce the ice thickness significantly. For these situations an evaluation of the thinning would strengthen the model.

Degree-day factor

The model validation of Brooks (2010) is based on data sets retrieved from river sites in Russia, Sweden, Yukon and British Colombia. None of the data sets were retrieved from Norway. Nevertheless, the ice growth study conducted shows that Brooks` work gives good results also for Norwegian river sites. For the two study areas the degree-day factor recommended by Brooks gave better results than use of the general values developed by Michel. This is an interesting finding as Brooks` analytical approach relates the values to specific regions. Thus, the determination of the degree-day factor is more specific. During the formation period a lower degree-day factor is used. This way, overestimates of thin covers are taken into account.

Two layers of ice cover

The situation with two layers of ice introduces a complexity which the Stefan formula is not able to simulate. It is found that observations are needed to study such local behavior in detail and to be able to manipulate the simulations to correspond with the actual behavior. It is not known how much the period with water on top of the ice reduced the first ice cover. Thus, the value of the constant ice thickness had to be estimated. Insulation from the air pocket as well as an overlying ice- and varying snow cover can argue for the assumption of a constant ice thickness.

3.5.2. Empirical criterion

By use of the Empirical criterion much simplified evaluations of the driving and stabilizing factors are used. However, this method may be sufficient to predict an ice cover breakup and does not require extensive field measurements for it to be applicable. Nevertheless, the need of historical data to determine the site-specific coefficient (K) and function (F) represents a weakness. K is for these study cases set as 1.5 by calibration which is outside the normal range from 2 to 10 (Beltaos, 1998). Several studies are needed to evaluate the range of this factor for high-gradient small streams further. $F(S_5)$ is neglected for all study cases. This is evaluated as reasonable for three of the breakup scenarios due to insignificant solar insolation towards the ice covers and low ATDD. Greater values of the ATDD in the period before the breakup in the lower part of Ingdalselva 28.02.13 and Sokna 01.02.05 introduce an uncertainty to this assumption. However, several data sets are needed to do a proper evaluation of the site-specific function. For this study it is therefore not taken into account.

In this study the Empirical criterion has simulated three of five ice breakups in high-gradient small streams. The two which failed may introduce the need for evaluation of several factors and further development of the criterion. The ice breakup which was not simulated in Sokna 2005/06 is believed to do with forces which are transformed from upstream parts of the river. The whole river went through a massive ice breakup at this date and it is therefore reasonable to believe that the ice cover in the studied reach have been subjected to ice forces which are not contained by the Empirical criterion.

For the upper part of Ingdalselva more local behavior is believed to be omitted by the criterion. The formation of a second ice layer introduces an air pocket and less contact between ice and boulders. The air pocket is most likely filled with water giving an uplift pressure and less contact with boulders is believed to give less anchor effect of the second layer. Observation some days after the ice breakup indicates that the first ice layer was stable which strengthens the theory about the boulders giving an anchor effect. The first layer is formed at a lower water level and is therefore formed around and into the boulders to a greater extent.

Formation of a full cover

In this study H_F is set as the average water level for the first seven days of a full ice cover. Another common way to determine this parameter is by setting it equal to the water level at the date of formation of a full cover. This date is often associated with uncertainty. An average assessment of the data is therefore chosen because it is evaluated to have a stabilizing effect. The criterion is sensitive considering the parameter H_F. Thus, effort should be put into determining the date of a full cover as accurate as possible. For the ice data which include camera observations this analyze is feasible. For Sokna 2005/06, where camera observation is lacking, the task is much more demanding and the uncertainty level increase considerably. This may be one explanation to less good results for this data set.

Water level measurements

The location of the pressure sensors introduces an uncertainty. The measurements of the water level variations are solid for the lower part of Ingdalselva and Sokna 2005/06 since the sensors were located at the actual observation sites. The upper observation site in Ingdalselva is located only 130 meters upstream from the lower part. However, 15 altitude meters separate the two sites and it is great differences in profile and flow conditions. By use of correlation between sensors at the actual sites the source of error is minimized. Nevertheless, the correlation formula introduces an uncertainty since R^2 is less than 1.0. For later studies pressure sensors at each observations site should be considered.

3.5. Future works

The need for a criterion which predicts the ice breakups in small streams are considerable. The results from this study show that the Empirical criterion can be applicable also for high-gradient small streams and makes a good foundation for further studies and development of new criteria. Lesson learned is that the field setup should be carefully planned. Installing pressure sensors at each observation site makes studies easier and measurements more reliable.

Cameras with a trigger function should be considered. Observations of the actual breakup are needed to study the driving forces more in detail. A wire connected to both the release trigger of the camera and the ice cover could make this possible. In addition, it should be considered solutions to make use of camera observations outside hours of sunlight.

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4. SUPPLEMENTARY INFORMATION

4.1. More detailed method description

4.1.1. Instrumentation

Water level calculations for the upper part of Ingdalselva

Manning formula is used to calculate the water levels at the upper part for recorded water pressures less than 58.32 cm (1.84 masl) at the lower part. Otherwise the correlation formula given in Equation 12 is used. The ice cover is taken into account in the calculations by evaluating an additional rough surface (Task Force, 1993). Normal flow and river width significantly larger than the water depth is assumed. The calculations are shown in Appendix E.

Climate data records

For Ingdalselva the current gauge station is located respectively 100 and 230 m from the lower and upper observation site. Data records considering the air temperature and solar insolation are used. Considering Sokna a temporary gauge station was located at the observation site during the winter season 2005/06. Station number 67280: "Soknedal" was used for the winter season 2012/13. This gauge station is located about 2 km north from the observation site. For Sokna only the air temperature records have been used. The location of the gauge station in relation to the observation sites is shown in Figure 13 and 14 presented in subchapter 3.2.

4.1.2. Stefan formula

Degree-day factor

To determine the correct degree-day factor for Sokna and Ingdalselva Figure 4 presented in subchapter 2.5.2 needs to be studied. A section of Norway where the location of the two rivers is shown is given in Figure 27.

Figure 27: Location of study areas relative to cluster areas (Brooks, 2010)

If the colors are compared to Figure 5 presented in subchapter 2.5.2., the representative values of the degree-day factor can be found in the last column in Table 9 given in the same subchapter. The area where Ingdalselva and Sokna are located matches cluster area 14. Thus a degree-day factor of 27.5 should be used.

Insulating snow cover

The snow is adapted to the model through use of buildings physics. The temperature gradient through the snow and ice is dependent on the material coefficients of both layers. By identifying the thermal resistance of the two layers separately the temperature at the boundary between the ice and snow (T_s) can be found. This temperature can then replace the air temperature in the expression of the AFDD when snow is present. This way the insulating effect of a potential snow cover is included. The formula for calculating AFDD is given in Equation 6 presented in subchapter 2.5.1.

The conductivity of both the ice and snow has to be decided. According to literature the conductivity of ice is more or less a constant value. Values found are 2.03 W m^{-1} °C^{-1} (Lundberg, et al., 2009) and 2.24 W m^{-1} °C^{-1} (Jasek, 2006). The value used for this study is set based on the given interval in combination with calibration. The conductivity of snow is more complex since the density varies significantly with temperature, wind conditions and age. A relation between conductivity and density exists. Snow with low density gives a high insulation effect because of larger air content. However, the relation is hard to make use of due to the difficulty in obtaining the snow density. Snow consists of different layers, each with its own density which varies in time (Lundberg, et al., 2009). Due to these difficulties the snow density is neither measured nor evaluated in detail for this thesis. Instead a value for the conductivity is assumed based on the interval which is given in literature, 0.05-0.6 W m^{-1} °C^{-1} (Byggforsk, 2007; Sturm, et al., 2002). Within this interval the value used for this study is decided through calibration. The calibrated value is used as a mean for the whole depth and the entire season.

Both the ice and snow is assumed to be homogenous materials. This is done in order to assume linear temperature gradients. The layout of the snow model which is implemented is shown in Figure 28.

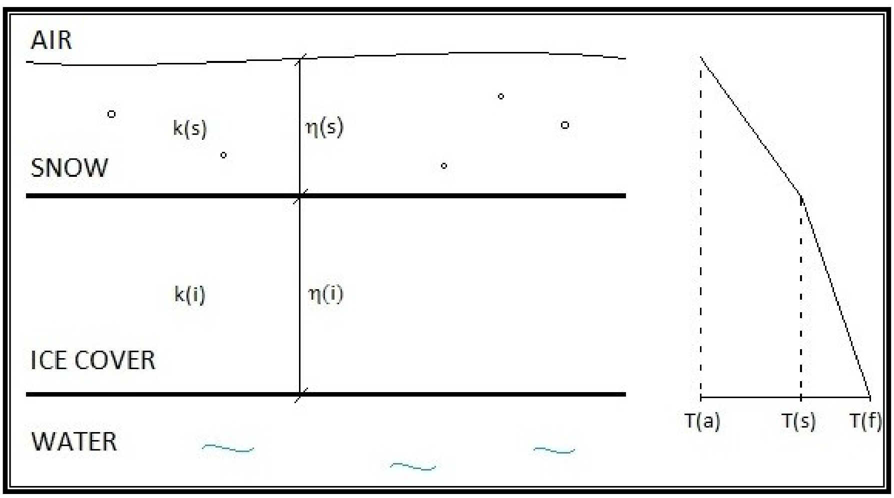

Figure 28: Layout of Snow model (Byggforsk, 2007)

Assuming the water temperature to be equal to the freezing temperature of water, 0°C, T_s can be calculated in accordance to Equation 8 presented in subchapter 2.6.1 (Byggforsk, 2007):

$$T_s = T_a + \left[\left(T_f - T_a \right) \frac{R_i}{R_s + R_i} \right] \quad \text{(Eq. 16)}$$

Table 20: Overview of parameters in formula calculating the temperature at top of the ice cover (Byggforsk, 2007)

Parameter	Description	Unit
T_a	Air temperature	[°C]
T_f	Freezing temperature of water	[°C]
R_i	Thermal resistance of ice	[W m^{-2} $°C^{-1}$]
R_s	Thermal resistance of snow	[W m^{-2} $°C^{-1}$]

The thermal resistance is calculated by use of Equation 9 presented in subchapter 2.6.1.

For this study there was no setup for local snow depth measurement in the rivers. These values had to be estimated based on the nearest snow depth measurement records in combination with camera observations. The gauge stations which are used are given in Table 21.

Table 21: Gauge stations used for snow depth records

Study area	Winter season	Station		Camera observation
		Number	Name	
Ingdalselva	2012/13	66070	Skjenaldfossen i Orkdal	Yes
Sokna	2005/06	66730	Berkåk-Lyngholt	No
Sokna	2012/13	67280	Soknedal	Yes

4.1.3. Empirical criterion

Penetration of solar insolation through a snow cover

$F(S_5)$ in the Empirical criterion include the effect warming weather and insolation has on the ice cover strength (Beltaos, 2008). A potential snow cover can reduce and in some cases neglect this effect (Sahlberg, 1988). To see if this is the case for the study areas the penetration of solar insolation through a snow cover has been evaluated.

The amount of shortwave radiation that reaches the snow/ice interface is modeled in three steps. First the snow albedo is encountered. Second, absorption occurs in the upper 0.1 m of the snow cover. Third, the remaining radiation decays exponentially down to the snow/ice interface. Which penetration formula is used depends on whether the snow depth is greater than 0.1 meters or not (Sahlberg, 1988). The formulas are given in Equation 10 and 11 presented in subchapter 2.6.2.

The parameter F_s is measured by a pyranometer for Ingdalselva. The pyranometer measures the solar radiation which reaches the instrument from the atmosphere. Reflection from the surface is not included. Considering Sokna no such instrument is found within the appropriate distance. Instead an Empirical formula based on the cloud cover has been used. This method is described in Appendix F. The method introduces less accurate insolation values for Sokna. However, in the absence of pyranometer measurements it is an accepted method (Alfredsen, pers.com).

The bulk extinction coefficient for snow varies mainly with snow type. In dry and compact snow K_s is approximately 20-30 m^{-1} and in melting snow K_s is in the range 10-15 m^{-1}. Like the bulk extinction coefficient the albedo varies with snow type. Reported values range from 0.50 for melting old snow to 0.95 for fresh dry snow (Sahlberg, 1988). A relation between K_s and α_s is made for this study. This is not based on any known methods. However, it was found sensible since both values change with snow type. To use a relation between the two parameters is both time saving and easier to implement than separate evaluations. The relation developed for this study is given as:

$$K_s = 50 * \alpha_s - 17.5 \qquad \text{(Eq. 17)}$$

If the snow depth is zero both K_s and α_s is zero. The snow albedo is found from an Eepirical formula given as (Harstveit, 1984):

$$\alpha_s = -0.13 * (1 - C) - 0.05 * ln(t) + 0.87 \qquad \text{(Eq. 18)}$$

Table 22: Overview of parameters in formula for calculating the snow albedo (Harstveit, 1984)

Parameter	Description	Unit
α_s	Snow albedo	-
C	Cloud cover	-
T	Snow age	[days]

The penetration factor depends on the snow depth. For snow depths larger than 0.1 m, i_{os} = 0.1. For snow depths less than 0.1 m, i_{os} = 1-(9*η_s) (Sahlberg, 1988).

4.2. Further discussion

4.2.1. Instrumentation

Water level calculations for the upper part of Ingdalselva

The correlation obtained from the three day period is only used for recorded water pressures greater than 58.32 cm (1.84 masl). This is the lowest value recorded for the lower part during the three day period and corresponds to a water level at 15.77 masl at the upper part. Studying the profile shown in Figure 11 it can be argued that the correlation is valid only for water levels higher than this level. This is because of discontinuity in the profile at lower values. At low water levels only the lowest part of the river width contains water. It was necessary to simplify the cross section for this part of the profile such that the Manning formula could be used to calculate the water levels. A rectangular cross section was found reasonable considering the actual profile. The width (W) of this cross section is set as 14 m. In comparison the evaluated water depths (y) is less than 44 cm. The assumption of W >> y is therefore valid.

Theoretically a channel needs to be infinitely long before normal flow occurs. In practice certain assumptions is allowed (NVE, 2010). Upstream the current cross section the river has a relative continuous inclination. However, some bends and narrowing of the river occurs. A map of the relevant river stretch is shown in Figure 29. Because of the continuous inclination the flow is believed to be more influenced by frictional forces than acceleration forces. Thus, normal flow is a reasonable assumption although great uncertainty is included by the use of the Manning formula. This method is evaluated to be the best possible for this study. However, it must be emphasized that for further studies installation of pressure sensors at each study site should be conducted. This was discovered too late for installation of a pressure sensor at the upper part of Ingdalselva for the winter season 2012/13.

Figure 29: River stretch upstream the upper part of Ingdalselva

The water discharge which is used in the Manning formula is found from a discharge curve developed for a pressure sensor which has been replaced. There are some uncertainty adjacent to this curve because the location of the new pressure sensor is not yet been confirmed. For this study the records from the new pressure sensor have been used. GPS measurements of the water level and the current recorded water pressure indicates that the new pressure sensor have been placed at the same altitude as the sensor which is replaced. This is also what was attempted by Knut Alfredsen which installed the new sensor.

The assumptions discussed introduce uncertainty to the calculated water levels for the upper part of Ingdalselva. Nevertheless, it is seen as the best option considering that a pressure sensor at this site is lacking.

Climate data records

The recorded climate data which are used are evaluated as good for both Ingdalselva and Sokna 2005/06 due to the short distance between the gauge station and the observations site as shown in Figure 13 and 14. Considering Sokna 2012/13 the distance is greater. However, it is not expected large temperature differences between the two sites due to relative similar altitude and geographical conditions.

4.2.2. Stefan formula

Degree-day factor

The results from Brooks (2010) are based on a large geographic scale covering relatively large hydroclimatic regions. In a Norwegian perspective this will not cover the local variations between the two rivers being studied. An evaluation is therefore needed to look at potential differences between the two study cases.

Comparing the two rivers it is clear that Ingdalselva is exposed to more coastal climate than Sokna. Ingdalselva is located at the border between the coast and the inland, while Sokna is located further inland as shown in Figure 6. The effects of the coastal climate introduce higher normal values for precipitation and larger fluctuations of the temperatures. Both of which argue for a lower degree-day factor in Ingdalselva compared to Sokna.

Looking at the mean January temperature and precipitation for the two study cases the above section is substantiated by climate data. Ingdalselva has higher temperatures and more precipitation than Sokna, as shown in Table 23.

Table 23: Mean January Temperature and Precipitation of the study areas

Location	Mean January Temperature [°C]	Mean January Precipitation [mm]
Ingdalselva	-2.5	128
Sokna	-6.2	60

* The data is retrieved respectively from Lensvik and Berkåk weather stations

Cluster area 14 has the temperature -6.1°C and precipitation value of 145 mm as cluster means for January. These values are taken from Table 9 presented in subchapter 2.5.2. Compared to the values given in Table 23 it can be argued that Sokna is a good representative for Cluster area 14. The mean January temperature of -6.2°C corresponds well with the cluster mean of -6.1°C. The values are taken from relatively large hydroclimatic regions and the temperature should be given more attention as it relates better to the ice cover growth. Regarding Ingdalselva the mean January temperature of -2.5°C is significantly different from the cluster mean of -6.1°C. Thus, it can be argued that Ingdalselva should have a smaller degree-day factor than the value suggested for Cluster area 14. For this study the degree-day factors for Ingdalselva and Sokna are set as 26.0 and 27.5 respectively.

Insulating snow cover

It is found necessary to include the snow depth in the model for ice cover growth. Both the ice and snow is assumed to be homogenous materials. However, the simplification is more correct for ice then snow because there are greater differences in physical characteristics of the layers in snow. By use of mean conductivity values the layers in the snow and ice are already excluded and the assumption of homogenous materials yields. This is necessary for this study since no advanced snow measurements have been conducted, such as determining the snow density. Such measurements are comprehensive and are reasonable for this study considering the purpose and time limit.

An uncertainty to the estimated snow depths originates from the fact that no local snow depth measurement exist in the rivers. Nevertheless, the camera observations in addition to some field measurements reduce the level of inaccuracy. Considering Sokna 2005/06 camera observations are not available. The snow depth estimations this season are thus harder to conduct and introduce probably less accurate values. For further studies a local snow depth instrument should be considered. This will give even more detailed and accurate information.

4.2.3. Empirical criterion

Formation of a full cover

Considering the upper part of Ingdalselva the water levels which is calculated gives lower water levels during the formation of the second layer compared to the first layer. Seen from observations this is known not to be the case. The method used does not take into account the presence of the first ice layer when calculating the water levels during the period with both layers present. This could simply be included by adding the thickness of the first ice layer to the water levels. However, the ice layer will also affect the flow by introducing an additional surface roughness. Also this factor indicates that the calculated water levels for the second formation are underestimated.

In the model the water level during the second formation is only 1 cm lower than for the first. By including the affect of the first ice layer it is therefore clear that the difference would be opposite and by a larger amount in accordance with the observations. This is the background for the discussion regarding the anchor effect of boulders at the river bed. In this context the actual water level is important. However, it does not affect the functionality of the Empirical criterion since the criterion takes only the water level differences into account. In this case it is the relative water level difference which is important.

Overall

The need for a criterion which predicts the ice breakups in small streams are considerable. In Norway during spring there are often several news articles regarding damages from river ice breakups. A method to predict these events will provide the possibility to develop the emergency flood warning system to encounter river ice breakups. In addition hydro power companies can be warned such that intakes can be closed and spared for major damages.

It is important to emphasize that this study is only a start in the progress towards emergency flood warning systems. The model are built and tested only for small stretches of the rivers. However, with several ice studies the usual locations of ice breakups can be discovered. It is believed that the initial ice movement is dependent upon river geometry and is therefore in many cases limited to one or several certain locations of a river stretch. These locations can be worth focusing upon considering further studies, and research at such a location may be sufficient to describe the processes at hand.

By use of the empirical criterion the observations and results can not be transferred simply to other reaches of the same river or other rivers because of the site-specific coefficient and function. These parameters need to be evaluated for each river site. Thus, it is clear that the criterion in its present form is not sufficient for emergency flood warning. A criterion which can be transferred to any river site is desirable for this purpose. Nevertheless, several studies involving this criterion may lead to the discovery of factors which plays an important role and a new developed criterion more based on physical reasoning.

5. CONCLUSION

The Stefan formula is shown to present good simulations of the ice cover thicknesses for the two study areas. Disregarding the two situations with water on top of the ice cover the accuracy is found in the range +/- 4 cm for Ingdalselva and +/- 6 cm for Sokna 2012/13. This accuracy level shows the possibility of combining the Stefan formula with river ice breakup studies. In this study the method provides reliable values of the ice cover thicknesses which then can be used as input parameter to different criteria for the initiation of a river ice breakup.

The Empirical criterion shows promising results for this study in which three of five ice breakups in small steep streams were simulated by the criterion. The results show that the Empirical criterion which is developed for moderate-gradient large rivers may be applicable also for high-gradient small streams. However, several data sets are needed to be more specific about the applicability. Further studies should be conducted to discover several factors which need to be considered for better performance of the criterion. Such studies may lead to the development of new criteria for ice breakups in small streams.

6. FUTURE WORKS

Empirical criterion

The Empirical criterion can be a good foundation for further studies and development of new criteria. The Empirical criterion has now been tested on five known ice breakups in small streams. To determine the application of the criterion it is needed to be tested on several data sets.

In this study the Empirical criterion was used by including the Stefan formula to simulate the ice cover thickness. The field instrumentation required by this method:

- Pressure sensor for water level measurements
- Gauge station for air temperatures, solar insolation and snow depth
- Camera observation to determine the period of ice formation, date of full ice cover and date of ice breakup
- Regular ice cover thickness measurements for calibration of Stefan formula

In addition historical data is needed to be able to evaluate the site-specific coefficient and function. Thus, it is reasonable to continue the research in Ingdalselva and Sokna where data sets now exists. Another possibility is to search for historical data. Some data is retrieved by Norwegian Water Resources and Energy Directorate (NVE) in the period when observers were manually sent to the gauge stations for retrieval of river data. For Sokna such data was found. However it was not found sufficient because exact observations on the date of formation and breakup were lacking.

Lesson learned is that pressure sensors should be installed at each observation site. This makes measurements more reliable and analysis easier. Cameras with a trigger function should be considered. Observations of the actual breakup are needed to study the driving forces more in detail. A wire connected to both the release trigger of the camera and the ice cover could make it possible to increase the amount of pictures taken during the breakup. In addition, it should be considered solutions to make use of camera observations outside hours of sunlight. For this study all the ice breakups occurred during night.

Boundary constraint criterion

In addition to further studies regarding the Empirical criterion it will also be interesting to test other criteria developed for large rivers. Especially the Boundary constraint criterion since this is found to give encouraging results for moderate-gradient medium and large rivers. A large amount of field measurements are required for the criterion. The extent of these measurements was realized too late in this study for the ability to also test this criterion on the river ice in the study areas. Field instrumentation required when including the Stefan formula to simulate the ice cover thickness:

- Pressure sensor for water level measurements and water discharge
- River profiles measurements to set up a HEC-RAS model to be able to:
    - Evaluate the bed roughness
    - Evaluate the water surface slope
    - Set up a water level – water width relation
- Gauge station for air temperatures, solar insolation and snow depth
- Camera observation to determine the period of ice formation, date of full ice cover and date of ice breakup
- Flexural ice strength measurements
- Ice cover width measurements
- Regular ice cover thickness measurements for calibration of Stefan formula

In addition some parameters need to be set:

- Radius of curvature of the centerline of the river
- Ice cover roughness
- Hydraulic radius of the ice cover
- Specific gravity of ice
- Thickness of the porous accumulation under the solid ice sheet
- Site-specific empirical coefficient (0.3 - 1.5)

For further studies the focus should be on implementing the necessary field measurements before the ice season begins. This involves surveying of river profiles which needs to be conducted while the river is free of ice and at relatively low water. The flexural ice strength is needed by use of the Boundary constraint criterion. This parameter is possible to obtain from ice literature. However, most literature found is regarding large rivers, so a local setup for evaluating the flexural ice strength should be considered.

Overall

Further studies will increase the understanding of the ice breakup processes in small streams and enable development of new and improved ice breakup criteria. During the field studies it is important to focus on decisive behavior which is not obtained by the existing criteria. Such factors should be studied in detail and attempted implemented to the criteria.

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Appendix A

Ingdalselva

Figure A1: Camera setup lower part

Figure A2: Camera setup upper part

Camera observations Lower Part

Figure A3: 29.12.12 at 02:00 PM

Figure A4: 04.01.13 at 11:00 AM

Figure A5: 26.01.13 at 02:00 PM

Figure A6: 17.02.13 at 02:00 PM

Figure A7: 26.02.13 at 01:00 PM

Figure A8: 28.02.13 at 08:00 AM

Camera observations Upper Part

Figure A9: 01.01.13 at 03:00 PM

Figure A10: 04.01.13 at 11:00 AM

Figure A11: 27.02.13 at 08:00 AM

Figure A12: 28.02.13 at 08:00 AM

Sokna

Figure A13: Camera setup

Figure A14: 05.12.12 at 03:00 PM

Figure A15: 24.02.13 at 12:00 PM

Figure A16: 15.04.13 at 12:00 PM

Figure A17: 15.04.13 at 03:00 PM

Figure A18: 15.04.13 at 04:00 PM

Figure A19: 15.04.13 at 05:00 PM

Figure A20: 20.04.13 at 12:00 PM

Appendix B

Detailed overview of how the method for calculating the ice cover growth is set up:

CAMERA OBSERVATIONS		
Condition	**Date**	**Comment**
Formation		
Full cover		
Breakup		

FIELD OBSERVATIONS		
Date	**Ice cover [cm]**	**Snow [cm]**

ICE COVER THICKNESS

Stefan formula, parameters

Symbol	Unit	Description
T_a(mid)	°C	Mean air temperature
η_s	m	Snow cover thickness
R_{snow}	$W\ m^{-2}\ °C^{-1}$	Thermal resistance in snow
R_{tot}	$W\ m^{-2}\ °C^{-2}$	Thermal resistance in both snow and ice
T_{is} (mid)	°C	Mean temperature at top of ice cover
FDD	°C	Freezing degree days
S(AFDD)	°C	Accumulated freezing degree days
η	m	Ice cover thickness

Starting at the date of formation of the ice cover

Degree-day factor		*Conductivity factor*		
$\alpha_{h,\ formation}$	0.60	k_i	2.03	W/m°C
$\alpha_{h,\ full\ cover}$	2.60/2.75	k_s	0.25-0.35	W/m°C

Method

Date	T_a (mid)	η_s	R_{snow}	R_{tot}	T_{is} (mid)	FDD	S (AFDD)	η
	[°C]	[cm]	[Wm^{-2}°C^{-1}]	[$W\ m^{-2}$ °C^{-1}]	[°C]	[°C]	[°C]	[cm]

Determination of parameters and formulas

T_a(mid); retrieved from nearby gauging station

η_s; estimated from nearby gauging station and camera observations

$R_{snow} = \eta_s/k_s$

$R_{tot} = R_{snow} + \eta_{n-1}/k_i$

$T_{is}(mid) = T_a(mid)$ when $\eta_s = 0$

$T_{is}(mid) = T_a(mid)+[-T_a(mid)*R_{snow}/R_{tot}]$ when $\eta_s > 0$

$FDD = - T_{is}(mid)$

$S(AFDD) = FDD + S(AFDD)_{n-1}$ when $FDD > 0$

$\eta = \alpha_h * S(AFDD)^{0.5}$

Appendix C

Simulation of the thicknesses of the ice covers; calculated compared to the observed values:

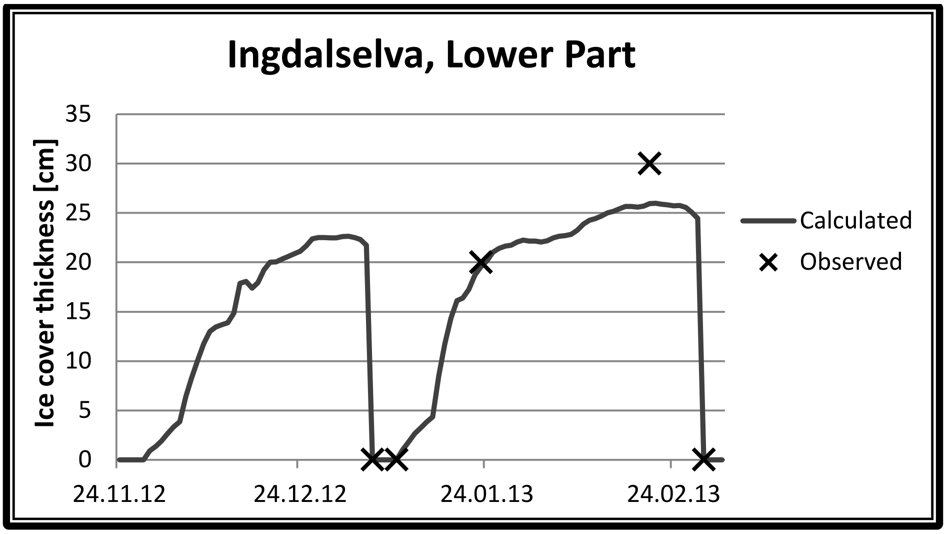

Figure C1: Simulation of the ice cover thicknesses in the lower part of Ingdalselva 2012/13

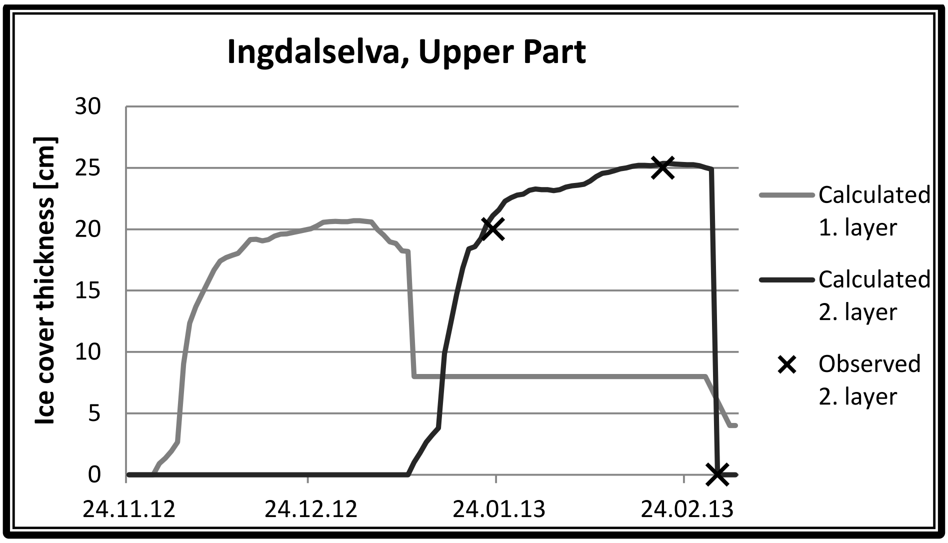

Figure C2: Simulation of the ice cover thicknesses in the upper part of Ingdalselva 2012/13

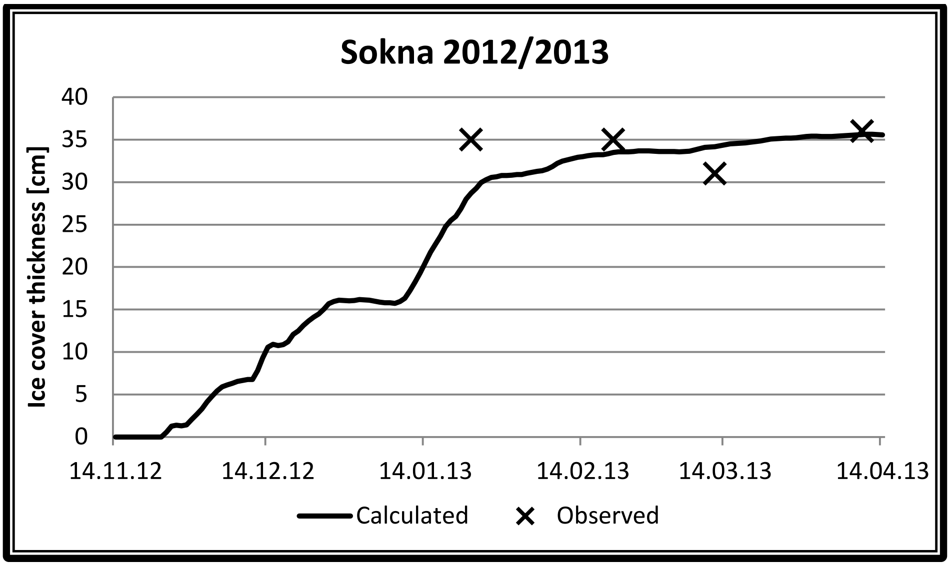

Figure C3: Simulation of the ice cover thicknesses in Sokna 2012/13

Appendix D

Empirical criterion:

ONSET OF A MECHANICAL BREAKUP		
Empirical criterion		
Symbol	**Unit**	**Description**
H_B	[m]	Current water level
H_F	[m]	Water level at the date of formation
K	-	Site specific constant
$F(S_5)$	[m]	Site-specific function

Results in numeric form:

INGDALSELVA LOWER PART				
			Driving	*Resisting*
	[m]	[cm]	[cm]	[cm]
Date	**WL (H_B)**	η	H_B **-** H_F	$K\eta$ **-** $F(S_5)$
01.01.2013	0.19	23	-13.35	33.97
02.01.2013	0.19	23	-13.15	33.78
03.01.2013	0.26	22	-6.57	33.48
04.01.2013	**1.04**	**22**	**71.30**	**32.62**
25.02.2013	0.16	26	-20.83	38.64
26.02.2013	0.18	26	-18.91	38.33
27.02.2013	0.31	25	-5.96	37.61
28.02.2013	**0.87**	**24**	**49.32**	**36.71**

INGDALSELVA UPPER PART				
			Driving	*Resisting*
	[cm]	[cm]	[cm]	[cm]
Date	**WL (H_B)**	**η**	**H_B - H_F**	**$K\eta$ - $F(S_5)$**
01.01.2013	12.86	21	-19.84	31.05
02.01.2013	13.02	21	-19.68	30.97
03.01.2013	18.09	21	-14.61	30.87
04.01.2013	**58.24**	**20**	**25.54**	**29.94**
25.02.2013	10.76	25	-20.99	37.89
26.02.2013	12.19	25	-19.56	37.77
27.02.2013	22.26	25	-9.48	37.55
28.02.2013	**53.02**	**25**	**21.27**	**37.36**

SOKNA 2005/2006				
			Driving	*Resisting*
	[cm]	[cm]	[cm]	[cm]
Date	**WL (H_B)**	**η**	**H_B - H_F**	**$K\eta$ - $F(S_5)$**
08.12.2005	42.28	13	-12.38	19.86
09.12.2005	41.54	15	-13.12	23.17
10.12.2005	44.48	16	-10.19	24.13
11.12.2005	**74.49**	**16**	**19.83**	**23.49**
29.01.2006	38.94	23	-4.96	33.87
30.01.2006	45.91	22	2.01	32.60
31.01.2006	62.85	21	18.95	31.05
01.02.2006	**74.20**	**20**	**30.30**	**29.88**

SOKNA 2012/2013				
			Driving	*Resisting*
	[cm]	[cm]	[cm]	[cm]
Date	**WL (H_B)**	**η**	**H_B - H_F**	**$K\eta$ - $F(S_5)$**
12.04.2013	22.46	36	-27.94	54.26
13.04.2013	23.37	36	-27.03	54.22
14.04.2013	24.20	36	-26.20	54.17
15.04.2013	**50.27**	**35**	**-0.13**	**52.78**

Bold black text indicates an ice breakup which is both observed and simulated.

Red text indicated an ice breakup which is observed, but NOT simulated.

Blue text indicates water is observed on top of ice cover.

For all situations the site-specific function $F(S_5)$ is neglected.

Appendix E

Manning formula for calculating the water level at the upper part of Ingdalselva using a simplified rectangular cross-section:

Simplification:

The simplified profile was set by a width of 14 m. This corresponds to the width between 10 and 24 m from the left bank in Figure 11 (measured profile).

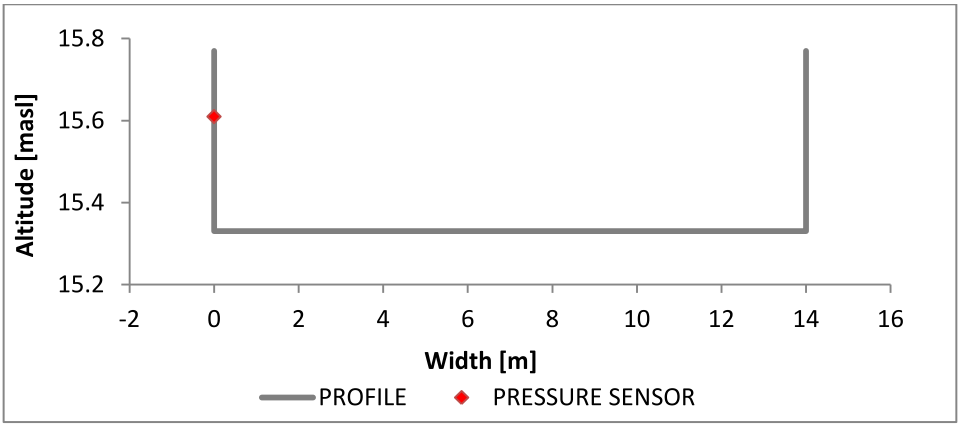

Figure E1: Simplified profile for the upper part of Ingdalselva

The location of the pressure sensor in the picture is only correct regarding the altitude. The actual location is not within the simplified profile. This pressure sensor is the one which was placed at the upper part for three days.

The simplified profile is used for calculating water levels at the upper part of Ingdalselva which is in the range of 15.33 – 15.77 masl. This corresponds to a pressure less than 58.32 cm (1.84 masl) measured by the pressure sensor at the lower part.

Assumptions:

- Normal flow is assumed for the current cross section
- W >> y (Width much larger than water depth)

Calculations:

Manning formula is used. The bed roughness is found through calibration for the minimum water level recorded in the 3 day period. This period the river consists of open flow. This is not the case for the water levels being calculated. Thus, the ice roughness is added to the Manning number for the actual calculations. This roughness has not been calibrated since no known values of the water level with an ice cover are available. For an ice covered river the hydraulic radius changes. The wetted perimeter will for these situations goes all the way around the water filled cross section.

Formulas used (Task Force, 1993):

$$Q = M * A * R^{2/3} * I^{1/2} \qquad \text{(Eq. E1)}$$

$$A = W * y \qquad \text{(Eq. E2)}$$

Open flow; rectangular channel and W >> y:

$$M = \frac{1}{n_b} \qquad \text{(Eq. E3)}$$

$$R = y \qquad \text{(Eq. E4)}$$

Ice covered river; rectangular channel and W >> y:

$$M = \frac{1}{n_c} \qquad \text{(Eq. E5)}$$

$$n_c = \left[\frac{{n_i}^{3/2} + {n_b}^{3/2}}{2}\right]^2 \qquad \text{(Eq. E6)}$$

$$R = \frac{y}{2} \tag{Eq. E7}$$

Table E1: Parameters included in the calculations of the water level

Parameters	Description	Value	Unit
Q	Discharge	From discharge curve	[m^3 s^{-1}]
W	Width	14	[m]
I	River bed inclination	0.01	-
n_b	River bed roughness	0.21 (Calibrated)	[s $m^{-1/3}$]
n_i	Ice cover roughness	0.02	[s $m^{-1/3}$]

Appendix F

Empirical formula for calculating the insolation towards the surface:

Formulas

$$Q_{s1} = Q_{ex}\,(k_1C_s + k_2\,SQRT(C_s) + k_3)$$

$$Q_{ex} = S/\pi*E^2*(\omega_s SIN\phi SIN\delta + COS\phi COS\delta SIN\omega_s)*689$$

$$\delta = 23.45*SIN[2\pi\,(n+284)/365]\,*\pi/180$$

$$D = -\tan\phi * \tan\delta$$

$$\omega_s = ACOS(D) \text{ for } ABS(D) < 1.0$$

$$E = 1 + [0.33*COS(2\pi n/365)] \text{ for } ABS(D) < 1.0$$

Symbol	Forklaring	Verdi	Enhet
Q_{s1}	Insolation towards surface		$W\ m^{-2}$
Q_{ex}	Insolation at top of the atmosphere		$W\ m^{-2}$
n	Day number		
δ	Inclination		Rad
D	Day length		Rad
ω_s	Sun angle		Rad
E	Eccentricity		Rad
S	Solar constant	1.94	$cal\ cm^{-2}\ min^{-1}$
ϕ	Longitude	62.94	°
k_1	Empirical factor	-0.16	
k_2	Empirical factor	0.81	
k_3	Empirical factor	0.07	
C	Mean cloud coverage	0-1	
C_s	1-C	0-1	

Cloud coverage was found from gauge station: “Berkåk-Lyngholt” for Sokna 2005/2006 and from gauge station: “Oppdal Sæter” for Sokna 2012/13.

Overview of attachments on CD

Excel files:

Ingdalselva 2012-13

- Analysis of water level at the upper part
- Climate data records
- Penetration of shortwave radiation
- River profile
- Stefan formula and Empirical criterion

Sokna 2005-06

- Climate data records
- Penetration of shortwave radiation
- Stefan formula and Empirical criterion

Sokna 2012-13

- Climate data records
- Penetration of shortwave radiation
- Stefan formula and Empirical criterion

Camera observations:

- Ingdalselva 2012-13
- Sokna 2012-13
- Excel file with comments

Time-lapse movies:

- Ingdalselva Lower part 2012-13
- Sokna 2012-13