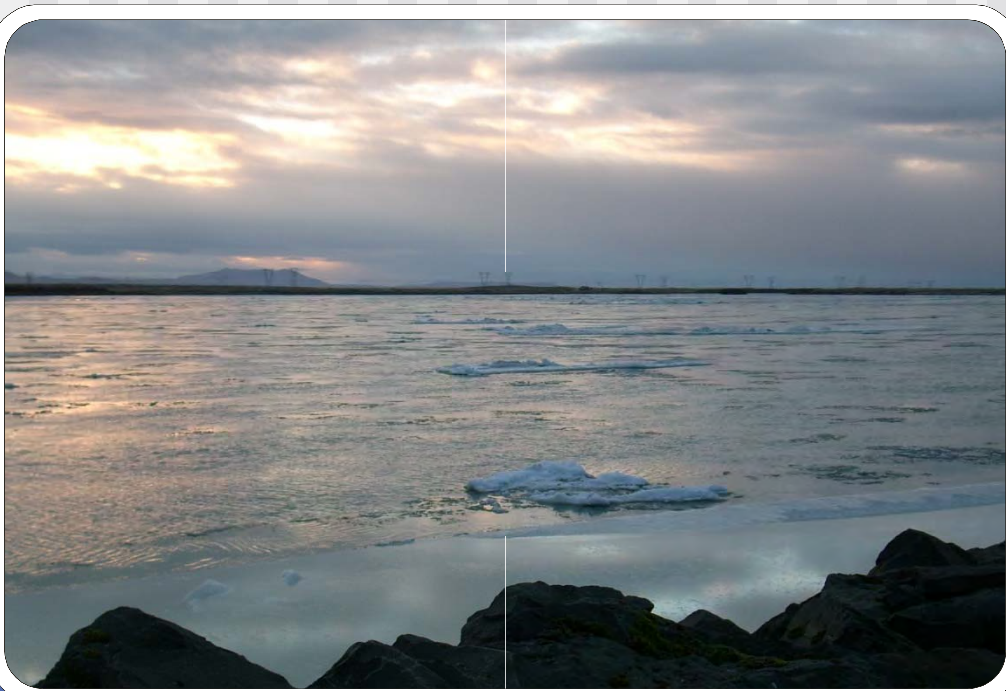
LV-2009/127

Þjórsá River
South Iceland
Hvammur and Urriðafoss Hydroelectric Projects

Ice Jam Evaluation



Landsvirkjun

December 2009

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Authors/Company:	Hörn Hrafnsdóttir/Verkís & Sigmundur Freysteinsson
Project manager:	Helgi Jóhannesson/LVP
Prepared for:	Landsvirkjun
Co operators:	Mannvit

Abstract: This report discribes a model work using the ice jam feature in HEC-RAS to model the possible ice jam formation above the intake ponds for Hvammur and Urriðafoss Hydroelectric Projects. The results indicate that if the currently planned construction order is followed, i.e. Hvammur, Holt, Urriðafoss, ice jams will form above the intake ponds but they should not cause problems. A small part of the new road along Hagalón Pond needs to be higher than currently planned. Changing the construction order calls for further investigation on the ice jam above Heiðarlón Pond and the implimentation of some countermeasures.

Keywords: Þjórsá River, Hvammur and Urriðafoss Hydroelectric Projects, Hagalón Pond, Heiðarlón Pond, ice jams, wide river ice jams, HEC-RAS.

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Landsvirkjun's project manager's signature

Helgi Jóhannesson

ÞJÓRSÁ RIVER
SOUTH ICELAND

HVAMMUR AND URRIÐAFOSS HYDROELECTRIC PROJECTS

ICE JAM EVALUATION

Project no.: 2007.0306 **December 2009**

Abstract

In Lower Þjórsá River in South Iceland three hydroelectric projects are proposed by the energy company, Landsvirkjun. These are the Hvammur, Holt and Urriðafoss Hydroelectric Projects. The new intake ponds for Urriðafoss and Hvammur Hydroelectric Projects, named Heiðarlón Pond and Hagalón Pond, will function as starting points for ice jams that can grow upstream from the intake ponds. In order to evaluate the possible ice jam formation, the river reaches in question were modelled using the wide river ice jam feature in the software HEC-RAS.

Ice investigations in Lower Þjórsá River date back to 1950, so quite a lot is known about the current ice regime. The ice jam at Urriðafoss has been monitored and aerial photographs give helpful information on the magnitude of open water surface during cold periods. The Urriðafoss Ice Jam grows during freezup periods and falls during break-up periods. Temperature measurements downstream of Búrfell Powerstation give information about how far downstream the water flows before it is cold enough to start producing ice. Relevant information was used to draw conclusions about some aspects of the model and the Urriðafoss Ice Jam was used for calibration purposes. The calibration showed that the ice jam feature in HEC-RAS can be used to model wide river ice jams in Þjórsá River as long as the river reach modelled does not include waterfalls or too steep parts. If the reach contains such features the ice jam seems to change its behaviour from a wide river ice jam to something else, probably a hanging dam.

The river reach modelled for the evaluation of the Hagalón Ice Jam is relatively flat, thus the ice jam formed there should be a typical wide river ice jam. The results of the modelling indicate an average waterlevel rise of 90 cm due to the freeze-up ice jam using steady discharge of 300 m^3/s. The highest waterlevel rise reached 1,5 m. A break up ice jam was also tested with an underlying flood of 1500 m^3/s. The reason for looking into a break up ice jam is that even though the Urriðafoss Ice Jam seems to be a freeze-up ice jam that falls, creating a free passage for the ice during break-up, the same does not necessarily apply to the Hagalón Ice Jam as the intake pond will trap the break-up ice. The waterlevel rise, in this case, was much higher but still similar to the waterlevel rise due to the design flood (a flood with 1000 years return period). In this case the water level rise at the upstream end of the dike is only one meter lower than the top of the dike. It has to be considered whether this is acceptable or not. This problem might be limited by using an ice boom. Additionally, the highway is designed too low over about 3 km and should be lifted higher or it might be flooded in the case of break-up ice jam.

The river reach from Heiðarlón Pond up to Árnes Rapids is also relatively flat and thus the ice jam is also a case of wide river ice jam formation. The results of the model gave an average water level rise of 1 m based on freeze-up ice jam with discharge steady at 300 m^3/s. The highest value calculated was 1,3 m. A break up ice jam was not tested in this model.

The reach up to Búði Fall was then added to the model. Model-runs were made assuming that the upper powerstations were not constructed first, and that the Árnes Branch would freeze over forcing all water to run down the Þjórsá River at Árnes. The calculated ice jam was much bigger than the one for the lower branch only. The average water level rise was 2,4 m with the highest reaching 6 m just below the Árnes Rapids. As the rapids are a steep portion in the river the question rises whether or not the ice jam is still a wide river ice jam below the rapids. The waterlevel rise of 6 m just below the rapids is the same as noted on a map in an article by Sigurjón Rist (Sigurjón Rist. 1962), but downstream of that location the map gives 4 m water level rise while the model calculates around 2 m. It is quite possible that below the rapids the ice jam might change from being a wide river ice jam into a hanging dam. This can be avoided if the ice is trapped in the river above the rapids.

Similarly, in the channel from the Árnes Rapids up to Búði Fall, the ice jam can be modelled as a wide river ice jam as it grows up to the pond below the waterfall but then it might change its

character and start to behave like a hanging ice dam. This could also be avoided if ice would be trapped at some location upstream of the waterfall, for instance close to Þjórsárholt.

The models, for both locations, give good information about what can be expected, but their limitations have to be kept in mind.

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Notation

The following symbols are used in this report.

g	acceleration of gravity (m/s^2)
k_0	tan ϕ
k_1	coefficient of lateral thrust = σ_y/σ_x
k_x	$\tan^2(45+\phi/2)$ if cohesion is neglected. Is thougth to be equal to the passive earth pressure coefficient K_p , laboratory experiments have given values in the range of 7-10 [p. 130 Beltaos,1995].
n_b	Manning's n for riverbed (s/m$^{1/3}$)
n_c	The composite Manning's n for ice covered river (s/m$^{1/3}$)
n_i	Manning's n for the underside of the ice (s/m$^{1/3}$)
p_i	ice jam porosity (noted as e in HEC-RAS)
s	is the specific gravity of ice
t	the accumulation thickness (m)
x	length along the stream direction (m)
A	the area of the open water surface (m^2)
B_i	the accumulation width (m)
L	latent heat of fusion (J/kg)
Q_i	production rate of solid ice (m^3/s)
R_{ic}	the hydraulic radius associated with the ice cover (m)
S_f	the friction slope of the flow
S_w	the water surface slope
Φ	heat loss from the water surface (W/m^2)
γ_e	$0{,}5\ \rho_i\ g\ (1\text{-}s)\ (1\text{-}p_i)$ (N/m^3)
ϕ	angle of internal friction of the ice jam
μ	$k_0k_1K_x(1\text{-}p_j)$, documented ice jams suggest values in the range of 0,8-1,3 averaging about 1,2. (p. 129-130 Beltaos)
ρ	density of water (kg/m^3)
ρ_i	density of ice (kg/m^3)
σ_x	longitudinal stress along the stream direction (Pa)
σ_y	lateral stress (Pa)
σ_z	vertical stress (Pa)
τ_b	shear resistance of the banks (Pa)
τ_i	shear stress applied to the underside of the ice by the flowing water (Pa)

1 Introduction

In Lower Þjórsá River in South Iceland, see Figure 1.1, three Hydroelectric Projects are proposed by Landsvirkjun. They are the Hvammur, Holt and Urriðafoss Hydroelectric Projects.

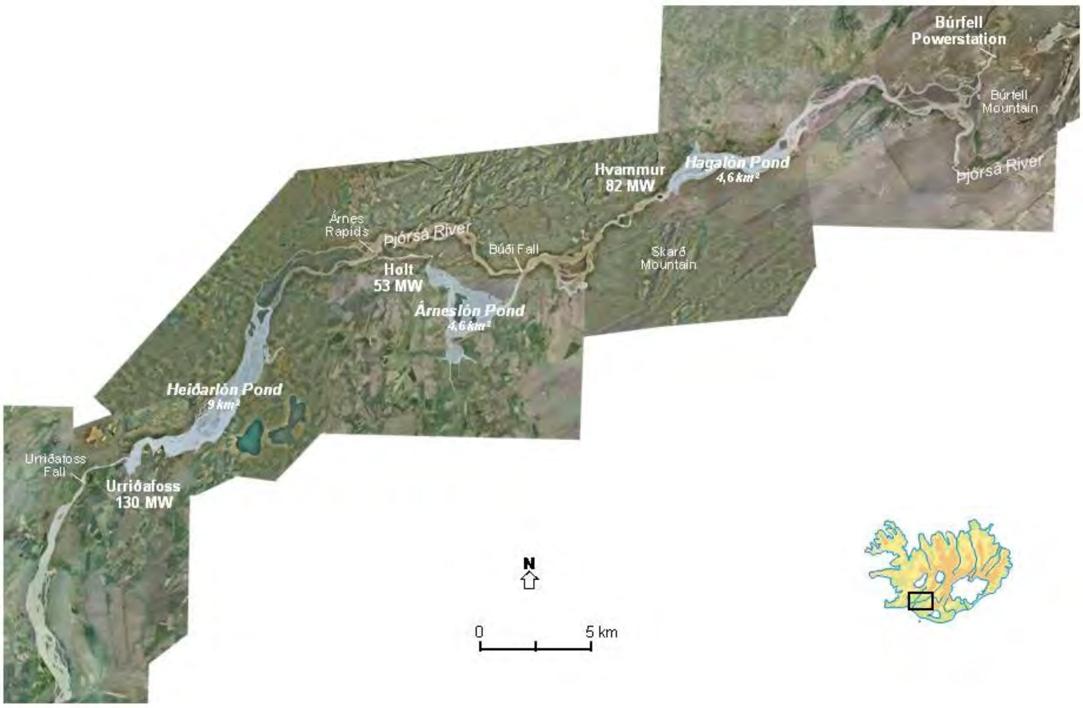

Figure 1.1 *An overview of Lower Þjórsá River including the proposed Hydroelectric Projects.*

Before 1970 two huge ice jams formed annually in this river reach. One, just below Búrfell Mountain, where the river spreads out after being confined to a canyon in the reach above and another in the canyon at and below Urriðafoss Fall. Additionally, an ice jam formed occasionally below Búði Fall. The waterlevel rise could be as high as 18 m in the biggest one and the volume of ice in the ice jams could reach about 40 Mm^3 (Sigurjón Rist, 1962, p. 22).

Today the conditions are different as reservoirs, diversions and hydroelectric projects in the upper reaches of the river have changed its ice regime. At present, ice jam only forms below Urriðafoss Fall. The proposed hydroelectric projects in Lower Þjórsá River will again change the river's ice regime. The new intake ponds for Urriðafoss and Hvammur Hydroelectric Projects can function as starting points for new ice jams that can grow upstream from the intake ponds. As the intake pond for Holt Hydroelectric Project is in a side branch with an ice diversion upstream it should not create a starting point for an ice jam as the other two.

In order to evaluate the possible ice jam formation it was decided to make a model of the river reaches from both dams and some distance upstream from the intake ponds. Herein, the models are explained and the results of the ice jam calculations presented. The software used was the wide river ice jam feature in HEC-RAS.

2 River ice basics

The purpose of this report is not to go deep into the physics of ice jam processes or ice formation as the main purpose is to use the HEC-RAS software to model ice jam formation in reaches of interest and speculate what might happen. Nevertheless, there are some basic concepts and processes that need to be addressed in order to explain what might happen and what is done in the modelling part.

2.1 Ice formation in rivers

2.1.1 Ice production

Ice in rivers is produced in two different ways, either as frazil ice or as surface sheet ice. The former forms in a turbulent flow where mixing is high within the cross section, while the latter forms where velocity is very low. For Lower Þjórsá River the major ice production contributing ice to ice jams is formed as frazil ice. At the riverbanks, surface sheet ice will form as border ice and also in side branches. This ice production is not important for ice contribution to possible ice jams but rather the opposite, i.e. its contribution to border ice growth is important as it limits the open water surface thus reducing frazil ice production. Part of the frazil ice will also add to the border ice growth.

Frazil ice production is given by the following formula:

$$Q_i = \frac{\Phi A}{\rho_i L} \qquad \textbf{Eq. 2.1}$$

where Q_i (m^3/s) is production rate of solid ice, Φ (W/m^2) is heat loss from the water surface, A (m^2) is the area of the open water surface, ρ_i (916 kg/m^3) is density of ice and L (333.400 J/kg) is latent heat of fusion (Ashton, 1986).

The variables in the denominator are constants while the variables in the nominator have to be calculated. The production rate is linearly dependent on the area of open surface so the open surface is very important. The heat loss is dependent on various factors among which the wind speed and temperature are the most important ones. Heat loss and ice production has been calculated for many winters and accounted for in reports by Gunnar Orri Gröndal and Victor Kr. Helgason (2003 and 2006) and will not be discussed further in this report. Snowfall and snowdrift will add to the ice discharge.

2.1.2 Ice jam types

The location of ice jams depends on where within the river reach ice can form a closed surface over a cross section. This can happen either by surface blockage, for example where there is a lake within the reach where surface lake ice covers the lake thus blocking inflowing ice from flowing further downstream, or by congestion, i.e. where the incoming ice discharge exceeds the local ice transport capacity. From this closed surface ice will accumulate and form an ice jam. The type of ice jam that will form depends on the thickness of the ice, flow depth and river velocity, or the longitudinal slope of the river.

If the velocity is low enough for the ice to stay on the surface (not entrained underneath the ice cover) and if the downstream forces are low enough for the inflowing ice not to be shoved together, the surface of the river will become covered with one layer of ice that grows upstream and freezes together in one layer. This ideal formation is called **juxtaposition**. The water level rise associated with this formation would only be caused by the additional wetted perimeter added by the ice cover. The velocity in the river needs to be lower than 0,5-0,7 m/s for this process to occur. The exact value differs for different conditions (White, 1999).

In most cases the ice cover formation is not that relaxed. The most usual form is the so-called **wide river ice jam**. This ice jam is mainly formed by frontal progression and shoving. The former happens when the velocity at the upstream edge of the ice jam is low enough for the ice to accumulate at the upstream end and after a while the downstream forces become to much for the ice jam to withstand so it is pushed and shoved together downstream. This formation leads to thicker ice formation than for the simple juxtaposition and sheet ice.

The third type, worth mentioning here, is the **hanging dam**. The hanging dam forms where the inflowing ice is entrained under the ice cover and deposits under the ice cover where the ice supply exceeds the local transport capacity. The right conditions for this formation are at river mouths entering lakes or reservoirs and in deep pools within rivers, especially where there is a reach of rapids upstream from the pool. This also applies to waterfalls and the pool below them.

Additionally it is customary to distinguish between the so called **freeze-up** and **break-up ice jam**. The former is formed early in the winter when the ice in the river is formed and the latter is formed by ice floes during the break-up period in the spring or, as is common in Iceland, during thawing periods in the winter time. The ice particles in a freeze up ice jam can be from very small frazil up-to well formed pancake ice and is usually smoother than the breakup ice jam. The Break-up ice jam is on the other hand formed by a former ice cover that has been broken up either by added discharge or due to the ice covers weakened condition in the spring. The break-up ice jam is rougher than the freeze-up ice jam. The velocity needed for inflowing ice to submerge under an ice cover is lower for freeze-up ice jam than break-up ice jams as the ice is much less developed in the freeze-up period and needs less drag to be submerged. In general the velocity needed for submergence of frazil flocs is in excess of 0,6-0,7 m/s (Beltaos, 1995).

2.2 Variables effecting the jam

There are various variables and properties of the ice that affect the ice jam. Some are more important than others and some are relevant to the modelling in this report and some are not. These variables are described in detail in Dr. White’s report (1999) and will not be discussed in any detail in this report. The variables used in the modelling are the porosity, angle of internal friction and the roughness of the ice cover. Only the last one of the three will be discussed here.

2.2.1 Ice cover roughness, n_i

The ice cover roughness, i.e. the roughness of the bottom of the ice jam, is one of the most explored hydraulic property of the ice cover (White, 1999). Research has shown that the roughness depends among other things on the ice the ice jam is formed of, the thickness of the ice jam and time from formation. The main results are:

- Break-up ice jams are rougher than freeze-up ice jams.
- Freeze-up ice jams made of loose slush are smoother than those made of dense slush.
- The thicker the ice jam, the rougher it is.
- The ice jams gets smoother with time.

Most investigations and tests have been focused on break up ice jams and all new reports found during the modelling focused on break up ice jams. One older report by Nezhikhovskiy is about roughness of freeze-up ice jams. He put forward a relationship between ice jam thickness and roughness for three types of floating ice, see Figure 2.1. In HEC-RAS there is an option for letting the software calculate the ice roughness and that option is most probably based on Nezhikhovskiy’s relationship for ice floes. The ice flow in Lower Þjórsá River will most likely be slush, probably dense slush. Because of that, a relationship was formulated from Nezhikhovskiy’s data for dense slush. The dataset is listed in Table 2.1 and equation 2.2 is a trend line for the dataset and the equation used in the calculations.

$$n_i = 0{,}0302\ln(t) + 0{,}0445 \qquad \textbf{Eq. 2.2}$$

The parameter t is the accumulation thickness measured in meters.

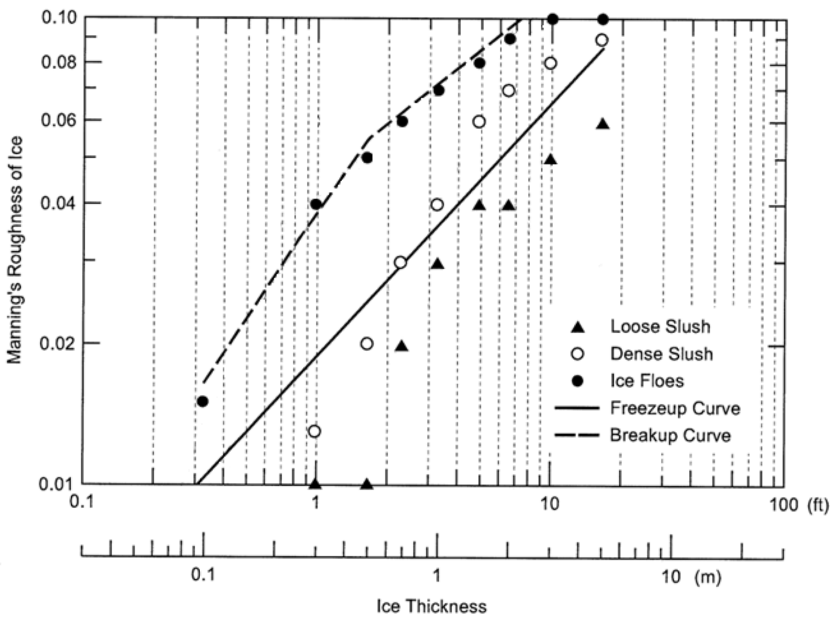

Figure 2.1 *Nezhikhovskiy's relationship. Figure taken from Dr. White's report (1999). The data for dense slush is shown as circles with white filling.*

Table 2.1 *The Nezhikhovskiy's relationship for dense slush (Nezhikhovskiy, 1964).*

t	n
0.3	0.013
0.5	0.02
0.7	0.03
1	0.04
1.5	0.06
2	0.07
3	0.08
5	0.09

3 Ice investigations in Lower Þjórsá River

3.1 Introduction to the Lower Þjórsá River

Þjórsá River is the longest river in Iceland, with a river length of about 230 km. Lower Þjórsá River is the part of the river that runs through the lowland below Búrfell Mountain. At Búrfell Mountain the river drops over 100 m. The riverbed in the lower reaches is below 122 m a.s.l. This part of the river is about 75 km long measured from below the gorge ending below Búrfell Mountain down to the see. The river is a mixture of spring-fed, direct runoff and glacial streams with catchment area at Urriðafoss Fall in excess of 7500 km^2.

Ice investigations in Lower Þjórsá date back to 1950, before the upper parts of the basin were developed for hydropower. By 1962 the ice conditions in Lower Þjórsá were well known (Sigurjón Rist, 1962). At that time three big ice jams were known in Lower Þjórsá River. Two of witch formed annually, the Búrfell Ice Jam and the Urriðafoss Ice Jam. The third one, Búði Ice Jam, formed regularly but not annually. In exceptional cases an ice cover formed on the flat area at Skeið, the river reach from above the Urriðafoss Gorge and almost up to Árnes Rapids. The location of the ice jams is shown in Figure 3.1.

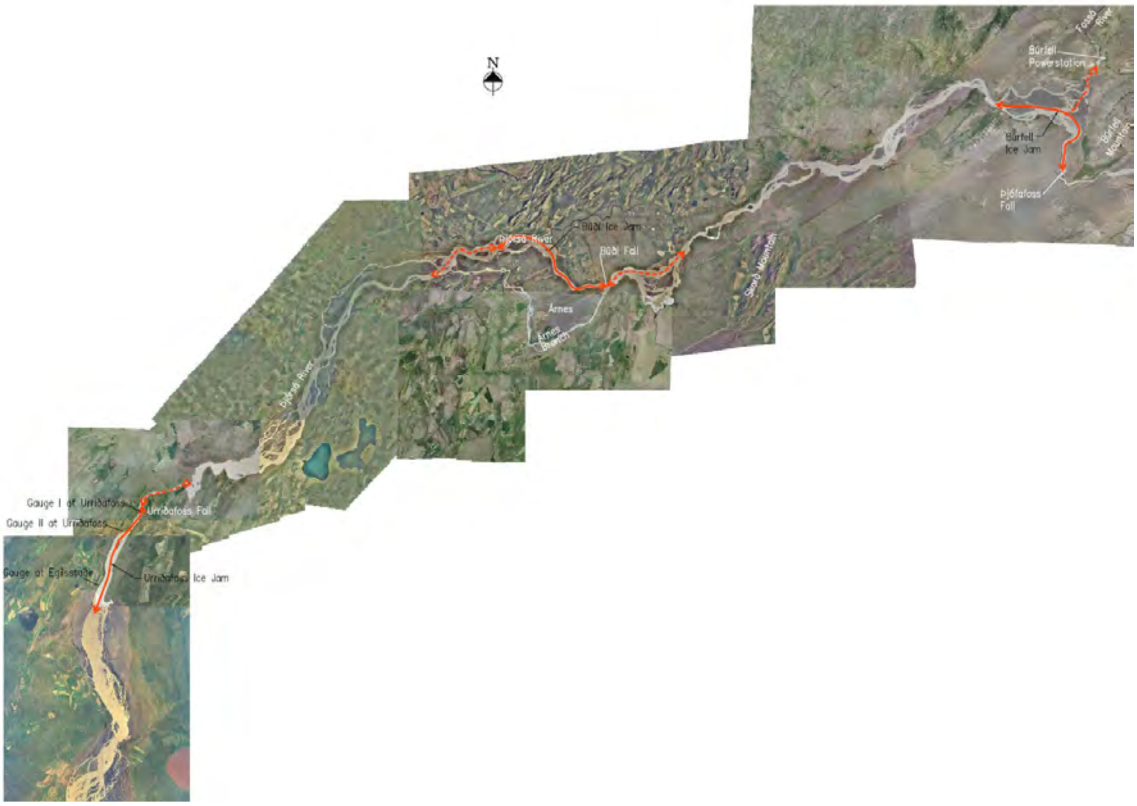

Figure 3.1 *Overview of Lower Þjórsá River. Gauging stations are marked in and the location of the ice jams that formed regularly before the ice got trapped in the upper reaches due to reservoirs and other constructions. An A3 version of this figure can be found at the end of this report before the Appendixes.*

The reason for the formation of the Búrfell Ice Jam was a long, relatively steep river reach upstream of Búrfell Mountain, where ice cover could not form due to high velocity. This open area of water surface produced huge amount of frazil ice. The frazil ice was carried down to the alluvial reach below Búrfell Mountain where the river slope was very little and shortly below Búrfell Mountain there is a narrow bend in the river where the ice flow was trapped, thus creating a closed surface behind which the ice flow would accumulate causing an ice cover to grow upstream and finally up the gorge into steeper slopes creating a push. A big ice jam formed, mainly from the waterfall and into the wide alluvial reach below Búrfell Mountain.

The reason for the formation of Urriðafoss Ice Jam is that there is an open water surface from the Búrfell Ice Jam, and later from the Búrfell Powerstation, all the way to Urriðafoss Fall, some 50 km. This open water results in enormous production of frazil ice. Below Urriðafoss Fall the river slope is very small. This reach gets covered by sheet ice from the frazil flow from upstream. In the plains below the gorge the cover is thin, but as the ice cover grows upstream into the gorge an ice jam starts to form. When the ice jam reaches the pond below the Urriðafoss Fall the ice jam starts to build up a voluminous ice jam, the Urriðafoss Ice Jam.

The development of the upper reaches did at first not influence ice conditions in Lower Þjórsá below Búrfell Powerstation because the ice from upstream was diverted from the intake pond, Bjarnalón, back into the river. Below the gorge, at the plains below Búrfell Mountain, the ice accumulated in a huge ice jam as before. Later big reservoirs were created upstream of Búrfell Powerstation that stopped the ice flow from upstream. Nowadays no ice jam forms at the roots of Búrfell Mountain. Additionally the regulated flow seems to have stopped the Búði Ice Jam from forming. But as this ice jam formed irregularly and the winter have not been as harsh lately, it can not fully be ruled out that Búði Ice Jam could form.

Urriðafoss Ice Jam, on the other hand, still forms but has not reached its former heights for many years, most likely due to milder winters lately.

3.2 Ice mitigation experience

The Búrfell Powerstation was operated several years before any dams were built upstream. At that time there were extensive open water surfaces upstream in Þjórsá and its tributaries, producing enormous quantities of frazil ice during cold spells. The ice had to be flushed past the river intake since this was a run of the river plant. The final design of the ice flushing facilities was based on physical model tests. The ice flushing was a delicate operation which was successful most of the time but failed one to three times every winter with serious consequences for power production (Jóhann Már Maríusson et. al., 1975).

Ice flushing is not relevant for Hvammur and Urriðafoss Hydroelectric Projects. At the Holt Powerstation the river intake is located downstream of a rather steep reach of river which will remain open during frost and produce frazil ice. Ice jam formation must be prevented by flushing the frazil over the Búði Dam. The design of the ice flushing facilities will be tested in a physical model. Experience from Búrfell Powerstation will be valuable in this respect.

3.3 Aerial reconnaissance

During development of the Upper Þjórsá, and until problems from frazil ice had been practically eliminated, frequent ice observation flights over the basin were implemented and ice conditions of Lower Þjórsá were also recorded. In the years from 1969 to 1984 19 trips were recorded. These observations confirmed previous knowledge of ice conditions. After the planning of hydroelectric projects in Lower Þjórsá started, the ice conditions have been documented with photographs in 10 flights in the years 2002 to 2005. Maps of open water area were made four times. These are published in reports from Landsvirkjun (Victor Helgason, 2002 & Gunnar O. Gröndal & Victor Helgason, 2006). The recorded open water surface downstream from Búrfell Mountain was in the range of 12 to 15 km^2.

3.4 Ice jam measurements

Estimates of the volume of the Urriðafoss Ice Jam have been made, based on longitudinal profiles of the jam. Sigurjón Rist (1962) estimated normal volume of the ice jam $20 \cdot 10^6$ m^3, varying from 10 to $40 \cdot 10^6$ m^3. Using elevation data, observed boundaries and a map in 1:5000 the volume of the jam on March 1 2002 was calculated $17 \cdot 10^6$ m^3.

The Búrfell Ice Jam, which is now history, was mapped and the volume calculated in March 1965 was $30 \cdot 10^6$ m³ (Sigmundur Freysteinsson, 1967, p. 23).

3.5 Water temperature

A few water temperature measurements have been made of the tailwater at Búrfell Powerstation. During frost periods the temperature is above zero, but lower than 0,1 °C.

Additionally measurements have been made further downstream but they have not always been successful. Figure 3.2 shows where these measurements were made and the graph on the figure shows the results. The graph shows that during frost periods the water can be supercooled about 2 km downstream of the powerstation.

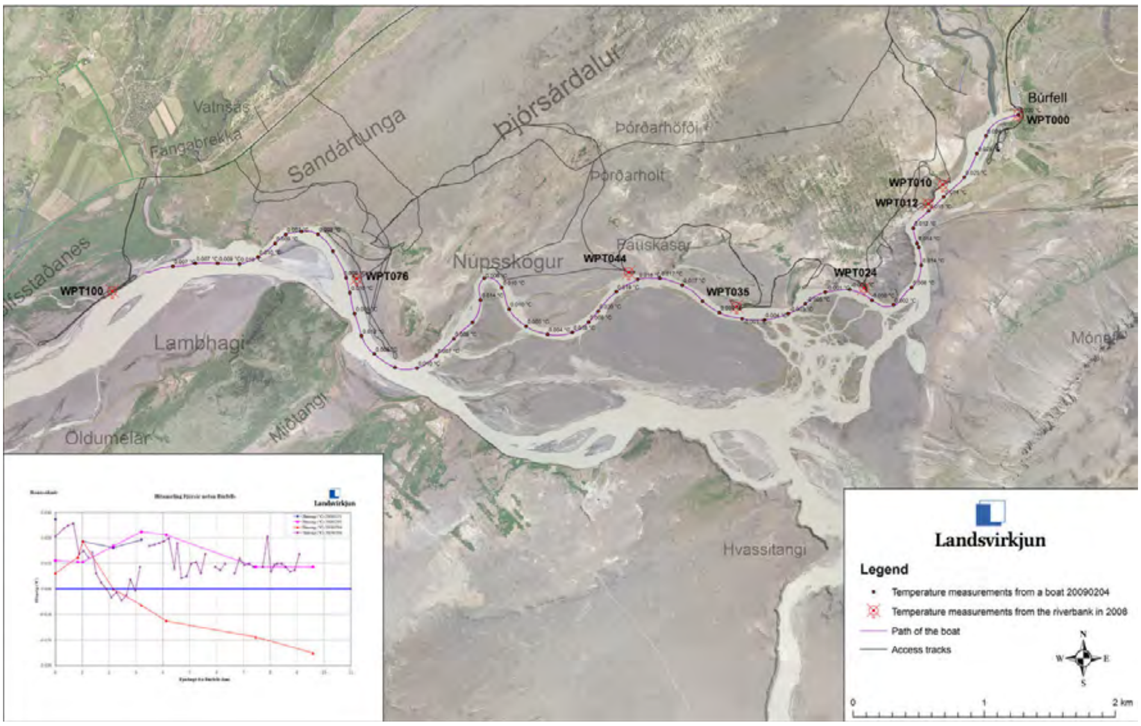

Figure 3.2 *Water temperature measurements below Búrfell Powerstation (Victor Kr. Helgason, 2009). An A3 version of this figure can be found at the end of this report before the Appendixes.*

3.6 Water level measurements

Continuous measurements of stage and discharge are made at vhm 30 upstream of Urriðafoss Fall. Elevation of the Urriðafoss Ice Jam has been observed with stage recorders at three locations since 2002. The results were used in calibrating variables used in HEC-RAS. Figure 3.1 shows the locations of the recorders.

3.7 Photographic surveillance

An automatic surveillance camera taking pictures overlooking Urriðafoss Fall and the gorge downstream every hour during daylight was set up by Landsvirkjun in January 2003. The pictures show ice formation in the river, ice jam advance up from Egilsstaðir to Urriðafoss Fall, movements of the jam and ice jam degradation.

Orkustofnun operated a surveillance camera at Þrándarholt in the winter 2003/04 and 500 m downstream of Urriðafoss Fall since 2004/05.

Data and pictures are in reports from Landsvirkjun (Gunnar O. Gröndal & Victor Kr. Helgason, 2003 & 2006).

3.8 Other rivers

In March 1997 investigation was made on the ice jam in Fnjóská River in the north of Iceland (Finnur Pálsson, 1997). The ice jam was up to 8 m in thickness. Six boreholes were made, of which 4 were deep enough for analysis. In all the boreholes water level was at about 2 m below the surface of the ice jam.

The density was calculated and the proportional density of the ice jam in comparison with density of water was plotted against depth in the bore holes. It was highest at the top where it in some places reached 0,8-0,9. Below the upper most 1 m the proportional density was mainly in the range of 0,054-0,067 with the average around 0,6 which gives porosity around 0,4.

The crystals were very homogeneous, around 0,2-0,4 cm in diameter.

4 HEC-RAS

HEC-RAS is a software from the U.S. Army Corps of Engineers. HEC stands for the Hydrologic Engineering Center and RAS for River Analysis System. The software numerically solves the well known and relevant equations for one dimensional open channel flow. For further information on its underlying equations and numerical schemes we refer to the Hydraulic Reference Manual (Brunner, 2008).

The parts of the software we are focusing on are the routines for modelling wide river ice jams developed by Mr. Steven F. Daly of the Cold Regions Research and Engineering Laboratory (CRREL). The ICEJAM model, which was developed by Flato and Gerard at the University of Alberta, Edmonton, Alberta, forms the basis of the solution approach for the ice jam profile modelling option in HEC-RAS (Healy & Hicks, 1999).

The wide river ice jam is the common ice jam created by collapsing, or shoving, thickening and lengthening until it reaches a balance between the opposite forces. In this case the jam is thought to respond as a floating granular mass (Beltaos, 1995). All stresses acting on the jam are ultimately transmitted to the channel banks. The ice jam force balance equation for the wide river ice jam is:

$$\frac{d(\overline{\sigma}_x t)}{dx} + \frac{2\tau_b t}{B_i} = \rho_i g S_w t + \tau_i \qquad \textbf{Eq. 4.1}$$

where σ_x is the longitudinal stress along the stream direction, t is the accumulation thickness, τ_b is the shear resistance of the banks, B_i is the accumulation width, ρ_i is the ice density, g is the acceleration of gravity, S_w is the water surface slope and τ_i is the shear stress applied to the underside of the ice by the flowing water.

From the equation it can be seen that it balances changes in the longitudinal stress in the ice cover and the stress acting on the banks with the two external forces acting on the jam, i.e. the gravitational force attributable to the slope of the water surface and the shear stress of the flowing water on the jam underside (Brunner, 2008). [1]

The following assumptions are made for this force balance equation:

- σ_x, τ_i and t are constant across the width.
- None of the longitudinal stress is transferred to the channel banks through changes in stream width or horizontal bends in the plan form of the river.
- The stresses acting on the jam can be related to the mean vertical stress using the passive pressure concept from soil mechanics and the mean vertical stress results only from the hydrostatics forces acting in the vertical direction.
- There is no cohesion between individual pieces of ice. A reasonable assumption for breakup ice jams.

Thus the vertical stress is:

$$\overline{\sigma}_z = \gamma_e t \qquad \textbf{Eq. 4.2}$$

Where

$$\gamma_e = 0{,}5 \rho_i g (1 - s)(1 - p_i) \qquad \textbf{Eq. 4.3}$$

1 This and the following paragraphs about the equation are taken almost without any changes from the Hydraulic Reference Manual chapter 11 on Ice-covered Rivers.

Where p_i is the ice jam porosity (assumed to be the same above and below the water surface) and s is the specific gravity of ice. The longitudinal stress is then:

$$\overline{\sigma}_x = k_x \overline{\sigma}_z \quad \textbf{Eq. 4.4}$$

where:

$$k_x = \tan^2\left(45 + \frac{\phi}{2}\right) \quad \textbf{Eq. 4.5}$$

where ϕ is the angle of internal friction of the ice jam.

The lateral stress perpendicular to the banks can also be related to the longitudinal stress as:

$$\overline{\sigma}_y = k_1 \overline{\sigma}_x \quad \textbf{Eq. 4.6}$$

where k_1 is the coefficient of lateral thrust.

The shear stress acting on the bank can be related to the lateral stress:

$$\tau_b = k_0 \overline{\sigma}_y \quad \textbf{Eq. 4.7}$$

where:

$$k_0 = \tan\phi \quad \textbf{Eq. 4.8}$$

The under-ice shear stress is estimated as:

$$\tau_i = \rho g R_{ic} S_f \quad \textbf{Eq. 4.9}$$

Where R_{ic} is the hydraulic radius associated with the ice cover and S_f is the friction slope of the flow.

With all this equation 4.1 can be rearranged into:

$$\frac{dt}{dx} = \frac{1}{2k_x\gamma_e}\left[\rho' g S_w + \frac{\rho g R_{ic} S_f}{t}\right] - \frac{k_0 k_1 t}{B} \quad \textbf{Eq. 4.10}$$

Which is the equation solved in HEC-RAS for wide river ice jams.

Most rivers fall into the wide river category but it is better to check. Narrow jam can not exist for plausible parameters except if width versus depth is less than 7 (Beltaos, 1995). In the Lower Þjórsá River the narrowest part is wider than 50 m and the deepest part is about 6 m so this ratio can go as low as 8 but is usually more like 100 (width usually around 200 m and depth about 2 m). The river should thus classify as containing wide river ice jams.

Some of those symbols stand for something that is a constant like g and ρ_i, other symbols are calculated by iteration in the software, like t and S_w and then there are the variables that need to be given by the user. These variables effect the calculations and need to be considered carefully. They are ϕ and p_i. In addition the steady flow calculations need the Manning's n coefficient for the underside of the ice, n_i. These three variables are the variables that the user has to specify and can be different between sites and within the ice-jam.

There is one other thing worth mentioning about the software. The ice modelling part can only handle steady state flow. That means four additional assumptions:

- The flow is steady.
- The flow is gradually varied.
- The flow is one dimensional.
- The river channel has “small” slopes, less than 1:10.

In addition to the above it is important to mention the following limitations to the ice-jam module in HEC-RAS.

- The ice jam can not become grounded in HEC-RAS, i.e. water is always allowed to flow under the ice jam never blocking the cross section completely (Healy & Hicks, 1999).
- The model does not include seepage through the ice jam (Healy & Hicks, 1999).
- The user has to decide how far upstream the ice jam grows.
- The user has to estimate and fix the thickness of the ice jam at its upstream and downstream end.
- The user has to give the limiting minimum thickness of the ice jam (if the software calculates less thickness than this given thickness it assumes the jam has this minimum thickness).
- It does not model hanging dams.
- The model assumes fixed cross sections but the river bed and banks are in some places made of alluvial material so the ice jam might affect the shape and size of the cross sections.

In Lower Þjórsá River the possibility of a grounded ice jam is very low both because the flow is very steady during the cold winter months and because the ice jams are usually freeze-up ice jams and they are less likely to become grounded than breakup ice jams.

There is the possibility of a hanging dam forming in Lower Þjórsá River as pointed out by Dr. Spyros Beltaos, (2009). Calibration of the Urriðafoss Ice Jam site, see appendix 2, indicates the formation of a hanging dam there and pictures from the old Búrfell Ice Jam suggest a hanging dam in the gorge. The possibility of a hanging dam within the modelled reaches will be discussed in the relevant chapters.

5 Available data for model creation and calibration

5.1 Cross-sections

Figure 5.1 shows the location of all available cross-sections in the river from Búrfell Mountain down to Heiðarlón Dam site. The cross-sections are taken at different times and the technique used is not always the same. Table 5.1 gives all the relevant information about the cross-sections.

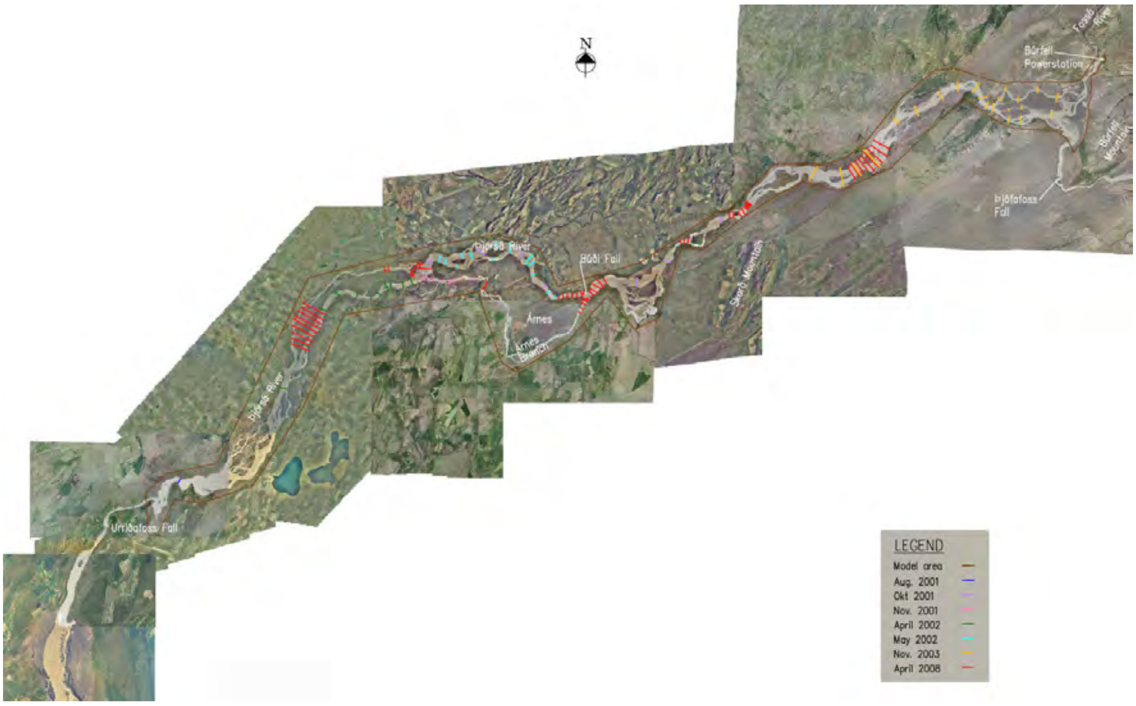

Figure 5.1 *Overview of all available cross-sections between Heiðarlón Dam site and Búrfell Mountain. An A3 version of this figure can be found at the end of this report before the Appendixes.*

Table 5.1 *Basic information about the cross sections.*

Time of measurement	Method	What measured			Location of cross sections
		Depth	Location	Elevation in m a.s.l.	
Aug. 2001	Normal*	X	-	-	At the cable at Krókur
Oct. 2001	With a stick from a boat	X	X	-	At various places between the Hagalón Dam site and Árnes Rapids. Not used.
Nov. 2001	NA	X	X	-	Downstream end of Árnes Branch
April 2002	With a stick from a boat	X	X	X	From the upper end of the dike up to Árnes Rapids.
May 2002	ADI[д]	X	X	X***	Between Árnes Rapids and Búði Fall.
Nov. 2003	ADI	X**	X**	-	Above Hagalón Dam site.
April 2008	ADI	X	X	X	Numerous cross sections close together at various places, see Figure 5.1.

* during discharge measurements.
** difficult data.

*** water level measurement not always made at the same location as the cross-sections and not necessarily at the same time, thus not exact.

Д ADI; Acoustic Doppler Instrument

The cross section from August 2001 was made during discharge measurements where the primary interest was the discharge, not the cross section or its exact location. Thus this cross section only gives depth and length in line from the cable. The elevation and exact location has to be estimated. As this is the only cross section in that area it is better than nothing and was used but with care.

The cross sections from October 2001 were taken in various places between the Hagalón Dam site and Árnes Rapids, on the 24-26th. The method was a stick and a boat.

The cross sections from November 2001 were taken in the downstream end of Árnes Branch. As the model did not cover this part, these cross sections will not be discussed further.

The cross sections from April 2002 were taken between the upper end of the dike along Heiðarlón Pond up to Árnes Rapids, on the 23rd, 24th and the 26th. The method was a stick and a boat except for cross section 10 that was measured on the 22nd with Acoustic Doppler Instrument (ADI). The discharge was above 600 m^3/s during the fist two days, but around 300 m^3/s on the last day. The scheduled cross section locations marked 11 and 13 were not measured due to shallows in the river according to the measurement data.

The cross-sections from November 2003 are the most difficult cross-sections to use as the original data was lost. The cross sections were taken with Acoustic Doppler Instrument (ADI) from a boat and the only available information found was an info table and two graphs showing a) the path of the boat and b) the depth along the path of the boat. The location of the endpoints was measured with a handheld GPS instrument with accuracy measured in meters (probably correct within 10-20 m). In order to use the data the following steps were taken. Firstly, the location and depth of the measured points were approximately connected and then they were given an approximated elevation based on the longitudinal profile measurements (not completely useable as the discharge was different). The final elevation was adjusted during the calibration process and will be discussed in the appropriate chapter. The accuracy is thus not very good for these cross-sections but they are though usable.

The cross-sections from April 2008 have the best data to work with. Measurements were made with Acoustic Doppler Instrument in a boat and the data gives information about bathymetry and water-level in every measured point and its exact position and time.

In addition to the cross sections marked on the figure extra measurements were taken in the reach from Árnes Rapids up to the bottleneck in the river short distance below Búði Fall. These measurements were not taken perpendicular to the flow. It was more like a ziczac along the river to get a better idea about the bathymetry, thus these measurements are not marked on the figure but they are shown on Figure 7.1 and used in the model for the reach from Árnes Rapids up to Búði Fall, see chapter 7.1.2.

5.2 Longitudinal water surface profile

The water surface profile of Lower Þjórsá has been measured three times, 1956, 1995 and 2008. As only the last one is used in the model, the older ones will not be discussed here. The measurements took place between the 6th and the 30th of May. Figure 5.2 shows the measurements. The colour of the measured points depends on the date of measurement and on who did the measuring.

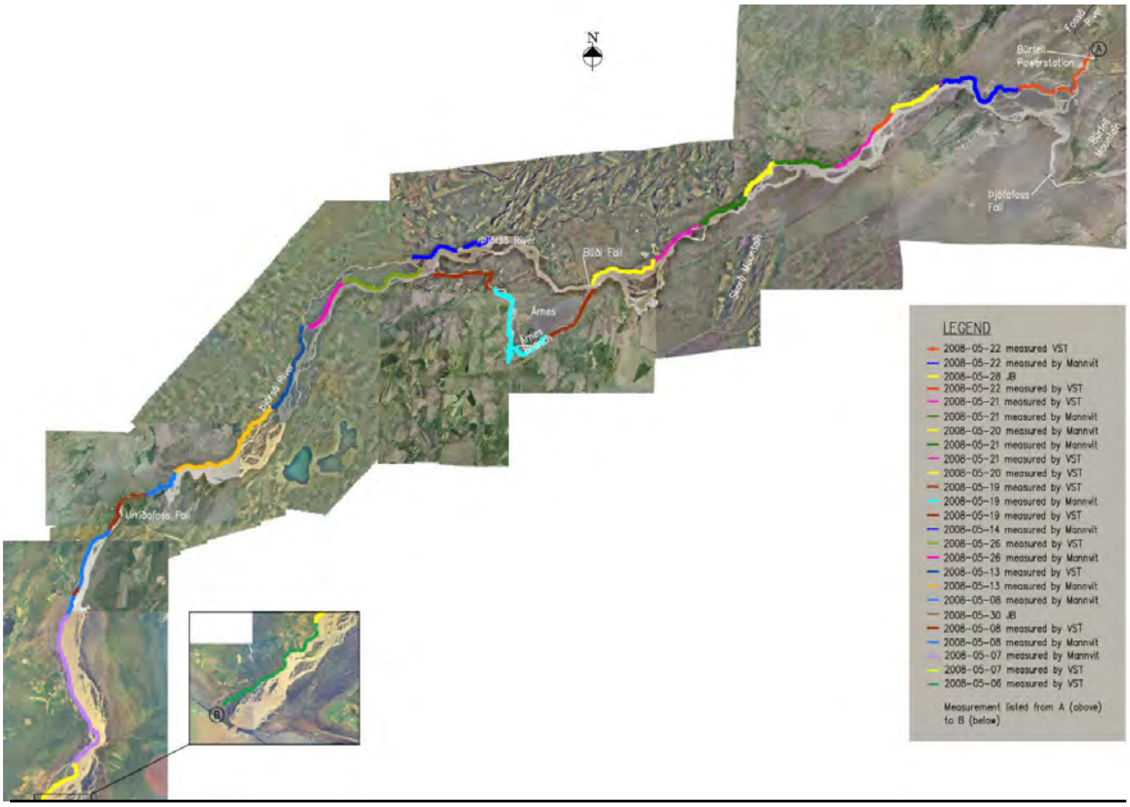

Figure 5.2 *Overview of the longitudinal water surface profile measurements. An A3 version of this figure can be found at the end of this report before the Appendixes.*

5.3 Geometry data from aerial photography

The latest data on geometry above water came from aerial photography. The company Samsýn extracted data points and break-lines from aerial photos taken in 2000, 2001 and 2007. Table 5.2 shows relevant information about the aerial photography and expected accuracy. Figure 5.3 gives an overview of the aerial photographs taken. Only the points closest to the river were used, see the line marked model area in Figure 5.1, as the data is massive in size so it was necessary to cut the data down to usable size.

Table 5.2 *Information about aerial photography.*

Date of flight	time	Elevation	Expected accuracy	Taken by
19.8.2000	10:00-10:27	2000 m	± 0,2 m	Swedesurvey / Landmælingar Íslands
3.9.2001	12:45-12:52	2000 m	± 0,2 m	Swedesurvey / Landmælingar Íslands
9.7.2007	15:20-16:00*	2750 m	± 0,3 m	Blom Aerofilms

* From Búrfell Mountain to Hagi.

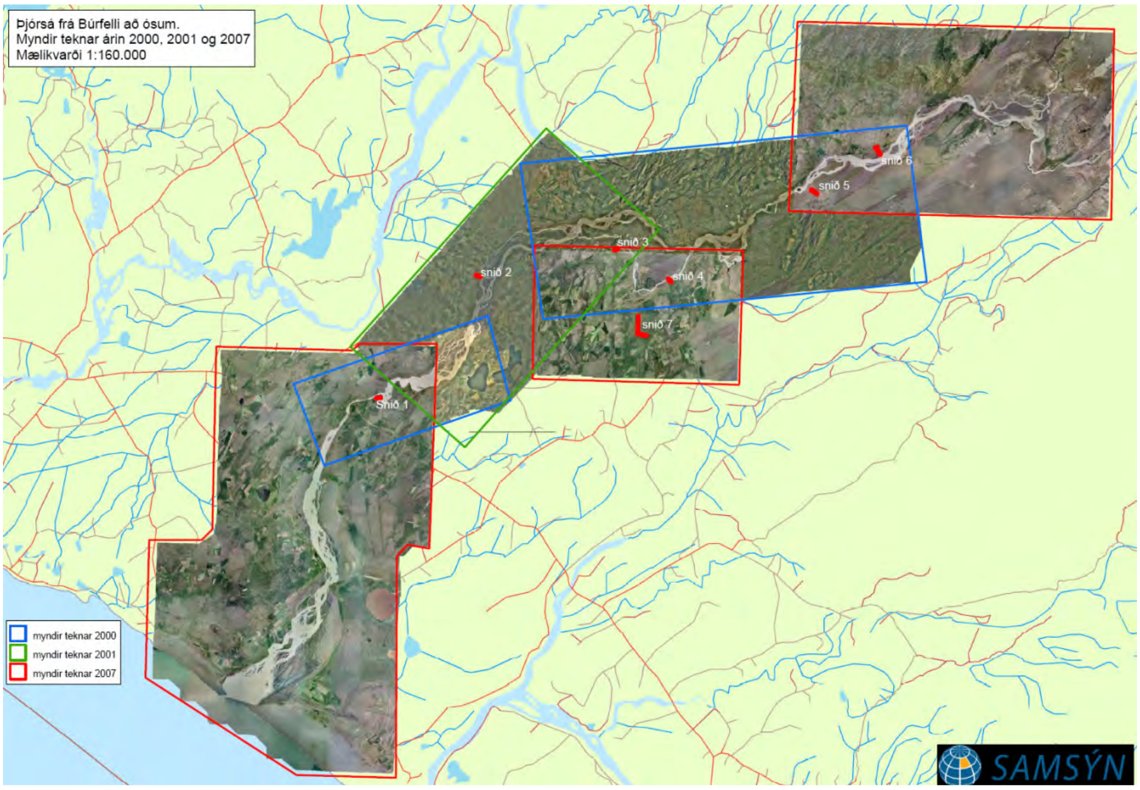

Figure 5.3 *Overview of the aerial photographs used (Samsýn, 2008). An A3 version of this figure can be found at the end of this report before the Appendixes.*

5.4 Discharge

As cross section measurements, aerial photos and longitudinal profile measurements were taken at different times the discharge is very important in order to make use of the data.

The constant measurements at vhm 30, upstream of Urriðafoss Fall, were used. In addition discharge from Sultartangi Powerstation was used and energy output from Búrfell Powerstation was used to calculate discharge through the powerstation (calculated by Landsvirkjun). The difference between discharge at Sultartangi and Búrfell should then give discharge in Þjórsá past Búrfell Powerstation. In addition measurements are made in Fossá River but data from that location is not always available.

In order to use the discharge measurements from these locations the time it takes the water to travel between them and relevant measurement location had to be estimated in order to get an estimate on the discharge at the time the measurements were made. This was done for all data used in the calibration processes.

6 Hagalón Ice Jam model

6.1 The model

Hagalón Pond is the name of the intake pond for the proposed Hvammur Hydroelectric Project. Its location is shown on Figure 1.1. At its upstream end an ice jam will form and grow upstream and downstream into the intake pond. A model was made in HEC-RAS in order to calculate the equilibrium ice jam above Hagalón Pond, here after called the Hagalón Ice Jam. The site of the main dam was chosen as the downstream boundary of the model. The upstream boundaries, where the river is divided into two branches, where chosen at cross sections S4 and S4b, see Figure 6.1. Measured cross sections exist further upstream but as there are no available cross sections for the short part from section 3 to 4b, they were impossible to use. Additionally the temperature measurements indicate that little ice is produced above cross section S4 as it is relatively close to the Búrfell Powerstation outlet so this should not influence the results.

The uppermost part of the model covers the lowest part of the former Búrfell Ice Jam. But as that ice jam no longer forms, due to the upstream development, this should not affect the Hagalón Ice Jam, at least not when all powerstations are operational.

In order to make the modelling easier the software WMS (Watershed modelling system from Aquaveo) was used to help in the creation of the cross sections in HEC-RAS. In the software it is relatively easy to create 3D geometry and extract the cross sections for HEC-RAS straight from it.

The data points from the geometry based on the aerial photographs were used above water and the measured cross sections below water. The cross section data from 2008 were used in 3D and coupled together with the geometry data above water. The data from the 2003 cross sections was used in a slightly different way. Because the boat did neither cross in a straight line nor necessarily perpendicular to the flow, an approximation was made. The final cross sections used in HEC-RAS need to be perpendicular to the flow. In the case of areas where a 3D geometry model had been made the cross sections were made by drawing the cross section lines and WMS calculated the depth in the cross section. In case of the cross section from 2003 the same applied to the part of the cross sections above water but below, the cross section points were used by assuming the same depth in the line of flow so if the measured cross section was partly downstream or upstream of the cross section the assumption was made that the depth would be the same in the direction of flow. Most of the measured cross section points lay within 10 m from the location of the cross section used in the model. One was partly 30 m away and two partly slightly less than 70 m. As the longitudinal slope of the river is small in this area this action can not cause more error in depth than about 5 cm where the measured points are furthest away from the location of the used cross section.

For the lowest part of the model there were no measured cross sections, except closest to the dam. Where no cross sections were available a depth was assumed and modified in the calibration process.

Figure 6.1 shows the location of the cross sections, both measured and those made in WMS and extracted into HEC-RAS.

The boundary conditions at the downstream end of the model were chosen as a normal waterlevel in the calibration process and a fixed water surface elevation of 116 m a.s.l in the ice jam modelling. A normal waterlevel was used as boundary condition in the model at the upstream boundaries.

In some parts of the river the cross sections are far a part. In order to keep the distance smaller for better calculations in HEC-RAS, additional cross sections were made by using the linear cross section creation tool in HEC-RAS. In figures of the model the original cross sections made and calibrated are the ones shown as black points on the profile figures and dark green on overview figures. The additional cross sections made by HEC-RAS are shown as grey dots on the profile figures and as light green lines on the overview figures.

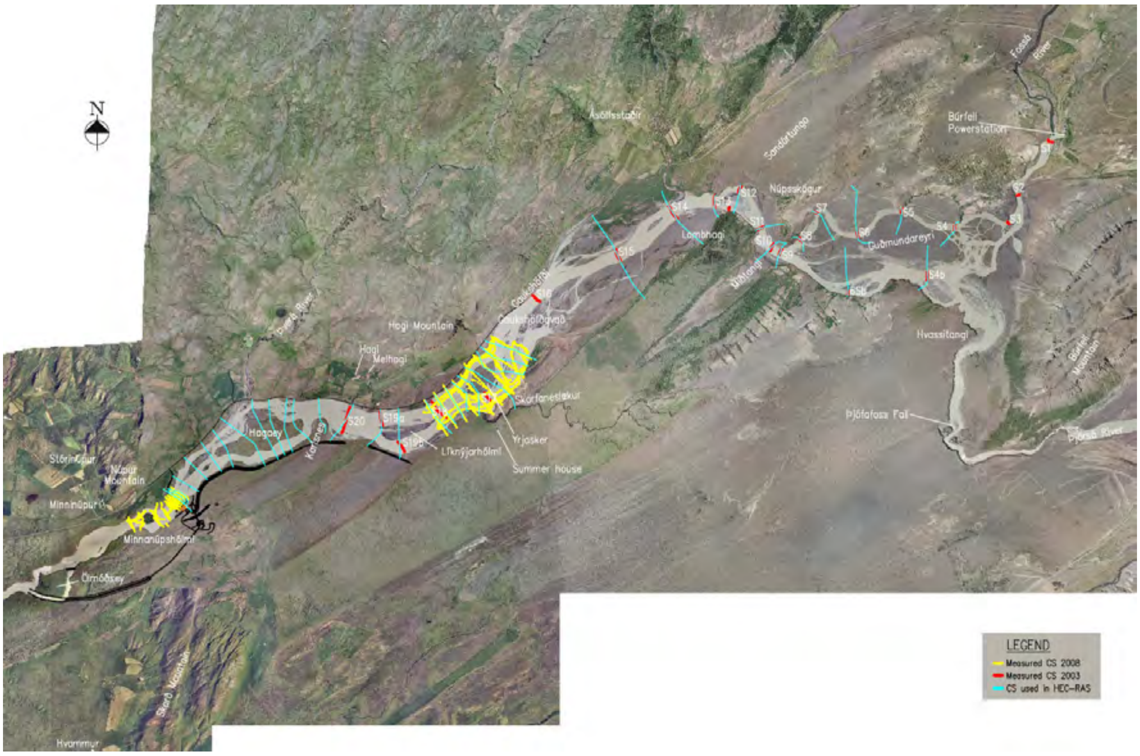

Figure 6.1 *An overview of both measured cross sections (CS) in the model area and the location of the cross sections used in the Hagalón model. An A3 version of this figure can be found at the end of this report before the Appendixes.*

6.2 Calibration of the model - without ice

The model created in HEC-RAS had to be calibrated for flow without ice. The calibration parameters were Manning's n for the riverbed, hereafter called n_b, and in some cases the elevation of the river-part of the cross section had to be calibrated, i.e. elevation adjustments where the measurements were not fixed in elevation, see table 5.1.

As the technique used for the cross section measurements and the discharge during both the cross section and the longitudinal profile measurements was not always the same, the model had to be calibrated by focusing on smaller reaches at a time, i.e. parts with similar discharge during measurements. Figure 6.2 shows the whole longitudinal profile of the model and the arrows mark parts within the river where cross sections could be calibrated together. In the following chapters each part will be discussed separately.

6.2.1 The Hagalón Pond

The lowest part is the Hagalón Pond, from the dam site up to Karlsnes. Closest to the dam site, see the green dotted ellipse in Figure 6.3, the cross section data from 2008 were used but the main part of the pond has no measured cross section data. But as this part of the model will be in relatively deep water, see Figure 6.3, after the construction of the dam, it was not considered as important as the rest of the model and was not calibrated in any way except that the uppermost part, see the red dashed ellipse in the figure, was adjusted in the calibration process of the upstream cross sections, SN20 and SN19A, by changing the elevation of the bottom in the river and n_b.

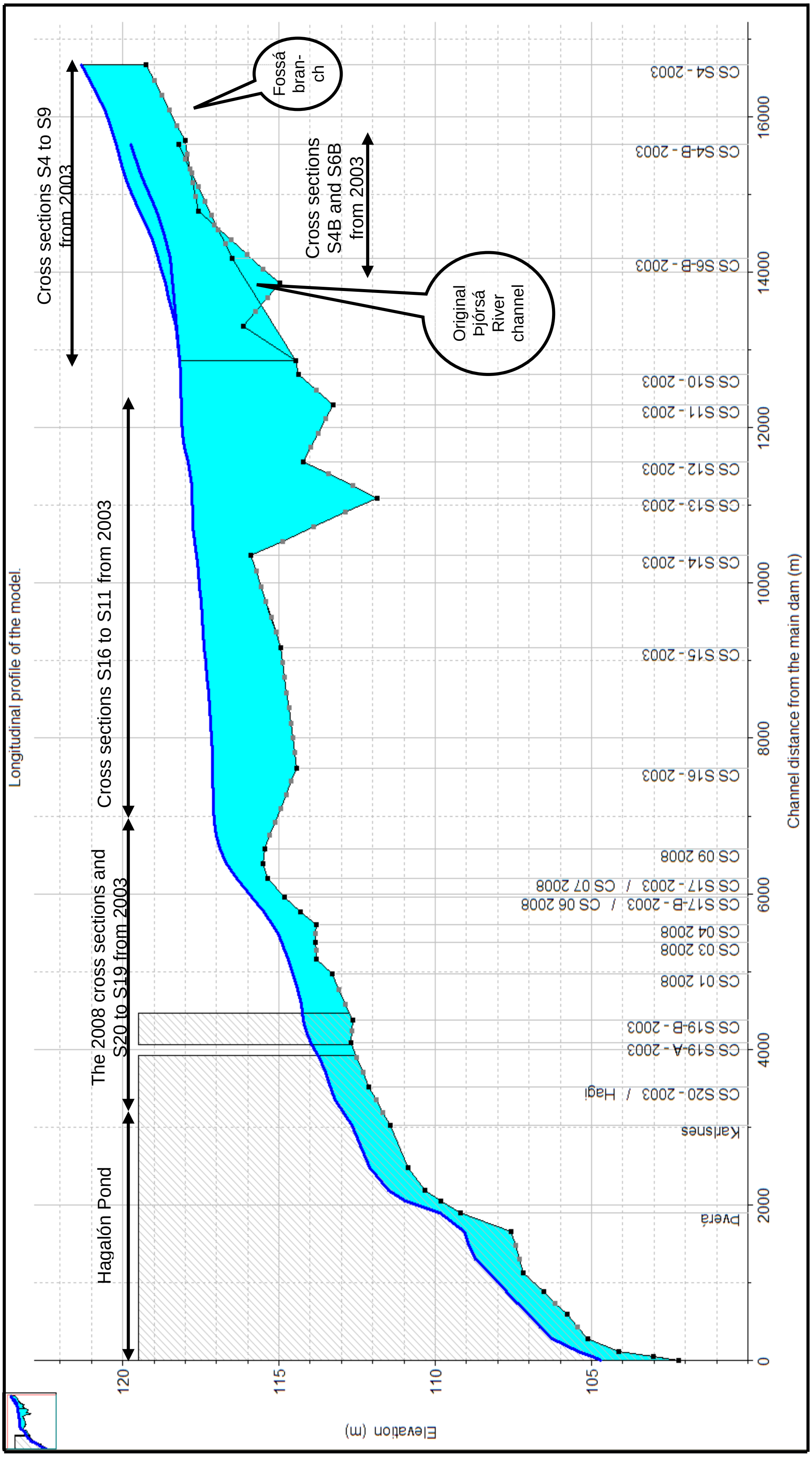

Figure 6.2 *Longitudinal profile of the modelled part of the river. The black dots on the riverbed mark out cross sections extracted from WMS, while the grey ones are interpolated cross sections made by HEC-RAS solely made from adjacent cross sections. The blue line marks the water level in the river and the grey hatched area shows were the dike is located along the river.*

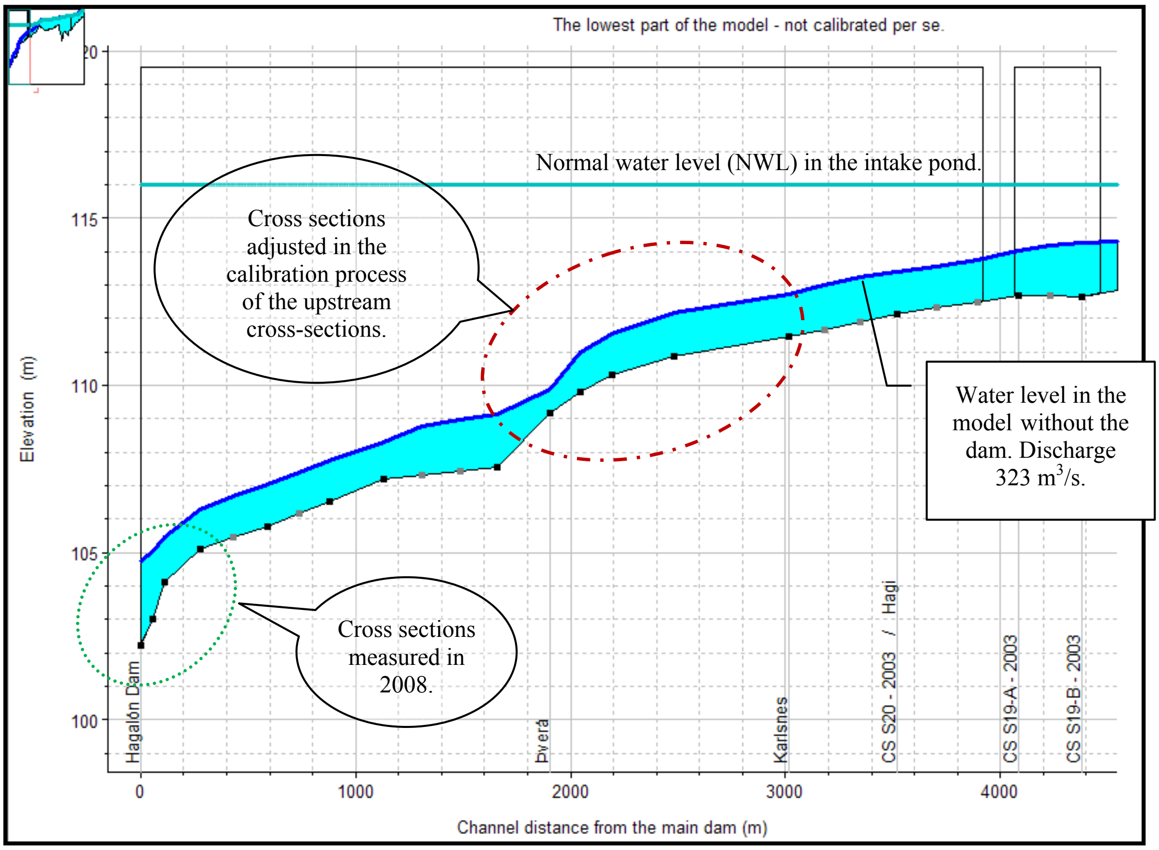

Figure 6.3 *Longitudinal profile of the Hagalón Pond.*

6.2.2 The 2008 cross sections and S20 to S19 from 2003.

When the cross section measurement around Yrjasker took place in 2008 the discharge was approximately 300 m^3/s. Coincidently the same discharge was in the river when cross sections 19 (A and B) and 20 were measured in 2003 so these cross sections can be calibrated together. Additionally the longitudinal profile of the river in this river reach was measured on the same day and the discharge was similar for all the cross sections, 510 m^3/s on average. For the 2008 cross sections only n_b had to be calibrated. On the other hand both n_b and the elevation of the river part of the cross sections from 2003 had to be calibrated. Additionally a few cross sections downstream were treated in the same way, as mentioned in the previous chapter.

Figure 6.4 shows how well the calculated water surface profile matches the observed water surface, OWS, in the cross sections for both discharges. The maximum difference is 16 cm, the average deviation from measured value is 5 cm and the standard deviation is 6,5 cm.

The calibrated value of n_b for the 5 upper most cross sections was 0,04, which is quite high. But as the riverbed in this part is known to be lava this is considered a plausible value. The lowest values are the three downstream most cross sections from 2008. There n_b was calibrated to 0,025. Below the steep part, above those cross sections, gravel is likely to settle and give this lower value. The 2003 sections fall in-between these extremes and were in the range of 0,028-0,033.

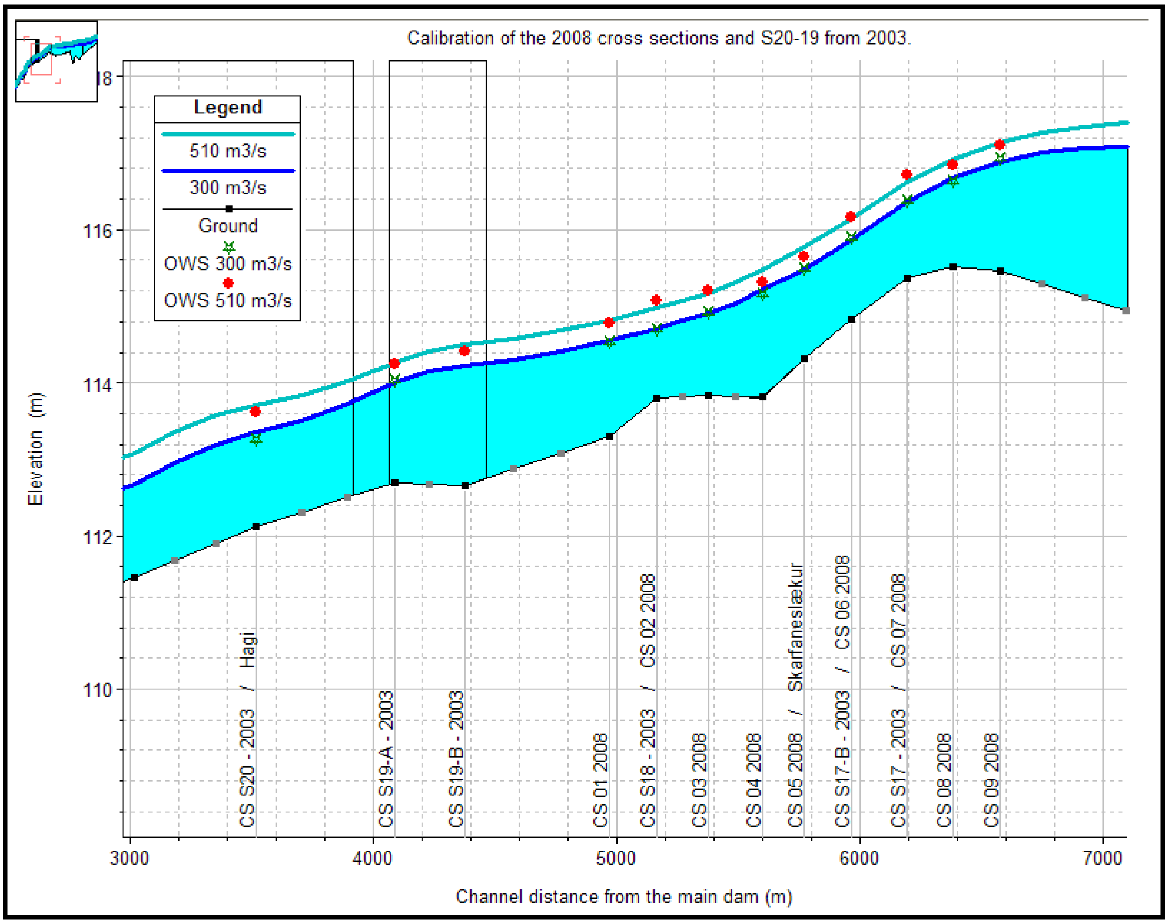

Figure 6.4 *Calibration of the cross sections taken in the summer of 2008 and cross sections 19 & 20 from 2003.*

6.2.3 Cross sections S16 to S11 from 2003.

In this part of the river both n_b and the elevation of the river part of the cross sections had to be calibrated. The discharge was also about 300 m^3/s during the cross section measurements but about 610 during the longitudinal profile measurements.

Figure 6.5 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference is 20 cm, the average deviation from measured value is 6 cm and the standard deviation is 8 cm.

The calibrated value of n_b for these cross sections are relatively low or in the range of 0,018-0,025 with the average value of 0,022 except for one cross section (CS S12) that got the value of 0,04. In this cross section the river is divided by a reef and the cross section measurements on either side of the reef do not align. Nevertheless, the cross section was used but it is not as reliable as the others.

The other cross sections have relatively low Manning value so the reliability of the calibration was questioned by the modeller. But after looking into the matter in more detail and seeing that in this section of the river the river bed is mainly gravel the values were accepted. On page 40 in Fluvial Processes in River Engineering by Chang is a table by Henderson (1969) that lists plausible values of Manning's roughness coefficient for various materials. There is an equation for n_b for clean straight alluvial channels. The equation is:

$$n_b = 0{,}031 d^{1/6} \qquad \textbf{Eq. 6.1}$$

where d is equal to d_{75} in feet.[2]

In a report on sedimentation in Hagalón Pond (Hörn Hrafnsdóttir, 2006) there are particle size distribution curves for bed material samples taken from the river in the reach from Búrfell to Núpur. Based on these values the n_b for the alluvial parts of the river are likely to be around 0,02.

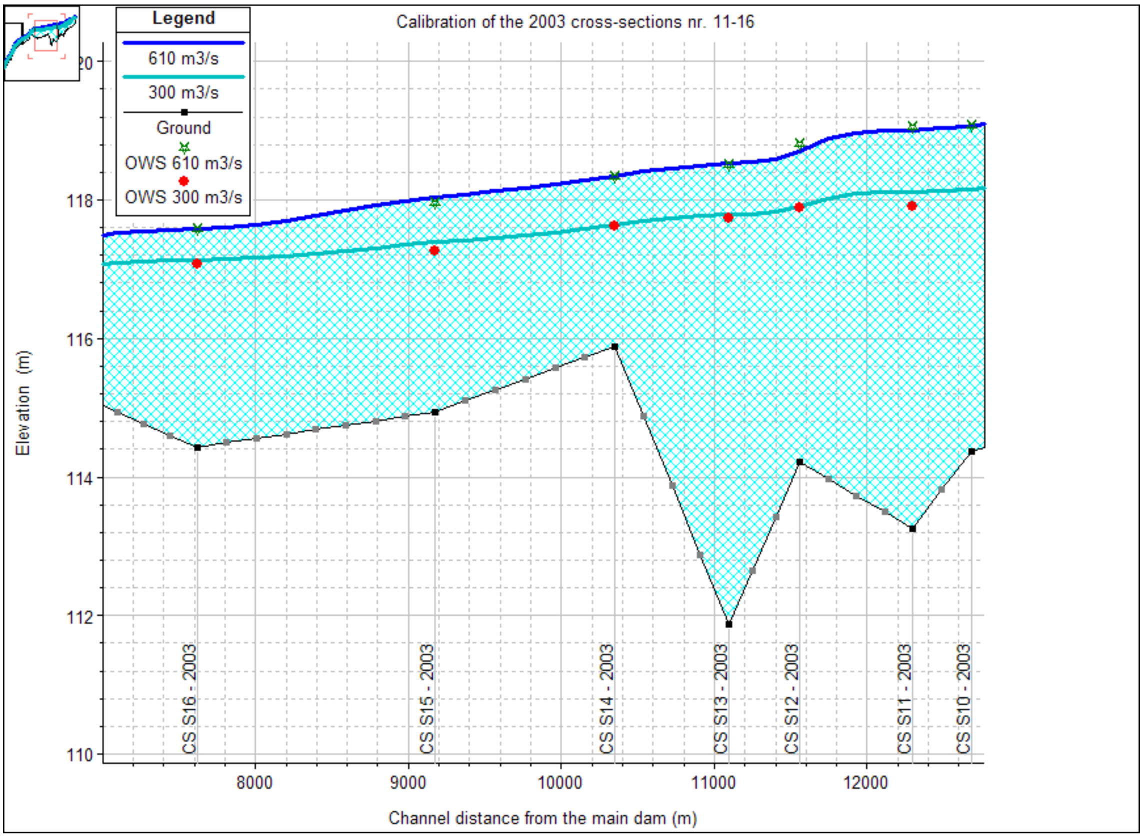

Figure 6.5 *Calibration of cross sections nr. 11-16, from November 2003.*

6.2.4 Cross sections S4 to S9 from 2003.

These cross sections are in the northern branch around Guðmundareyri. Additionally the first cross section downstream of the junction is included in this calibration, see Figure 6.6. Upstream the tailwater from Búrfell Powerstation enters Fossá River and is shortly after divided into two branches around Guðmundareyri where part of the water flows the shortest way into Þjórsá River while the other part takes a longer path and enters Þjórsá River further downstream. How the flow is split is not fully know but as the discharge was also measured during the cross section measurements an estimate could be made. The need to estimate the discharge in these branches adds to the inaccuracy in the model in these reaches (both the southern and the northern one).

Both n_b and the elevation of the river part of the cross sections had to be calibrated. The discharge in the river was about 240 m^3/s during the cross section measurements and the estimated part in the northern branch was 150 m^3/s. During the longitudinal profile measurements the discharge in the river was about 610 m^3/s and the estimated part in the northern branch about 166 m^3/s.

2 75% of the gravel stones have a smaller diameter than this size.

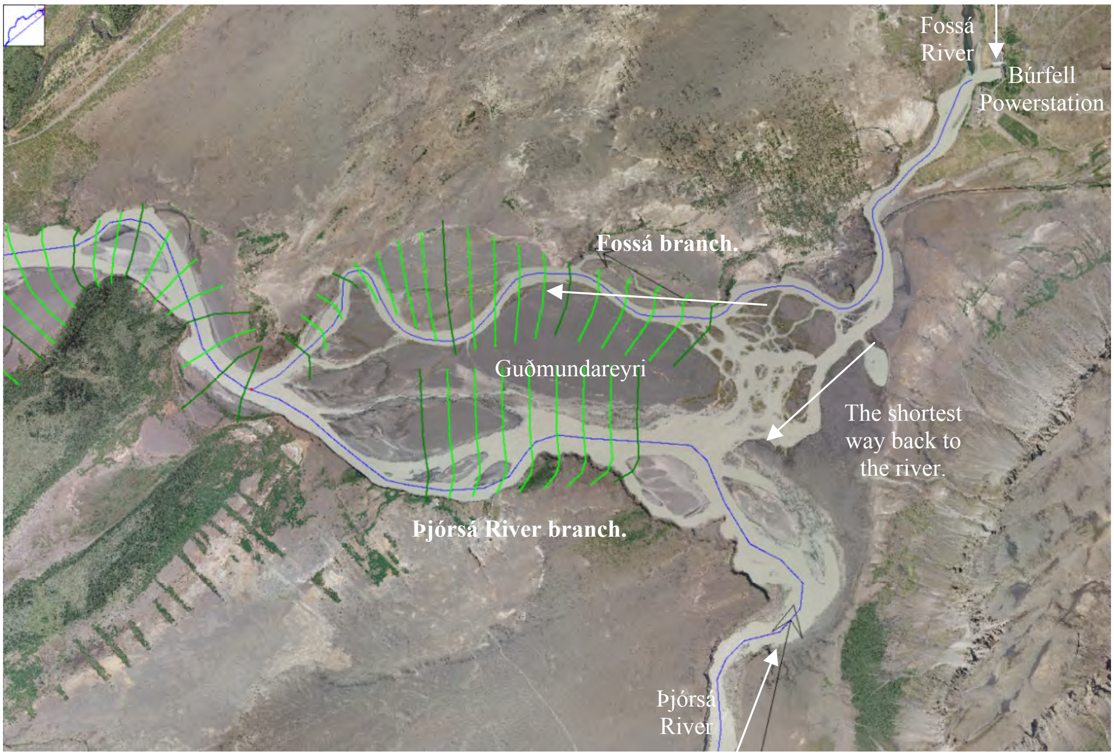

Figure 6.6 *Overview of Guðmundareyri and the model reaches and cross sections on both sides.*

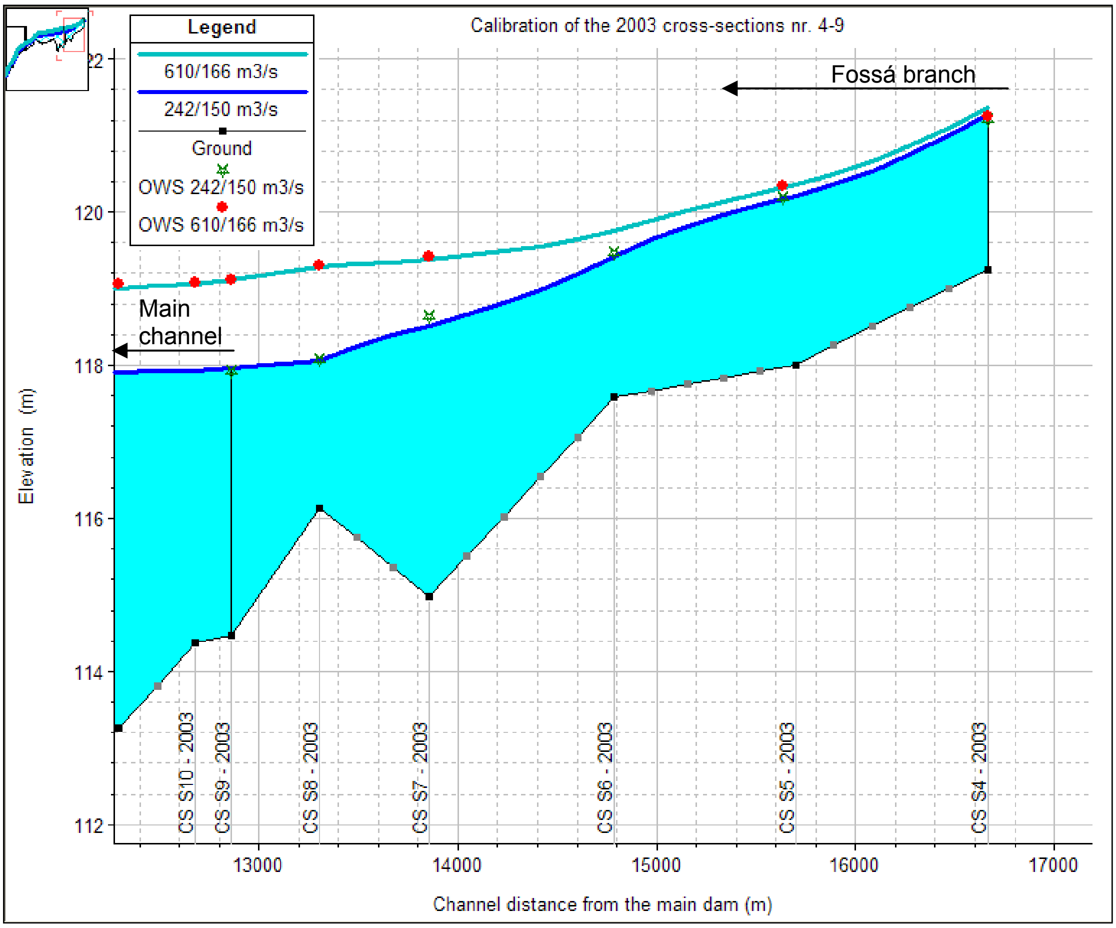

Figure 6.7 *Calibration of cross-sections nr. 4-9, from November 2003.*

Figure 6.7 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference is 14 cm, the average deviation from measured value is 5 cm and the standard deviation is 7 cm.

The calibrated values of n_b for the cross sections in the northern branch lie in the range of 0,028 to 0,035 with the average value of 0,031. The cross section in the main river downstream of the junction got the value of 0,02.

6.2.5 Cross sections S4B and S6B from 2003.

These cross sections are in the southern branch around Guðmundareyri, see Figure 6.6. The same applies for this branch as the northern branch regarding added inaccuracy in the model due to estimation of the discharge.

Both n_b and the elevation of the river part of the cross sections had to be calibrated. The discharge in the river was about 320 m^3/s during the cross section measurements and the estimated part in the southern branch was 161 m^3/s. This branch was not measured when the longitudinal profile of Lower Þjórsá River was measured in 2008. In order to have some other data to calibrate the model to, the aerial photography was used but the accuracy is not as good. Thus the accuracy of this branch is questionable. The discharge in the river at the time of the aerial photographing was about 380 m^3/s and the estimated part in the northern branch about 216 m^3/s.

Figure 6.8 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference is 27 cm, the average deviation from measured value is 14 cm.

The calibrated values of n_b for these cross sections were 0,02 and 0,035.

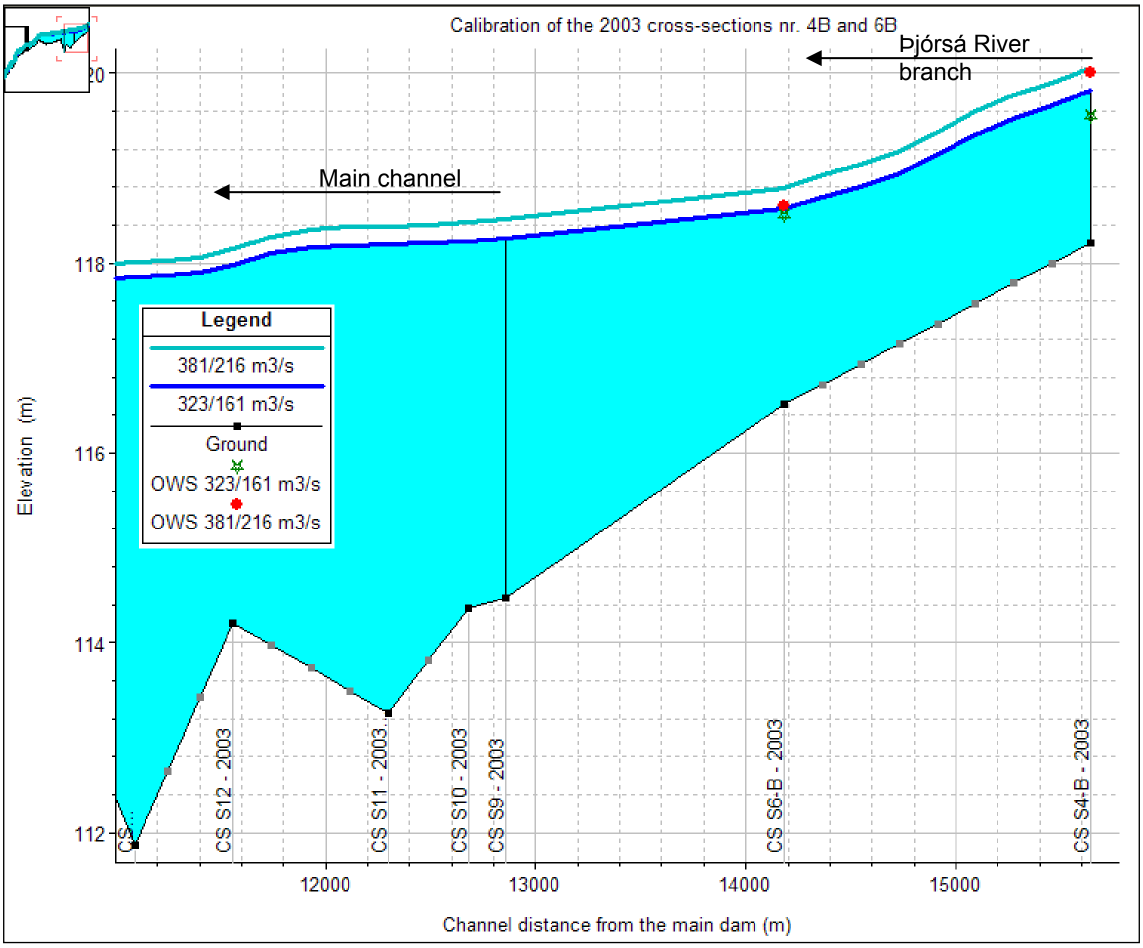

Figure 6.8 *Calibration of cross-sections 4B and 6B, from November 2003.*

6.3 Calibration with ice – the ice variables

The Urriðafoss Ice Jam was used to calibrate the ice variables used in the Hagalón model. However, it should be noted that there might be some difference between the ice variables at those two locations. The calibration is covered in appendix 2 and the results are as follows:

$n_i = 0{,}0302 * \ln(t) + 0{,}0445$ $\quad p_i = 0{,}4$ $\quad \phi = 45°$

Where n_i is Manning's n for the underside of the ice, t is the accumulation thickness, p_i is the ice jam porosity and ϕ, the angle of internal friction. In addition n_i was forced to be $\geq 0{,}02$.

As the values of the ice variables can have big influence on the calculated ice jam some experts abroad were contacted and consulted. The correspondence with them is included in the report in appendix 1. The result of this correspondence supported what was done and narrowed the range assumed possible for the variables.

6.4 Ice jam modelling

6.4.1 Modelling with expected variables

Figure 6.9 shows the longitudinal profile of the river with and without ice jam formation for a discharge of 300 m^3/s. The grey area shows the location and height of the dikes on the southern bank of the river.

The minimum ice cover thickness in the model was set to 0,2 m in the whole river reach. Ice jam formation was allowed everywhere except in the lowest and highest cross-sections simply due to limitations in HEC-RAS. As the influence of the ice jam dies out in the reservoir quite a distance upstream of the dam, this limitation in the downstream end has no effect on the ice jam calculation.

Figure 6.6 shows the upstream end of the model. During periods of cold spells, when an ice jam could be formed, discharge would be at its minimum and controlled by the powerstations upstream. No, or at least very little, discharge would be in the original Þjórsá River channel bypassing Búrfell Powerstation. Discharge in Fossá River would be very small and the main discharge in Lower Þjórsá River would come through Búrfell Powerstation. The distance from the powerstation to the upper end of the model is almost 3 km. Temperature measurements indicate that supercooling of the water starts to occur between 2 and 3 km from the powerstation see figure 3.2. That indicates that the model reaches sufficiently far upstream, as little ice can be produced upstream of the upper most cross section. It also indicates that the limit of 0,2 m thickness of the ice jam at the upstream end should not influence the results as there is not much ice production above it.

Manning's roughness factor, n_i, had to be iterated and the values ended in the range of 0,02-0,078 with the average value of 0,032. The water level rise due to the ice jam formation was on average 0,91 m, with the highest value of 1,5 m and the lowest of 0,64 m. The ice cover thickness got the average value of 0,77 m, the thickest part reached 3,4 m and the thinnest got the minimum value given beforehand.

The volume of ice in the ice jam is almost 4 Mm^3.

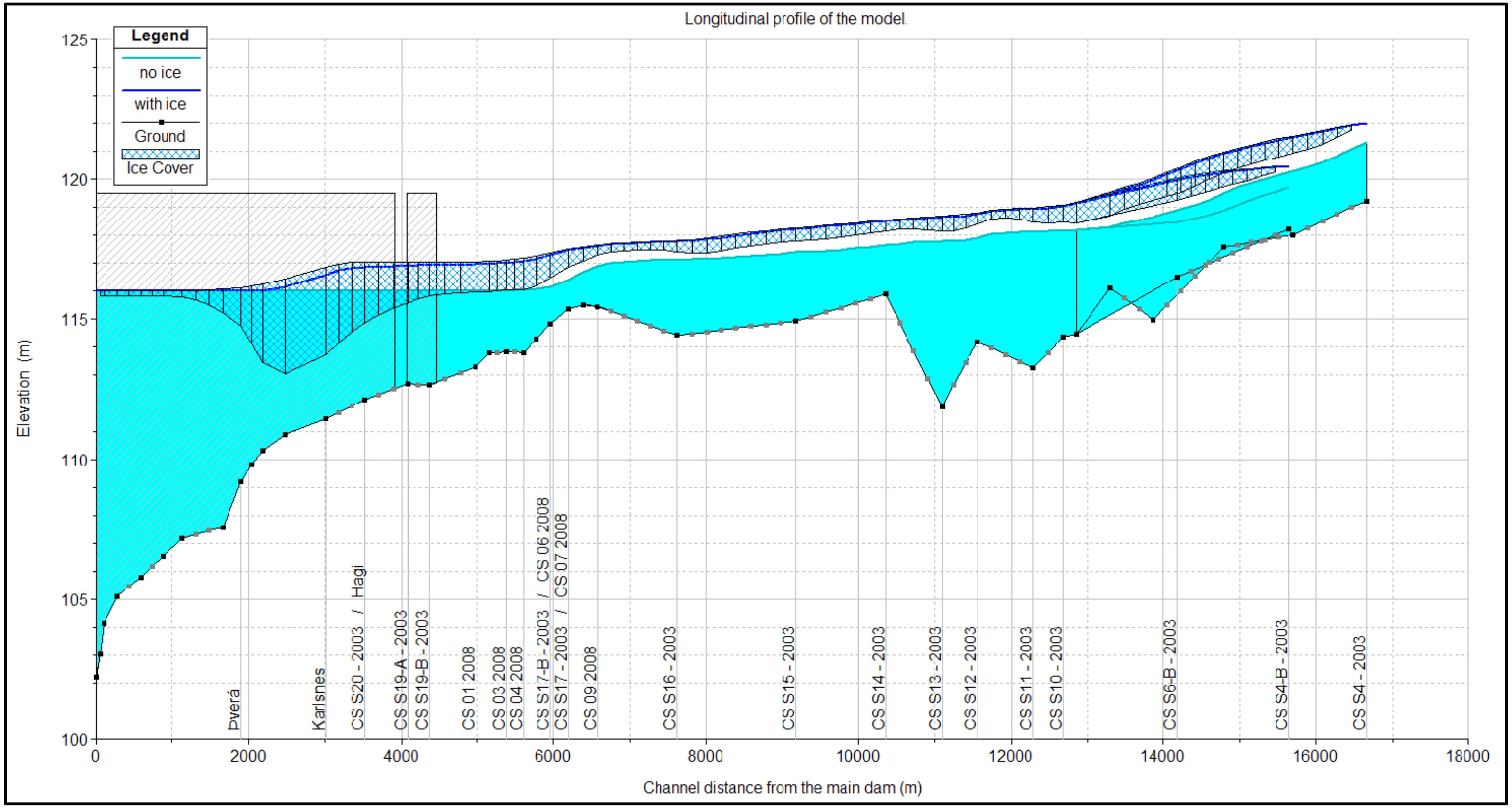

Figure 6.9 *The longitudinal profile of the expected equilibrium state of the Hagalón Ice Jam and the profile for open surface flow for comparison. Steady state discharge of 300 m^3/s was used in both runs.*

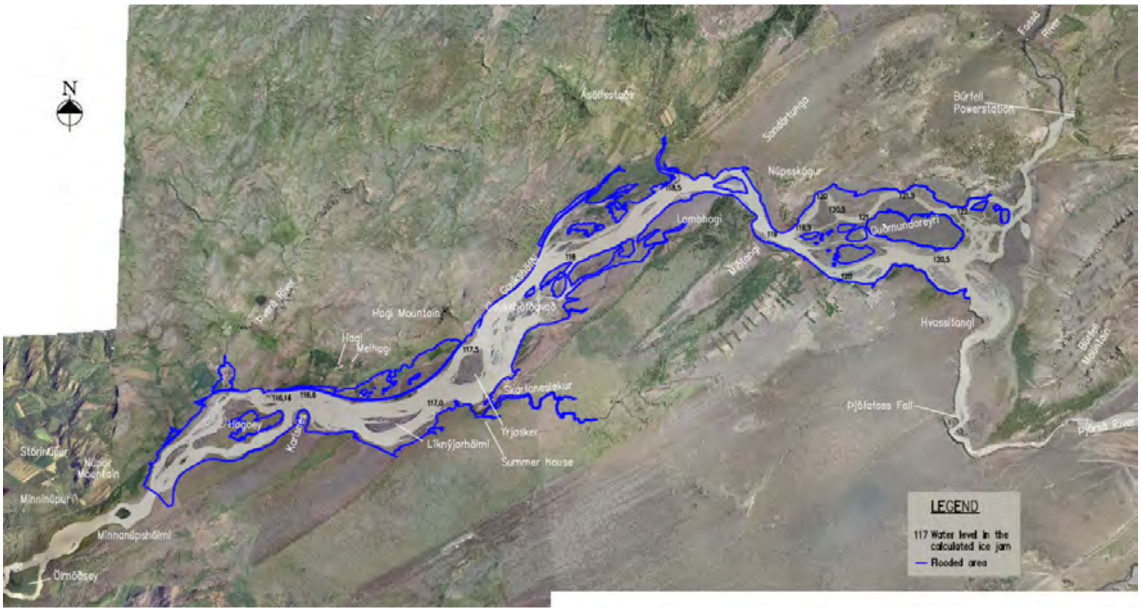

Figure 6.10 *Overview of how high the water can rise due to a continuous wide river ice jam reaching all the way up to the roots of Búrfell Mountain. Discharge 300 m³/s. An A3 version of this figure can be found at the end of this report before the Appendixes.*

Figure 6.9 shows the expected equilibrium state of the ice jam if the cold spell's duration is long enough to produce all the ice needed for the ice jam to evolve all the way. Often the cold spells are shorter so the jam can not evolve this far upstream. Appendix 3 shows various forms of the Hagalón Ice Jam using the same parameters but limiting its growth. These figures also indicate how the ice jam could evolve during its growth.

Table 6.1 gives event examples of ice production capability of the reach in the model if the surface would stay open the whole time. The heat loss was taken from a report on ice survey at Tangafoss and Upper Þjórsá River (Sigmundur Freysteinsson, 1972).

Table 6.1 *Examples of calculated ice production during cold spells.*

	Ice production in Mm^3 per 2,1 km^2.	Number of days	Production in $Mm^3/km^2/day$	
			average	maximum
21. Feb. – 27. Marz 1965	6,3	35	0,09	0,30
6. Dec. 1962 – 22. Feb. 1963	16,3	79	0,10	0,38
4. Dec. 1957 – 14. Marz 1958	28,7	101	0,14	0,24
8. Nov. 1950 - 20. April 1951	40,9	164	0,12	0,29

The periods picked were severe cold periods. The open surface above the reservoir is about 2,1 km^2 but as the ice jam grows upstream the open water surface is reduced, thus reducing the production of ice. Most of the ice in the ice jam is located within the pond so in the beginning of the ice jam formation, after the initial ice cover on the intake pond has formed, the open water surface area will be similar, for some time or until the lowest part has reached its equilibrium. Figure A3.4, in appendix 3, shows the ice jam as it has grown only half a kilometre upstream of the intake pond and already it includes almost 3/4 of the ice volume of the fully formed ice jam. After that the ice jam will grow fast upstream and as it covers the surface the ice production capacity will be less and less until no ice will be produced as no active open water surface will be left for ice production. Thus the ice volumes given for the events listed in Table 6.1 would in reality only grow up to 4 Mm^3 and then all ice production would stop as no active open water surface would be left to produce more ice. Based on the average production per day, see column 4 in the table, the ice jam could be fully developed in less than 15 days during cold spells.

6.4.2 Possible variations from expected variables

The variables used for ice in HEC-RAS are difficult to determine and can be different for different scenarios. The calculated ice jam, in the previous chapter, showed an ice jam using the expected ice properties values. In this chapter small variations from the expected values are tested.

In Figure 6.11 the angle of internal friction has been lowered from 45° to 40°. This change shovs the ice further into Hagalón Pond and thickens the ice at that location, i.e. in the intake pond. Further upstream the ice thickness is similar to the expected ice jam but the water level rise is higher as the downstream end of the ice jam has lifted the water level higher. Upstream of the junction in the northern branch the ice jam is again thicker.

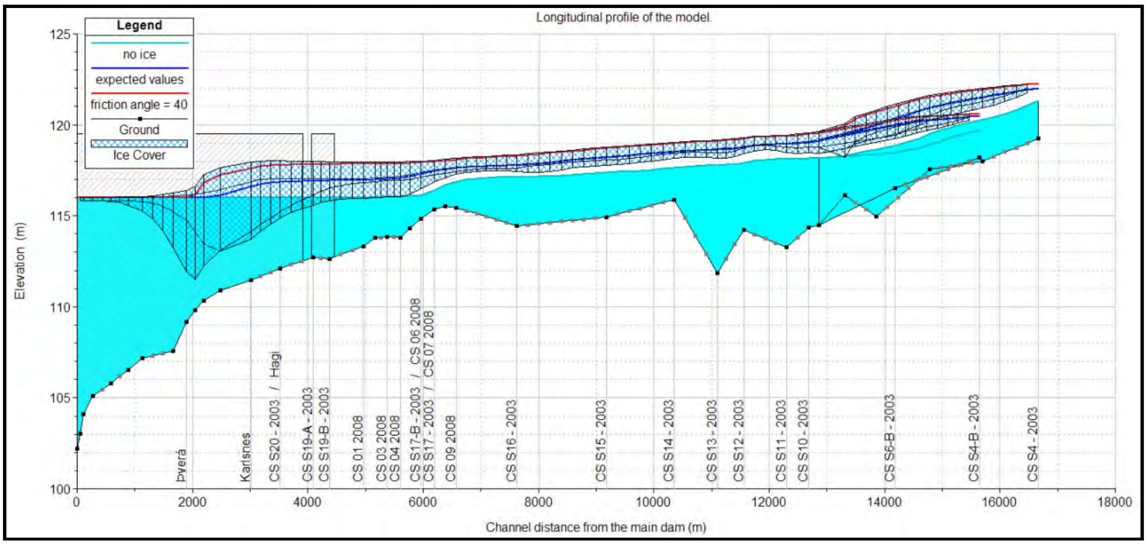

Figure 6.11 *The longitudinal profile of the Hagalón Ice Jam where ϕ has been lowered to 40°.*

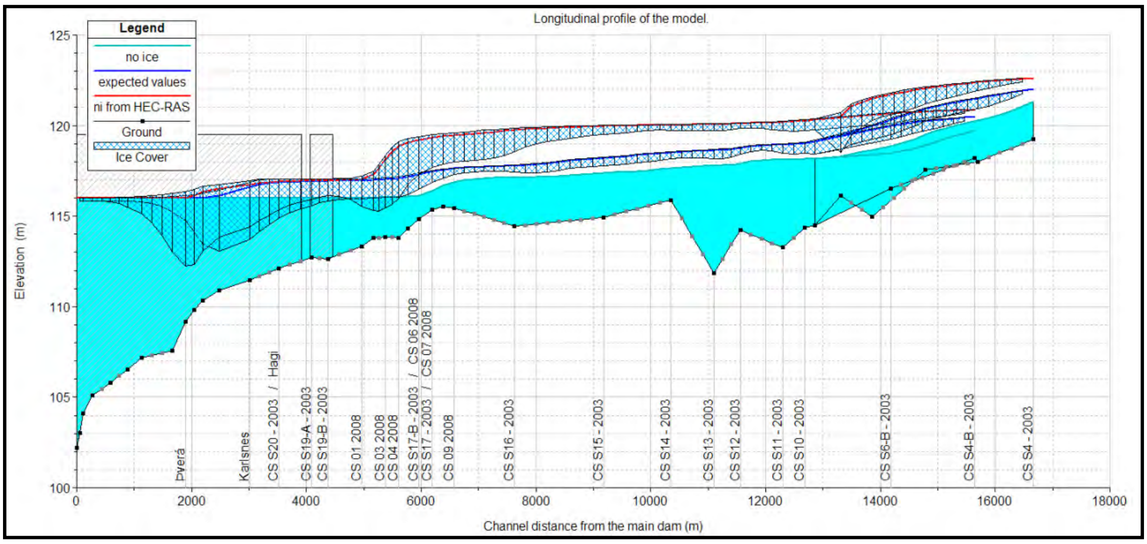

Figure 6.12 *The longitudinal profile of the Hagalón Ice Jam where n_i has been calculated in HEC-RAS, i.e. using the Nezhikhovskiy's relationship for ice floes.*

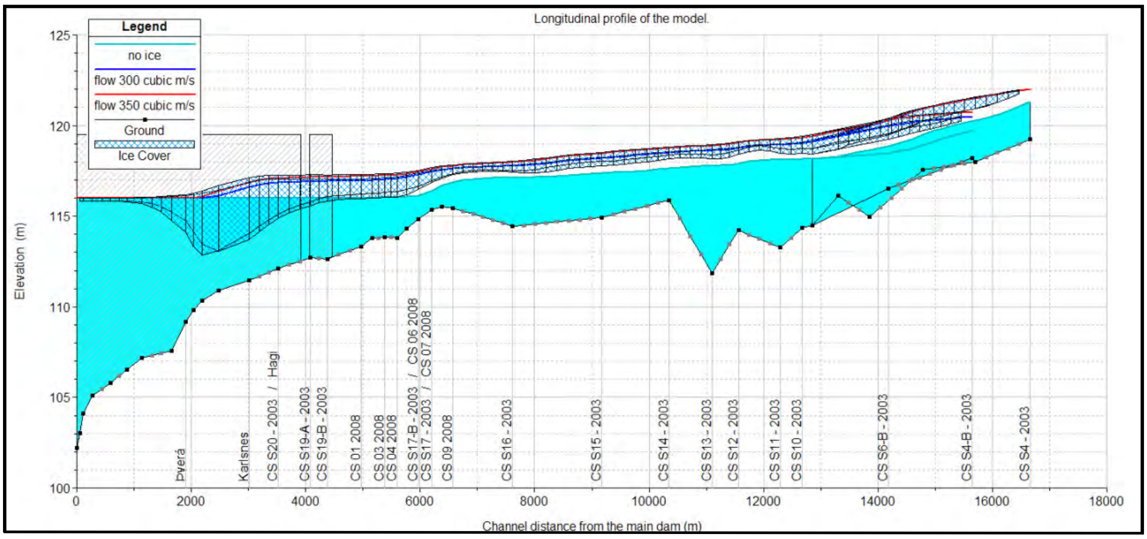

Figure 6.13 *The longitudinal profile of the Hagalón Ice Jam where the flow has been changed from 300 m³/s to 350 m³/s. Expected values used for ice variables.*

In Figure 6.12 the software is given the task of calculating the roughness factor, n_i. As HEC-RAS is made for break-up ice jam it is assumed that it uses the Nezhikhovskiy's relationship for ice floes instead of dense slush in the expected ice jam. This will give higher values for the roughness factor leading to thicker ice jam. The main change in this case is the abrupt change in both thickness and waterlevel downstream of the Yrjasker reef.

In Figure 6.13 the discharge has been changed from 300 m^3/s to 350 m^3/s. The change is minimal, only a slight rise in waterlevel and thickness.

6.4.3 The possibility of a breakup ice jam

In Iceland there is marine climate so the winter time is usually divided into many cold and warmer spells. Thus it depends on the length and the severity of the cold spells how far upstream the ice jam can grow. Figure 6.9 shows its final state if the cold spell is long and cold enough for the ice to cover the whole reach. In reality it might often not grow this far upstream and thus often be less than shown on the figure. All the variables are calibrated to a freeze-up ice jam but in reality we might have a few thawing periods in-between the cold spells, thus the question arises; can we get a big breakup ice jam?

Ice in a breakup jam would have to come from the same area as we are looking at for the freeze-up ice jam even though some ice might come from the small tributary of Fossá river and the old reach of Thjórsá River bypassing the Búrfell Powerstation, but ice from these reaches would always be small in proportion to the ice in the ice jam in the modelled reach. Thus we can conclude that the mass of breakup ice could not be more than the ice mass in the freeze-up ice jam, which is about 4 Mm^3.

Below are two figures showing results from breakup ice jams formed in a sudden winter-flood with 1500 m^3/s discharge, breaking up fully developed freeze-up jam, cleaning all the ice rubble in its wake, creating a breakup jam in the intake pond. The freeze-up ice jam and water level with no ice jam using a discharge of 300 m^3/s is included in the figures for comparison. Additionally black points have been added showing the likely profile of the design flood for the hydroelectric project, i.e. a flood, without any ice, with a recurrence interval of 1000 years.

In the first figure the inbuilt calculation of n_i in HEC-RAS that assumes a breakup ice jam was used. Other parameters are the same except of course the flow. In the second one it was assumed that the angle of internal friction is higher for a break-up ice jam than for a freeze-up ice jam, so it was set to 50°. This is a value assumed realistic for break-up jams (Beltaos, 2007 and 2009). The difference between the two is mainly that the former is pushed closer to the dam and the water surface profile is lower.

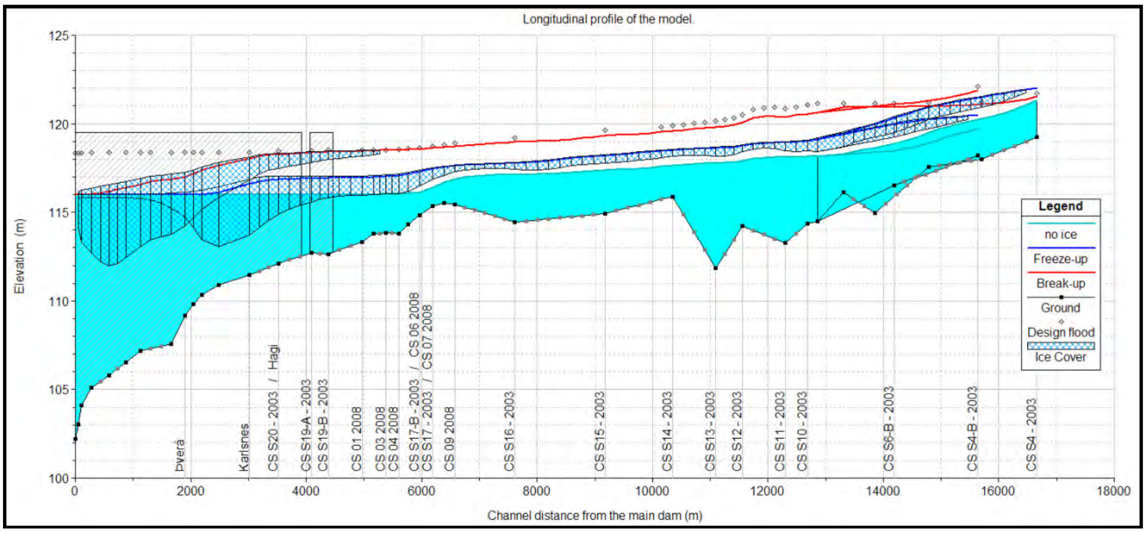

Figure 6.14 *The longitudinal profile of a possible break-up ice jam with expected values, a discharge of 1500 m^3/s and same ice mass as the freeze-up ice jam. Water level for no ice and expected freeze-up ice jam for discharge of 300 m^3/s and the design flood for the hydroelectric project is also shown.*

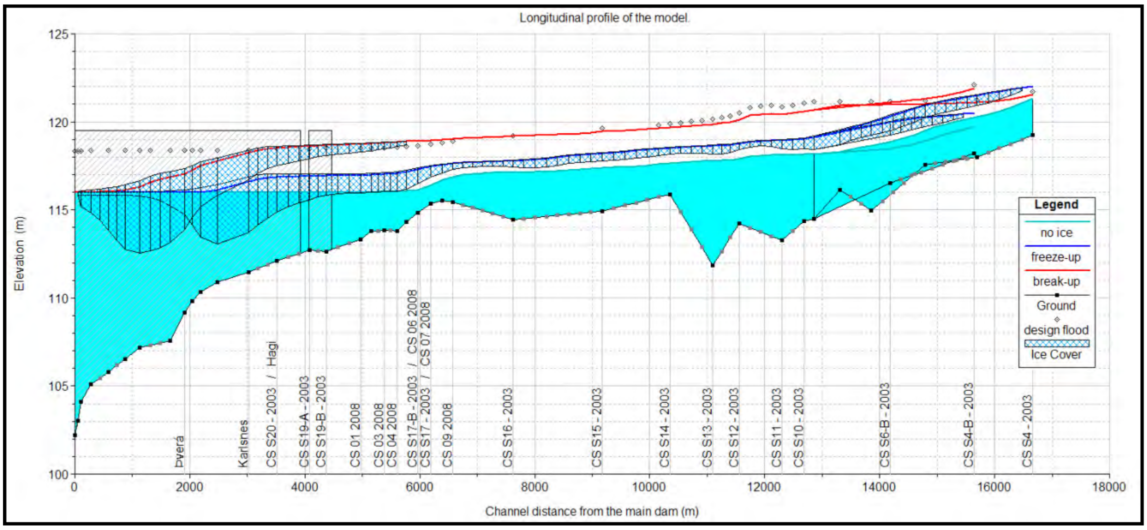

Figure 6.15 *The same as above, but with the internal friction angle for the break-up ice jam changed to 50.*

The waterlevel rise due to the expected freeze-up ice jam is far below the expected water level in the design flood whereas the break-up ice jam could possibly reach the same water level or rise slightly above it. The gates, used to keep the waterlevel in the intake pond at 116 m a.s.l., are located low enough to be problem free despite the ice reaching the dam.

6.4.4 Structures and other things of interest close to the river

The dikes at the southern bank of the river are a part of the Hvammur Hydroelectric Project, shown on all the profile figures as gray hatched areas and their location can be seen on figure 6.1. Their design height is 119,5 m a.s.l. This height seems to be adequate for freeze-up ice jam assuming the values for the ice properties are realistic. Even with variations in the variables used and discharge the freeze-up ice jam seems to give low enough water level for the dikes. The break-up ice jam, on the other hand, causes higher water level at the upstream end of the dikes with only a meter to spare. This indicates either that the dikes should be higher at its upstream end or a close surveillance is needed, at least to start with. An ice boom (or two) could be used to lower the water level of the break-up ice jam.

On the northern bank of the river lies the highway. It is scheduled to be moved or changed from Minnanúpshólmi up to Gaukshöfði. Partly it will be brought closer to the river. According to Páll Bjarnason (2009) at Verkfræðistofa Suðurlands, the current design assumes that the height of the road will be about 120 m a.s.l. close to the main dam site and not lower than 118 m a.s.l. along the intake pond. Where the land is higher than these lower values the road is assumed to be approximately 1,5 m above the land. The longitudinal profiles of the southern and western banks of the river, including the dikes and the highway are shown in Figure 6.16. Upstream of the junction in the river the banks are so high that there is no danger of the river flowing over them so the profile in the figure is only of the river downstream of the junction. Banks above the height of 125 are also not shown. Three ice jams are shown on the figure, the expected ice jam, the freeze-up ice jam where HEC-RAS computed the roughness factor, n_i, and the one for break-up ice jam using 50° for the angle of friction. In addition the design flood is shown for comparison.

The expected freeze-up ice jam is below the banks in all places, but for about 3 km it is only 1 m below the highway. At the same place the other two ice jams would have flooded the highway. The freeze-up one is unlikely but the break-up one is hard to ignore. It would thus be safer to lift the highway up in this area. The upper end of the dikes might also be lifted a little bit at least down to Karlsnes.

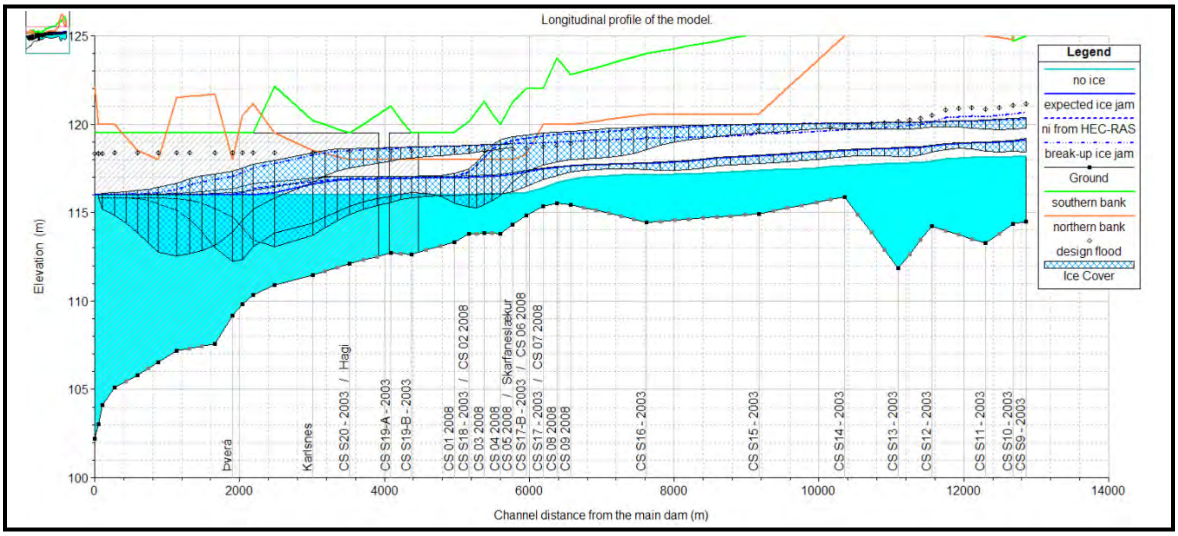

Figure 6.16 *The banks of the river with the longitudinal profile of the expected freeze-up ice jam and the two worst case scenarios calculated, as a comparison.*

The location of farms and summer houses close to the river can be seen on **Figure 6.10**. The summer house located on the bank of Skarfaneslækur has its ground elevation above 121 m a.s.l. and should thus not be in any danger from ice jams. The farms are located further from the river and the one with the lowest elevation is above 130 m a.s.l. so all the farms are well above possible ice jams and quite a distance away and thus safe.

6.4.5 Effects of possible dredging operations

Landfill behind the new highway, approximately from cross section S20 up to Gaukshöfði, is a part of the project and intended to give farmers a new land for farming. The effect of the dredging was tested in the model. Appendix 4 shows different ways of dredging, where, how much and the effect on the ice jam. The variations were all within the reach between Karlsnes and Gaukshöfði. The results indicate that dredging has almost no effect except when the whole reach was lowered as shown in the last case, see Figure A4.10.

7 Heiðarlón Ice Jam model

7.1 The model

Heiðarlón Pond is the name of the Intake Pond for the proposed Urriðafoss Hydroelectric Project. Its location is shown on Figure 1.1. At its upstream end an ice jam will form and grow upstream and downstream into the intake pond. A model was made in HEC-RAS in order to calculate the equilibrium ice jam above Heiðarlón Pond, here after called the Heiðarlón Ice Jam. The site of the main dam was chosen as the downstream boundary of the model.

Upstream of Urriðafoss Hydroelectric Project would be both Hvammur and Holt Hydroelectric Projects, according to current construction order of the projects. The current construction order is as follows:

1. Hvammur Hydroelectric Project
2. Holt Hydroelectric Project
3. Urriðafoss Hydroelectric Project

The main reason for this order is that each new project reduces the open water surface above the other proposed projects further downstream, thus lowering the risk of ice-problems for each project. Table 7.1 shows the open water surface areas as estimated from photos taken on the 11th of February 2002 (Victor Helgason, 2002). The table shows that the two proposed powerstations, upstream of Urriðafoss Powerstation, reduce the open water surface area from about 9 km^2 down to approximately 4 km^2 and even down to about 1 km^2 if the diverted ice at Búði Diversion is stopped in the River upstream of Árnes Rapids.

Assuming current construction order, all ice produced above Hagalón Dam would be trapped above the dam. Downstream of the dam the river reach is relatively steep all the way down to Búði Diversion. Búði Diversion marks the upstream end of Holt Hydroelectric Project and is located upstream of Búði Fall. Its purpose is twofold. Firstly, it is an intake into Árneslón Pond, located in the Árnes branch at Árnes. Secondly, it is designed to divert ice from the intake into the Þjórsá River branch at Árnes. In wintertime, especially during cold periods, the discharge in the river will just be enough for the powerstation and some minimal extra for ice skimming at the diversion structure. Most likely the ice, from the ice skimming, will be stopped in the reach between Árnes Rapids and Búði Fall, either by itself or with the help of some manmade retention structure. That would mean that no ice would enter the reach between Heiðarlón Pond and Árnes Rapids so all ice contributing to the possible Heiðarlón Ice Jam would have to be produced in the reach from the tailrace from Holt Powerstation down to Heiðarlón Pond. Thus, at first the reach from Árnes Rapids down to Heiðarlón Dam was modelled.

Later the reach from Búði Fall down to Árnes Rapids was added to answer some “what if?” questions. Those were: a) What would happen if Hvammur and Holt Hydroelectric Projects were not constructed? b) What if only Hvammur Hydroelectric Project would be present above Urriðafoss Powerstation?

In order to make the modelling easier the software WMS (Watershed modelling system) was used to help in the creation of the cross sections in HEC-RAS. In the software it is relatively easy to create 3D geometry and extract the cross sections for HEC-RAS.

The data points from the geometry based on the aerial photographs were used above water and the measured cross sections below water. The way the data was used is not the same for the first model and the added part so the discussion in this chapter has been divided into two subchapters.

Table 7.1 *Open water surface above some locations based on aerial photographs taken on the 11th of February 2002 (Victor Helgason, 2002). Comparison of open watersurface above the intake ponds with and without proposed HP upstream of each one. And finally comparison of areas.*

	A	B	C	D	E=C/D	F=C/11.2	G=D/11.2
	Open water area of each part.		Open water area contributing to ice formation above each intake pond.				
	Current situation.	With upstream projects.	With upstream projects operational.	Without proposed upstream projects.	Percent of ice producing area with current planning.	Ice producing area in current planning in comparison to the ice producing area for Urriðafoss Ice Jam.	Ice producing area above each pond, without other projects, in comparison to the ice producing area for Urriðafoss Ice Jam.
	km²	km²	km²	km²	%	%	%
Above Hagalón	2.1	2.1					
Hagalón	1.5	4.6	2.1	2.1	100%	19%	19%
Above Búði Diversion Structure	2.4	1.9					
Árneslón	0.0	4.8	1.9	6.0	32%	17%	54%
Þjórsá River branch at Árnes	1.8	1.0					
Upstream of Heiðarlón to Árnes Rapids	0.9	0.9					
Heiðarlón	2.4	9.0	3.8	8.7	43%	34%	77%
Heiðarlón, if the diverted ice at Búði stops in the Þjórsá River branch			0.9		10%	8%	

7.1.1 The reach between Heiðarlón Dam and Árnes Rapids

The cross section data from 2008 were used in 3D and coupled together with the geometry data above water. The 2008 data covers only a small portion of the reach at the upstream end of the Heiðarlón Pond. Above that, up to Árnes Rapids and down to the upstream end of the dike, the cross sections from April 2002 were used. Cross sections 10 and 12 were not used as they lie within the range of the cross section data from 2008. Nevertheless, the cross sections were compared to the 2008 data. The comparison showed that the river had moved slightly in the years between the measurements but the width and depth was similar, i.e. the characteristics of the cross sections were the same.

As no cross sections existed for the river within the pond area, except one at Krókur, assumed river bed was made for that part of the river except for the one at Krókur. That cross section (August 2001) had neither a position in plan nor elevation so both the elevation of the cross section and its exact location is only an educated guess, but nevertheless better than nothing.

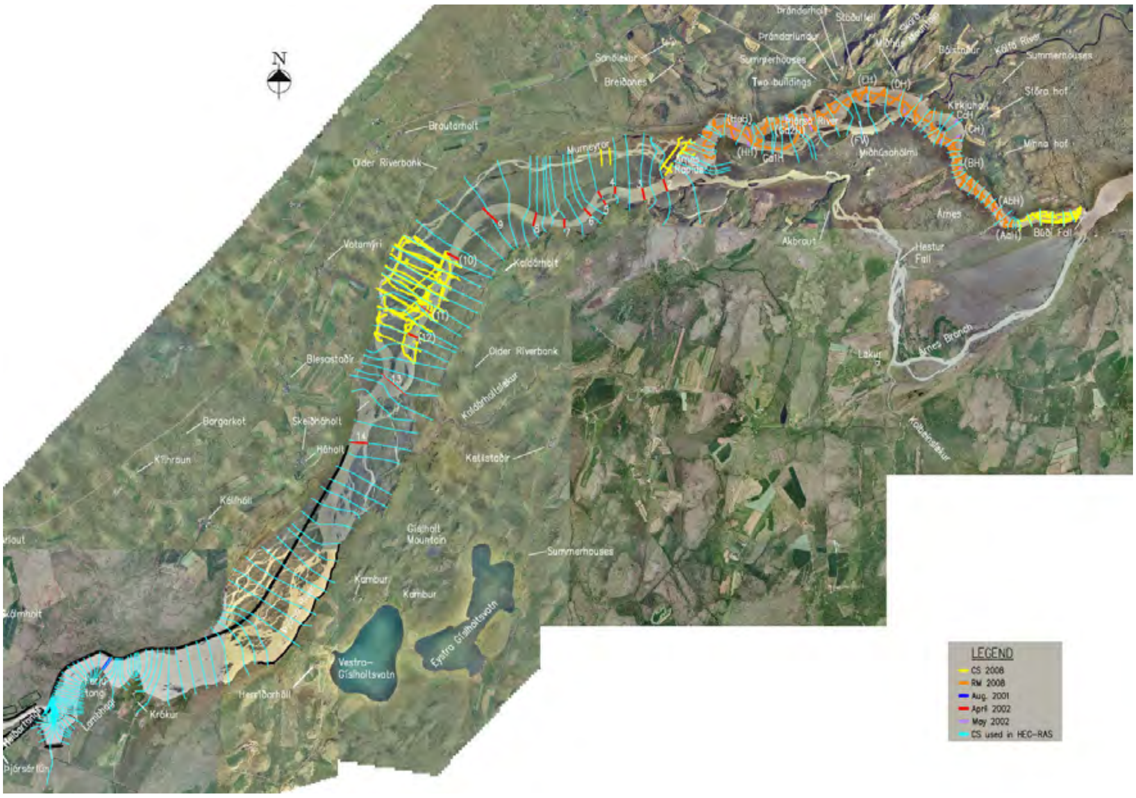

Figure 7.1 *An overview of both measured cross sections (CS) in the model area and the location of the cross sections used in the Heiðarlón model. An A3 version of this figure can be found at the end of this report before the Appendixes.*

Figure 7.1 shows the location of the cross sections, both measured and those made in WMS and extracted into HEC-RAS.

The boundary conditions at the downstream end of the model were chosen as a normal waterlevel in the calibration process and a fixed water surface elevation of 50 m a.s.l. in the ice jam modelling. A normal waterlevel was used as boundary condition in the model at the upstream boundary.

7.1.2 The reach between Árnes Rapids and Búði Fall

The cross section data from 2008 were used and coupled together with the geometry data above water. During the work on the Hagalón model a quicker way was found to work the cross sections into WMS so that method was used again for this reach, see the text about the 2003 cross sections in chapter 6.1, the same applies here for all used data. The data covers almost the whole reach but occasionally cross sections were necessary in HEC-RAS where no data points were taken and in these cases the riverbed was fictional except where there were available cross sections from May 2002. All other cross sections from May 2002 were ignored as it was much simpler to keep to one dataset.

Figure 7.1 shows the location of the cross sections, both measured and those made in WMS and extracted into HEC-RAS.

The boundary conditions are the same as for the lower reach model discussed in chapter 7.1.1.

7.2 Calibration of the model - without ice

The model created in HEC-RAS had to be calibrated for flow without ice. The calibration parameters were Manning's n for the riverbed, hereafter called n_b. The calibration of the lower part was done without the upper part and later the upper part, above Árnes Rapids was added and calibrated with the lower part attached.

As the technique used for the cross section measurements and the discharge during both the cross section and the longitudinal profile measurements was not always the same, the model had to be calibrated by focusing on smaller reaches at a time, i.e. parts with similar discharge during measurements. Figure 7.2 shows the longitudinal profile of the first model from the dam up to Árnes Rapids and the arrows mark parts within the river where cross sections could be calibrated together. Figure 7.7 shows the same for the upper part. In the following chapters each part will be discussed separately.

Before any calibration could start the way the water divides into the two branches around Árnes had to be looked into. Fortunately, cross section measurements were available for the upper most part of the Árnes Branch, see Figure 5.1. Additionally, this part had been measured in the longitudinal profile measurement trips giving us two datasets to work with, one with discharge of about 330 m^3/s and the other one with discharge of 600 m^3/s. As a first attempt some of the cross section where tested using the simple form of Manning's equation for steady and uniform flow. The result from that was that the discharge in the Árnes branch was somewhere between 10-30% of the total discharge of the river. As this is quite a wide span a second attempt was made assuming that the flow was far from being uniform and thus better to throw the cross sections into HEC-RAS. This narrowed the gap from 10-30% down to 12-13%. The calibration of this small model resulted in Manning's n for this part in the range of 0,025-0,035. The division of discharge ended in 12,5% in the Árnes Branch.

7.2.1 The Heiðarlón Pond.

Only one measured cross section existed in the reach from the Heiðarlón Dam up to cross section 14 from April 2002. This sole cross section had no fixed point usable to locate it correctly in the model. But as nothing better was available in this reach this cross section was used and its location both in plan and elevation was only an educated guess. The riverbed in this reach was made by locating the main channel from the aerial photographs and giving that part a trapezodal shape in 3D similar in depth and shape as cross section 14. The only water surface measurements available were the longitudinal profile measurements.

Figure 7.3 shows both calculated and measured waterlevel (OWS = observed water surface) for this part of the river.

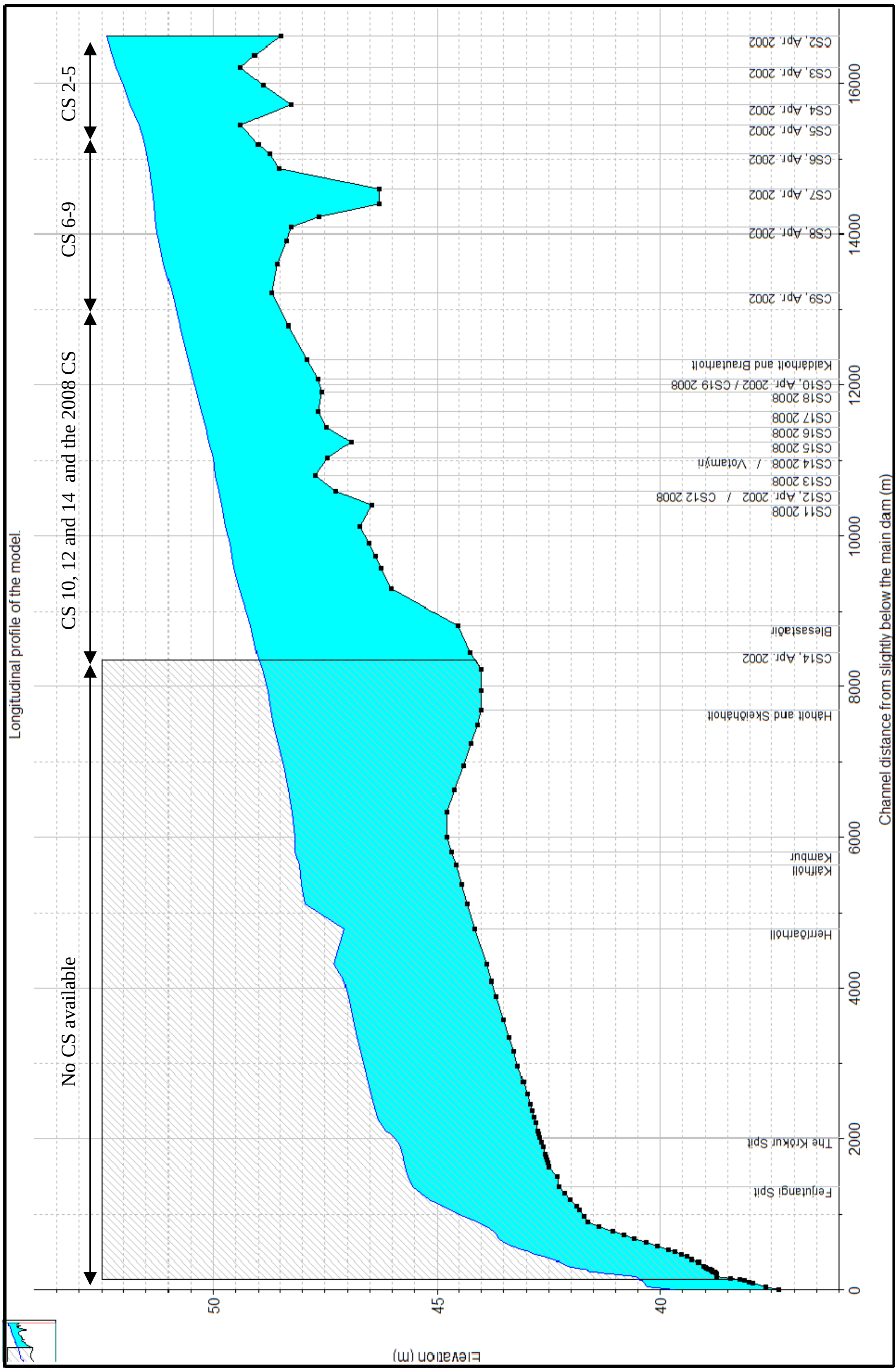

Figure 7.2 *Longitudinal profile of the modelled part of the river from the Dam site up to Árnes Rapids. The black dots on the riverbed mark out cross sections extracted from WMS. The blue line marks the water level in the river and the grey hatched area shows were the dike is located along the river.*

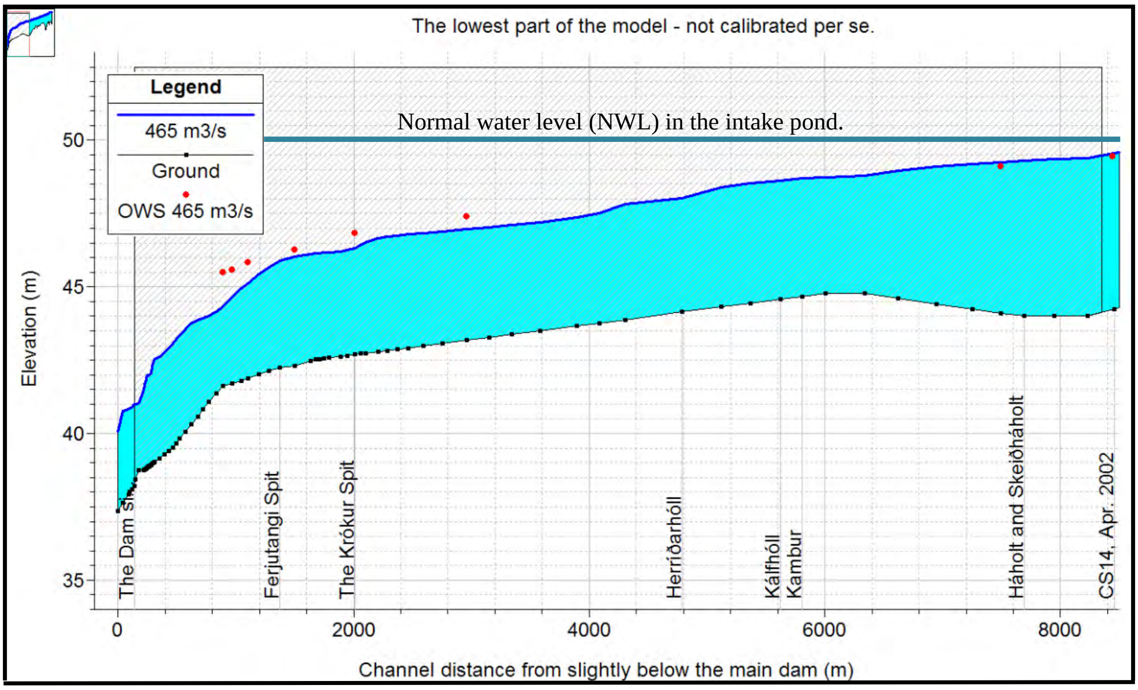

Figure 7.3 *Longitudinal profile of the Heiðarlón Pond. The shaded area is the dike and OWS stands for observed water surface.*

From station 0 almost up to station 4000 (4 km from the Dam site) the Mannings n was set to 0,04 but around station 4000 it was changed in two steps to 0,02 assuming the transition from lava bed into gravel/sand bed.

The correlation between the calculated and measured waterlevel is not as good as in the model for Hagalón Pond but considered all right as a first approach. If revisited the cross sections themselves should be adjusted and changed in addition to modification on Manning's n.

7.2.2 The 2008 cross sections and cross sections 10-14 from 2002.

The upper end of Heiðarlón Pond lies between cross sections 10 to 14. In 2008 9 cross sections were measured in this reach but when the calibration was made the discharge at the time of the measurements was unknown, thus it is possible to add one dataset to the current calibration later. The longitudinal profile measurements were used and the cross section measurements in 2002. The discharge at the time of the measurement of the longitudinal profile was about 465 m^3/s and about 400 m^3/s at the time of the measurement of cross sections 12 and 14. Cross section 10 was not used in the calibration. A discharge of approximately 10 m^3/s runs in a separate branch along the West bank of the river, the socalled Murneyri Branch. This branch develops at Árnes Rapids and rejoins the main river approximately at station 10600.

Figure 7.4 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference for the 2002 cross sections is 25 cm. The maximum difference for the longitudinal profile measurements (LPM) is 27 cm, the average deviation from measured value is 16 cm and the standard deviation is 5,3 cm. The calibration of the LPM could be made much better by lowering the n_b but that would result in worse outcome in the 2002 dataset. The difference in the n_b between this final result and the better calibration of the LPM was about 0,005. The composite Manning's n, n_c, for the river made up of both n_i and n_b is given by the equation:

$$n_c = \left(\frac{n_i^{3/2} + n_b^{3/2}}{2} \right)^{2/3} \qquad \textbf{Eq. 7.1}$$

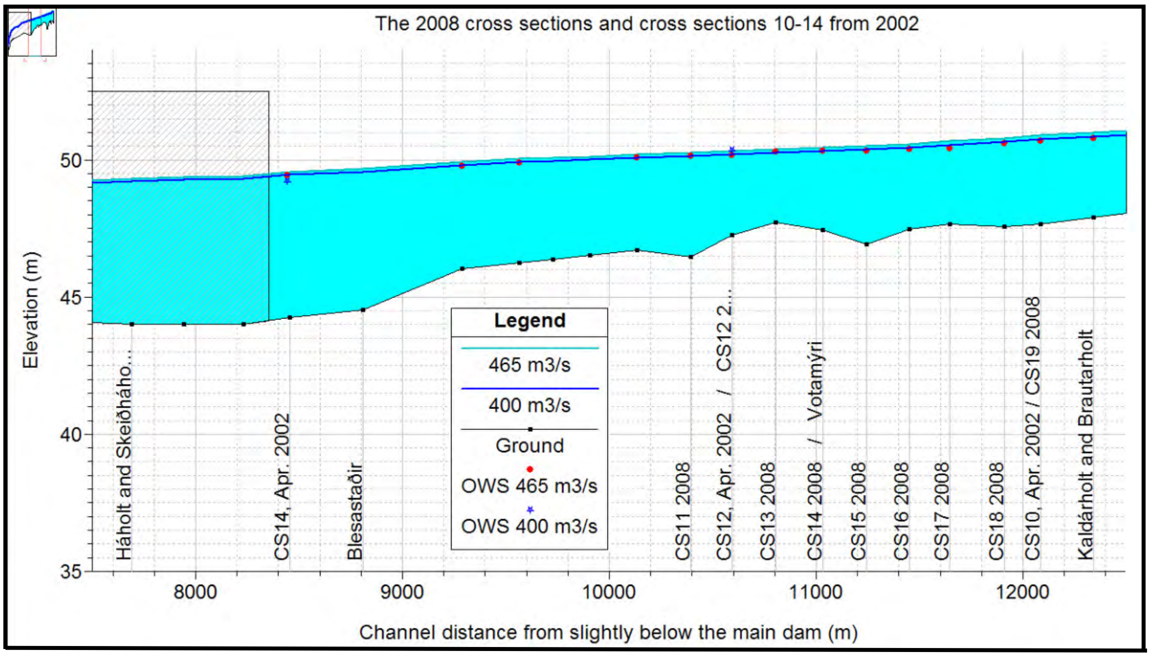

Figure 7.4 *Calibration of the cross sections from 2008 and cross sections 10-14 from 2002. The shaded area is the dike and OWS stands for observed water surface.*

The difference in n_c is only about 0,003 if n_i is 0,02 and n_b is changed form 0,023 to 0,028 and even less, less than 0,002, if n_i is set to 0,08 and the same done with n_b. Thus this difference in the composite Manning's number would change very little for ice covered river so this calibration was deemed satisfactory.

The final calibrated value of n_b was in the range of 0,024-0,028.

7.2.3 Cross sections 6-9 from 2002

In this part of the river the discharge during the LPM was the same as for the reach between cross sections 10-14. The discharge during the measurement of the four cross section in April 2002 were different. During measurements of CS 6 and 7 the discharge was about 705 m^3/s in the river in total, there of 15 m^3/s are assumed to go into the Murneyri Branch leaving 690 m^3/s in the calibration reach. For cross section 8 the discharge was 665 m^3/s in total, thus only 650 m^3/s in the reach calibrated. And for cross section 9 the same numbers were 730 m^3/s and 715 m^3/s.

Figure 7.5 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference for the 2002 cross sections is 11 cm, the average deviation from measured value is 7,2 cm and the standard deviation is 7,9 cm. The maximum difference for the longitudinal profile measurements is 30 cm, the average deviation from measured value is 25 cm and the standard deviation is 3,4 cm. Again the calibration of the LPM could be made much better by lowering the n_b but that resulted in worse outcome in the 2002 dataset. The 2008 data implies lower n_b values while the 2002 data needs higher values. Based on same reasoning as before, this calibration was deemed satisfactory.

The final calibrated value of n_b was in the range of 0,022-0,028, with an average value of 0,023.

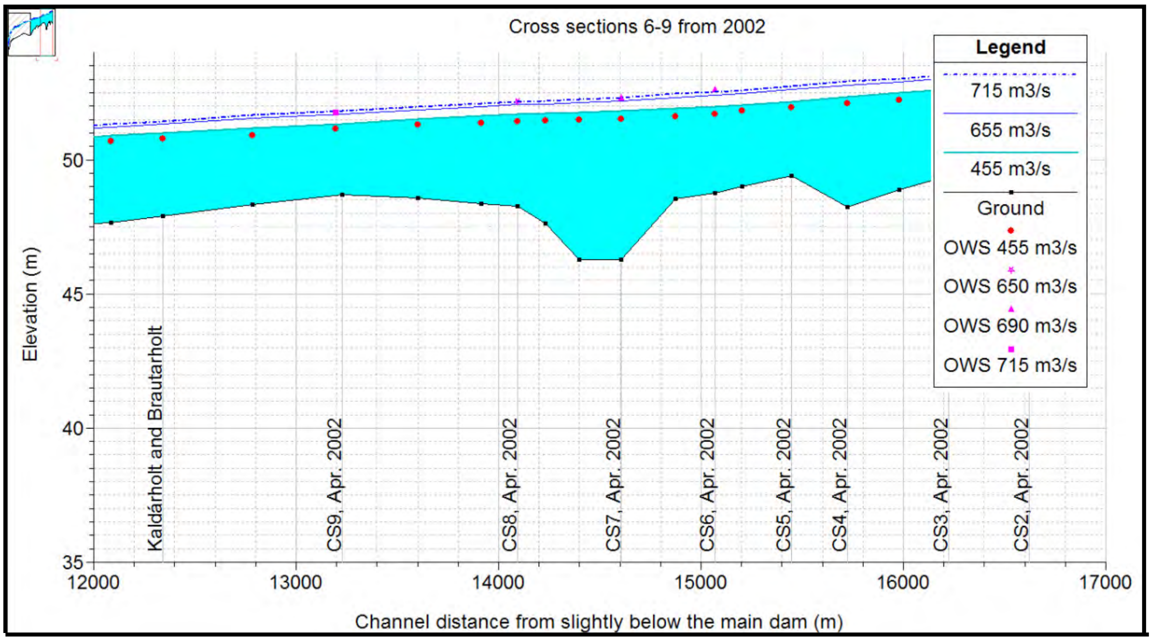

Figure 7.5 *Calibration of cross sections 6-9 from 2002. OWS stands for observed water surface.*

7.2.4 Cross sections 2-5 from 2002

In this part of the river the discharge during the LPM was the same as for the reach between cross sections 10-14. The four cross section measurements from April 2002 have very similar discharge of about 490 m^3/s (470-507), thereof 10 m^3/s are assumed to go into the Murneyri Branch leaving 480 m^3/s in the calibration reach.

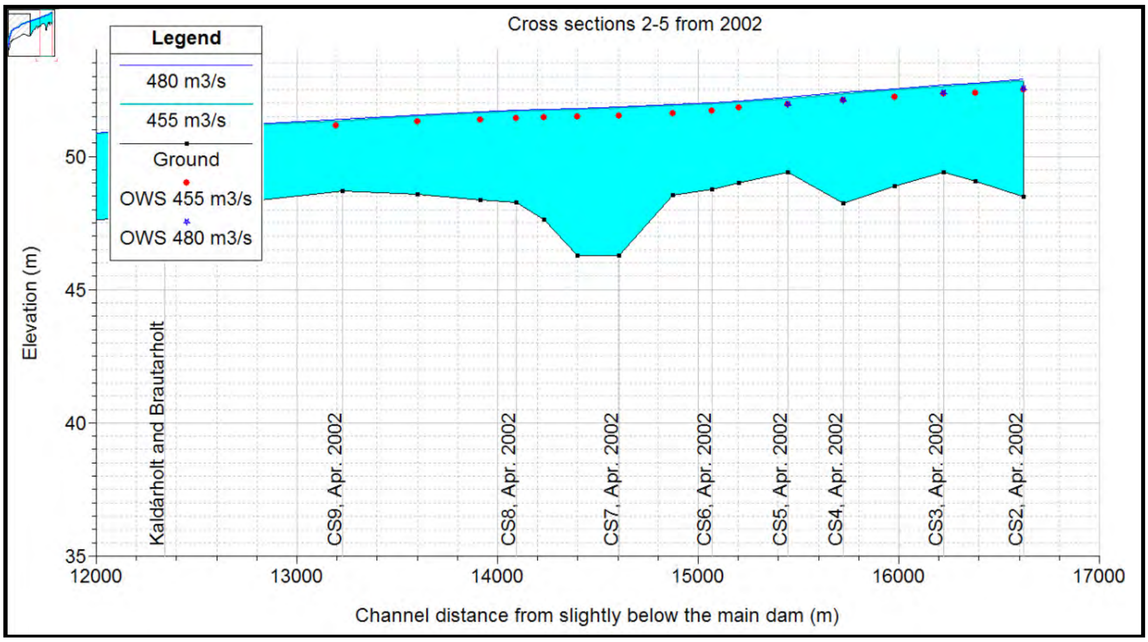

Figure 7.6 *Calibration of cross sections 2-5 from 2002. OWS stands for observed water surface.*

Figure 7.6 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference for the 2002 cross sections is 35 cm, the average deviation from measured value is 30 cm and the standard deviation is 4 cm. The maximum difference for the longitudinal profile measurements is also 35 cm, the average deviation from measured value is 29 cm and the standard deviation is 5 cm.

The discharge for both was in a similar range and a lower n_b would result in a better calibration for this reach but in order to get satisfactory results for the reach from CS 6-9, these higher values had to be used. This might indicate that during low flow the bed is sand and gravel covered but with higher discharge the sand and gravel is eroded exposing an underlying rock bed.

The final calibrated value of n_b was in the range of 0,024-0,026, with an average value of 0,025.

7.2.5 Árnes Rapids to Búði Fall, lower part.

Figure 7.7 shows the whole longitudinal profile of the model from Árnes Rapids up to the pool below Búði Fall. The calibration only had to be divided into two parts, upper and lower. In the lower part the bathymetry measurements from 2008 could be used for calibrating the model and in the lower part of the lower part longitudinal profile measurements were also available.

In this part of the river both the 2008 river bathymetry measurements and the LPM will be used in the calibration process. The discharge was around 513 m^3/s during the bathymetry measurements, resulting in discharge of approximately 450 m^3/s in the Þjórsá River branch. The discharge during the LPM was about 460 m^3/s, resulting in discharge of approximately 400 m^3/s in the Þjórsá River branch.

Figure 7.8 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference for the 2008 bathymetry measurements is 27 cm, the average deviation from measured value is 8 cm and the standard deviation is 10 cm. The maximum difference for the longitudinal profile measurements is 37 cm, the average deviation from measured value is 16 cm and the standard deviation is 20 cm. Interestingly the location of the worst calibrated cross sections were located where there were eyots (small islands) in the river. This is not strange as usually only one branch around the eyots were properly measured and also because the flow is not diverted into two branches in the model so the model does not represent the eyots properly. The calibration is much better if the comparison values around the eyots are ignored. Then the maximum difference is only 15 cm for the bathymetry data and 28 for the LPM. Similarly the average deviation from measured value would drop down to 6 cm and 12 cm for the BD and LPM. The eyots are thus the worst calibrated spots in this reach, mainly at their lower end. Never the less the calibration in the reach is quite good on average.

The final calibrated value of n_b was in the range of 0,02-0,04, with an average value of 0,033.

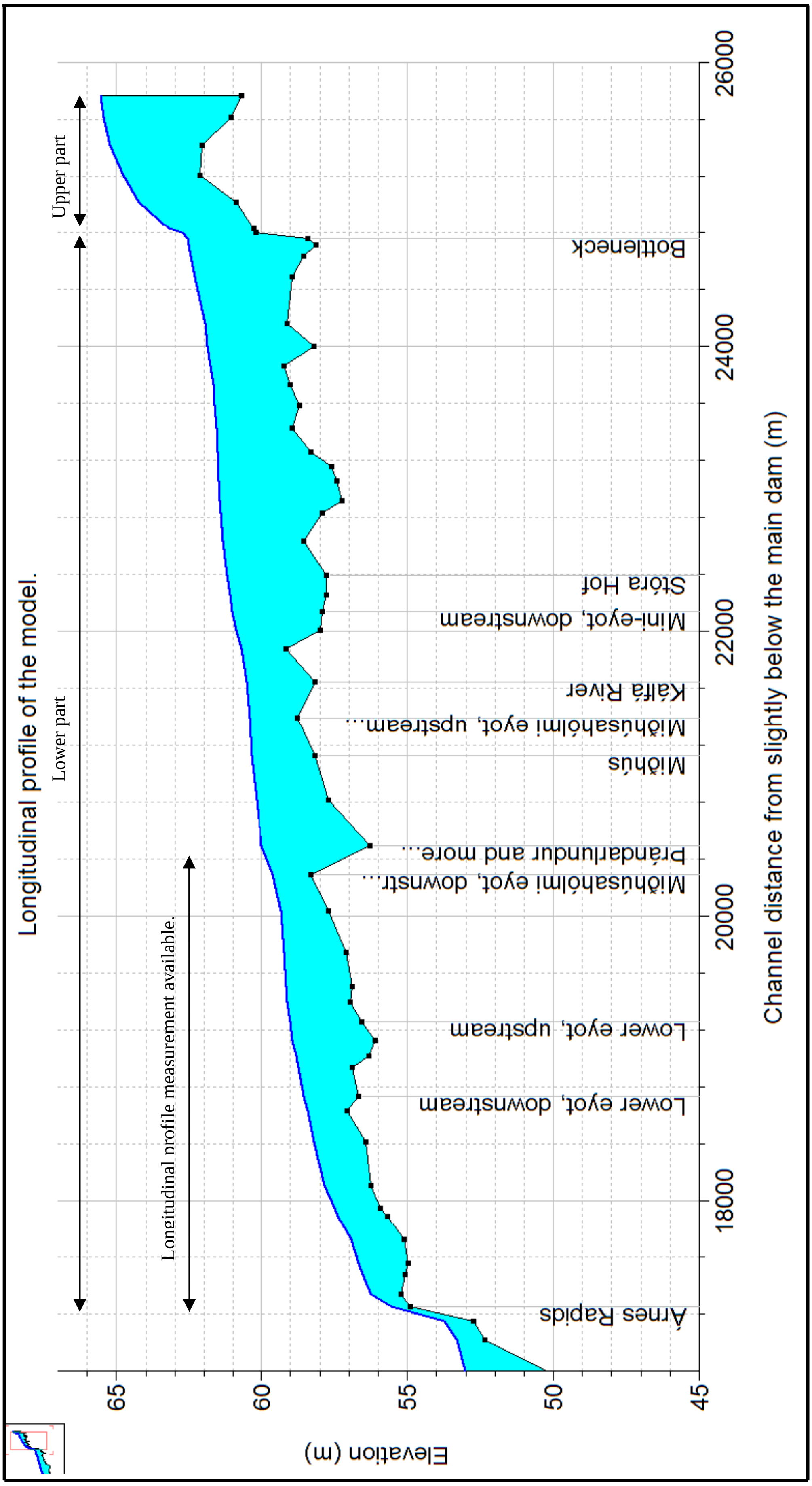

Figure 7.7 *Longitudinal profile of the modelled part of the river from Árnes Rapids up to Búði Fall. The black dots on the riverbed mark out cross sections extracted from WMS. The blue line marks the water level in the river.*

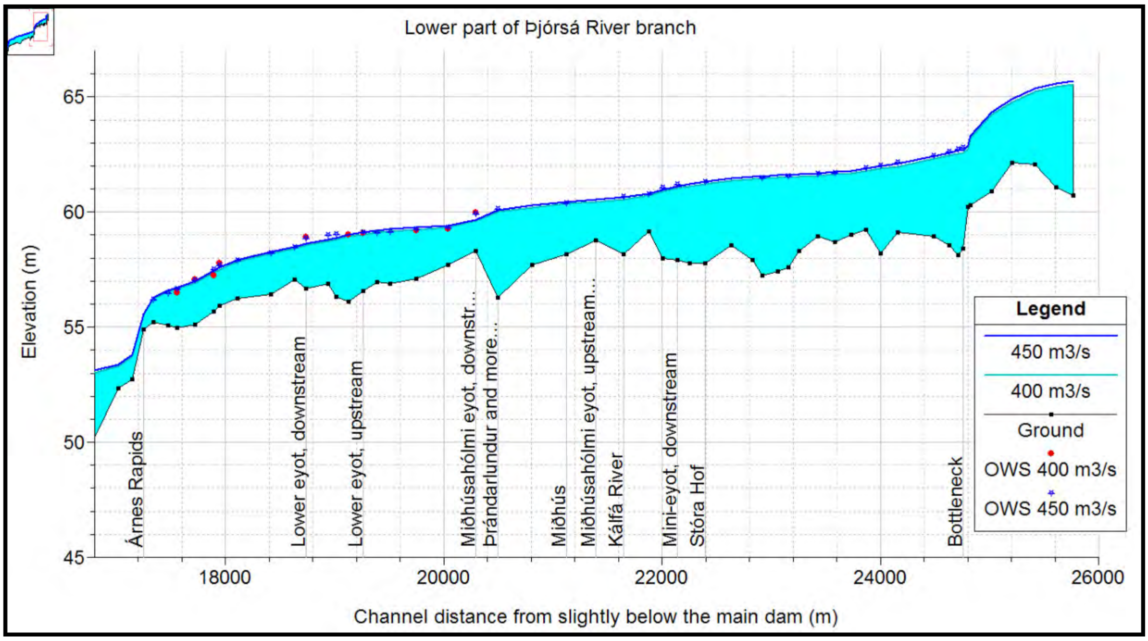

Figure 7.8 *Calibration of the lower part of the reach from Árnes Rapids up to Búði Fall. OWS stands for observed water surface.*

7.2.6 Árnes Rapids to Búði Fall, upper part.

In the upper part only the cross section measurements from 2008 are available for calibration as this part was not included in the longitudinal profile measurements. The discharge during the measurements was only about 260 m^3/s in the river, leaving only about 230 m^3/s in the reach in question.

Figure 7.9 shows how well the calculated water surface profile matches the measured water level in the cross sections for both discharges. The maximum difference for the cross sections is 29 cm, the average deviation from measured value is 12 cm and the standard deviation is 16 cm.

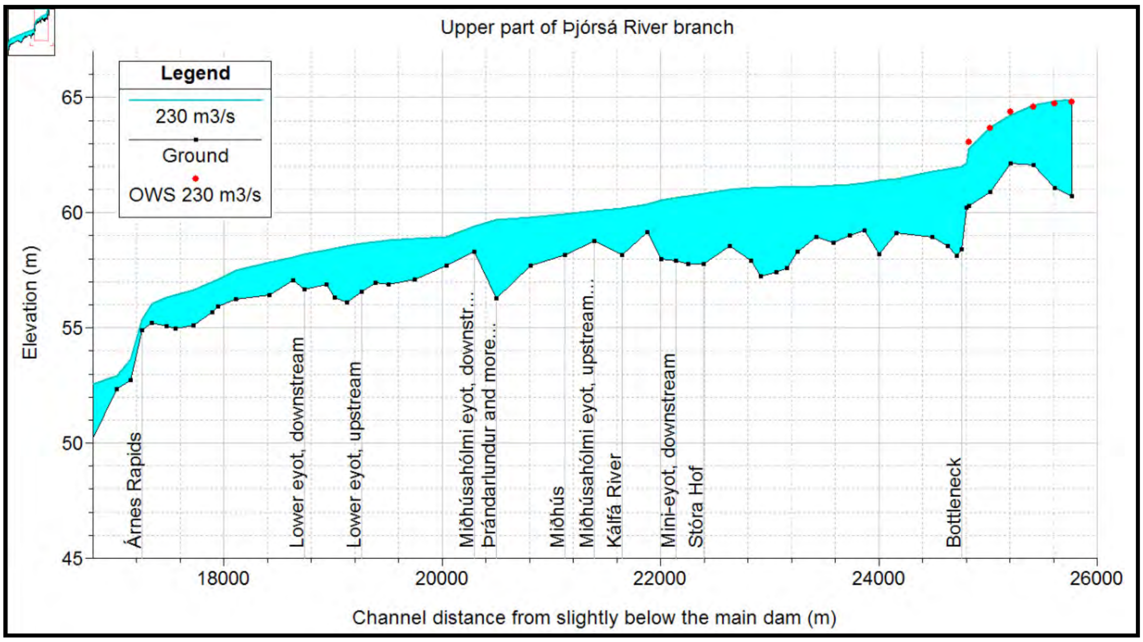

Figure 7.9 *Calibration of the reach from the bottleneck up to Búði Fall. OWS stands for observed water surface.*

The final calibrated value of n_b was in the range of 0,045-0,065, with an average value of 0,044. At first this seemed to be well above the usual limit of the Manning's n in the river but after some comparison to very rocky and steep rivers these values seemed to be all right if one assumes that the reach from the waterfall down to the bottleneck is very rough with the riverbed made of lava and big rocks. This is very plausible as this is a canyon below a waterfall with a bottleneck at its lower end thus probably trapping most of the big rocks created by the rivers formation of the waterfall through the centuries.

7.3 Calibration with ice – the ice variables

The Urriðafoss Ice Jam was used to calibrate the ice variables used in the model for Heiðarlón Ice Jam. However, it should be noted that there might be some difference between the ice variables at those two locations. The calibration is covered in appendix 2 and the results are as follows:

$n_i = 0{,}0302 * \ln(t) + 0{,}0445$ $\quad$ $p = 0{,}4$ $\quad$ $\phi = 45°$

Where n_i is Manning's n for the underside of the ice, t is the accumulation thickness, p_i is the ice jam porosity and ϕ, the angle of internal friction. In addition n_i was forced to be $\geq 0{,}02$.

As the values of the ice variables can have big influence on the calculated ice jam some experts abroad were contacted and consulted. The correspondence with them is included in the report in appendix 1. The result of this correspondence supported what was done and narrowed the range assumed possible for the variables.

7.4 Ice jam modelling

7.4.1 Modelling with expected variables

7.4.1.1 Heiðarlón Dam up to Árnes Rapids

Figure 7.10 shows the longitudinal profile of the river from the main dam site up to Árnes Rapids with and without ice jam formation for a discharge of 300 m^3/s. The grey area shows the location and height of the dike.

The minimum ice cover thickness in the model was set to 0,2 m in the whole river reach. Ice jam formation was allowed everywhere except in the lowest and highest cross-sections simply due to limitations in HEC-RAS. As the influence or the ice jam dies out in the reservoir quite a distance upstream of the dam, this limitation in the down stream end has no effect on the ice jam calculation.

At the upstream end the flow from the tailrace of Holt Powerstation would re-enter the river through the lower end of Árnes Branch. A small portion of the water used for ice diversion at Búði Fall, would run down the Þjórsá River Branch. The model only covers the reach up to Árnes Rapids and does not consider the effect of the small discharge flowing ice laden down the Rapids. This additional ice might add to the ice jam at the upstream end. But if the ice were to be stopped in the Þjórsá River Branch the ice would not affect the upper part of the ice jam as seen in this model.

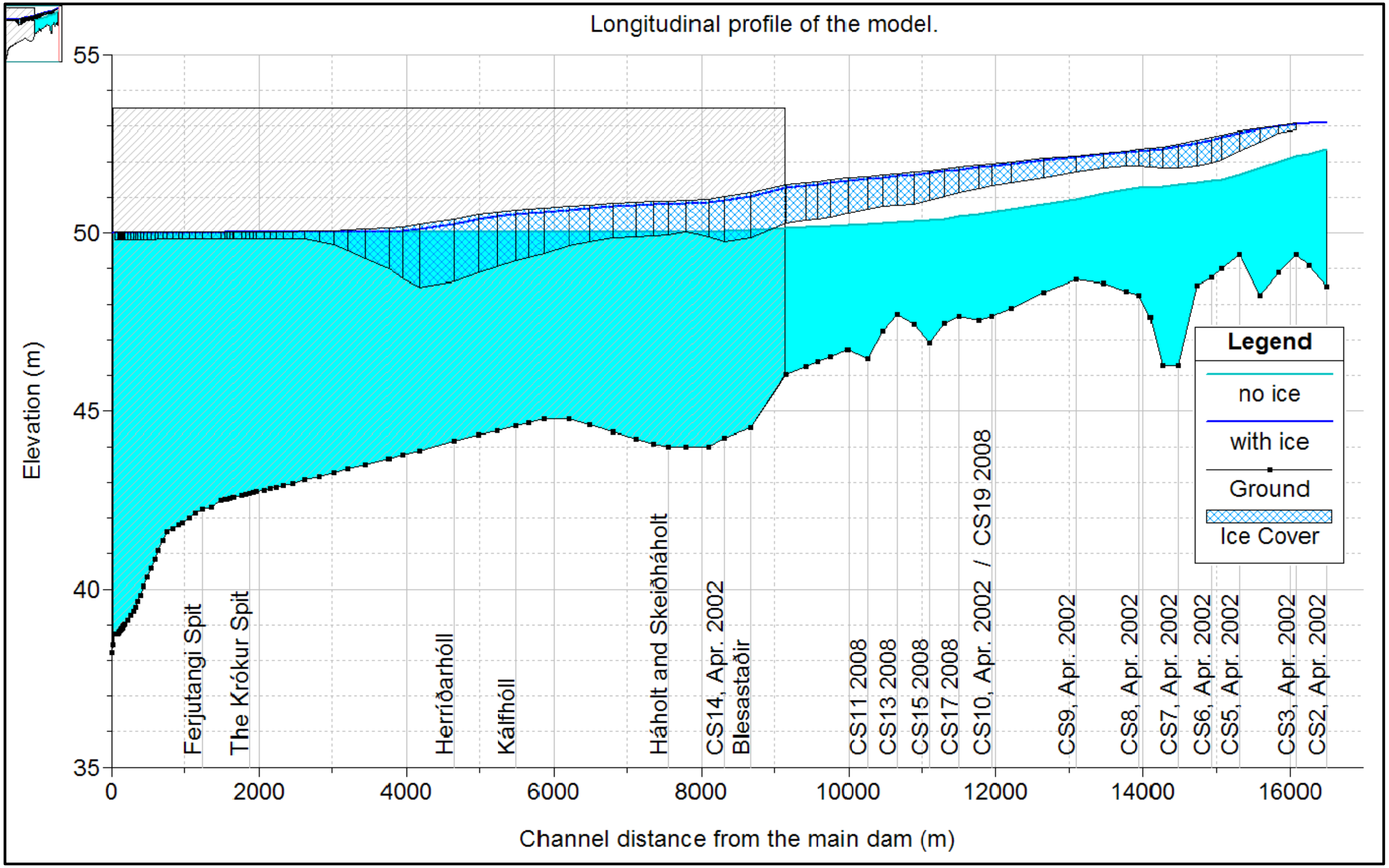

Figure 7.10 *The longitudinal profile of the expected equilibrium state of the Heiðarlón Ice Jam if only formed in the reach from the intake pond up to Árnes Rapids. The profile for open surface flow is included for comparison. The discharge is 300 m^3/s in both runs.*

The distance from Holt Powerstation to the upper end of the model is almost 3 km, the same as in the model for Hagalón Ice Jam. The energy head is much lower in Holt Powerstation than in Búrfell Powerstation so the temperature of the water might be slightly lower entering the tailrace in Holt Powerstation then at Búrfell. Nevertheless, ice formation would not start until some distance from the powerstation. Some ice might form in the tailrace above the upper end of the model and add slightly to the ice jam at its upper end. This would end in an equilibrium state slightly upstream of the upper end of the model within the tailrace leading to higher watersurface in the tailrace.

Manning's roughness factor, n_i, had to be iterated and the values ended in the range of 0,02-0,062 with the average value of 0,029. The water level rise due to the ice jam formation was on average 1,0 m, with the highest value of 1,3 m. The ice cover thickness got the average value of 0,9 m and the thickest part reached 1,8 m. Both averages do not include areas within the pond with no water level rise or with ice thickness equal to the given minimum.

The volume of ice in the ice jam is almost 8 Mm^3 including overbank ice, but around 3 Mm^3 without it. Figure 7.11 shows how far the water can spread due to higher waterlevel caused by the ice jam.

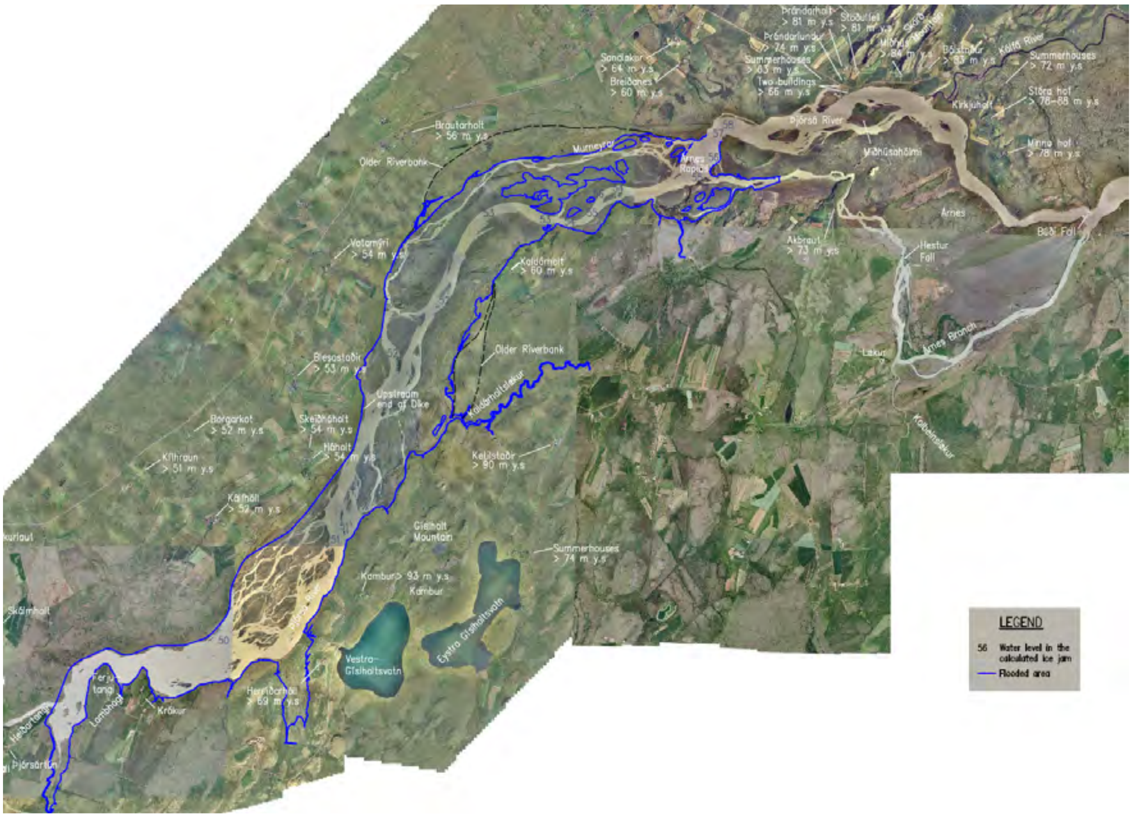

Figure 7.11 *Overview of how high the water can rise due to a continuous wide river ice jam reaching all the way up to the shallows below Árnes Rapids. Discharge 300 m^3/s. An A3 version of this figure can be found at the end of this report before the Appendixes.*

7.4.1.2 Heiðarlón Dam up to Búði Fall

Figure 7.12 shows the longitudinal profile of the river from Heiðarlón Dam up to Búði Fall with and without ice jam formation for a discharge of 300 m^3/s. In this case Holt Hydroelectric Project has not been built and it is assumed that Árnes Branch will almost freeze over resulting in all the discharge flowing in Þjórsá River. It is also assumed that the ice jam formed in the river up to the pool below Búði Fall will be a wide river ice jam formation.

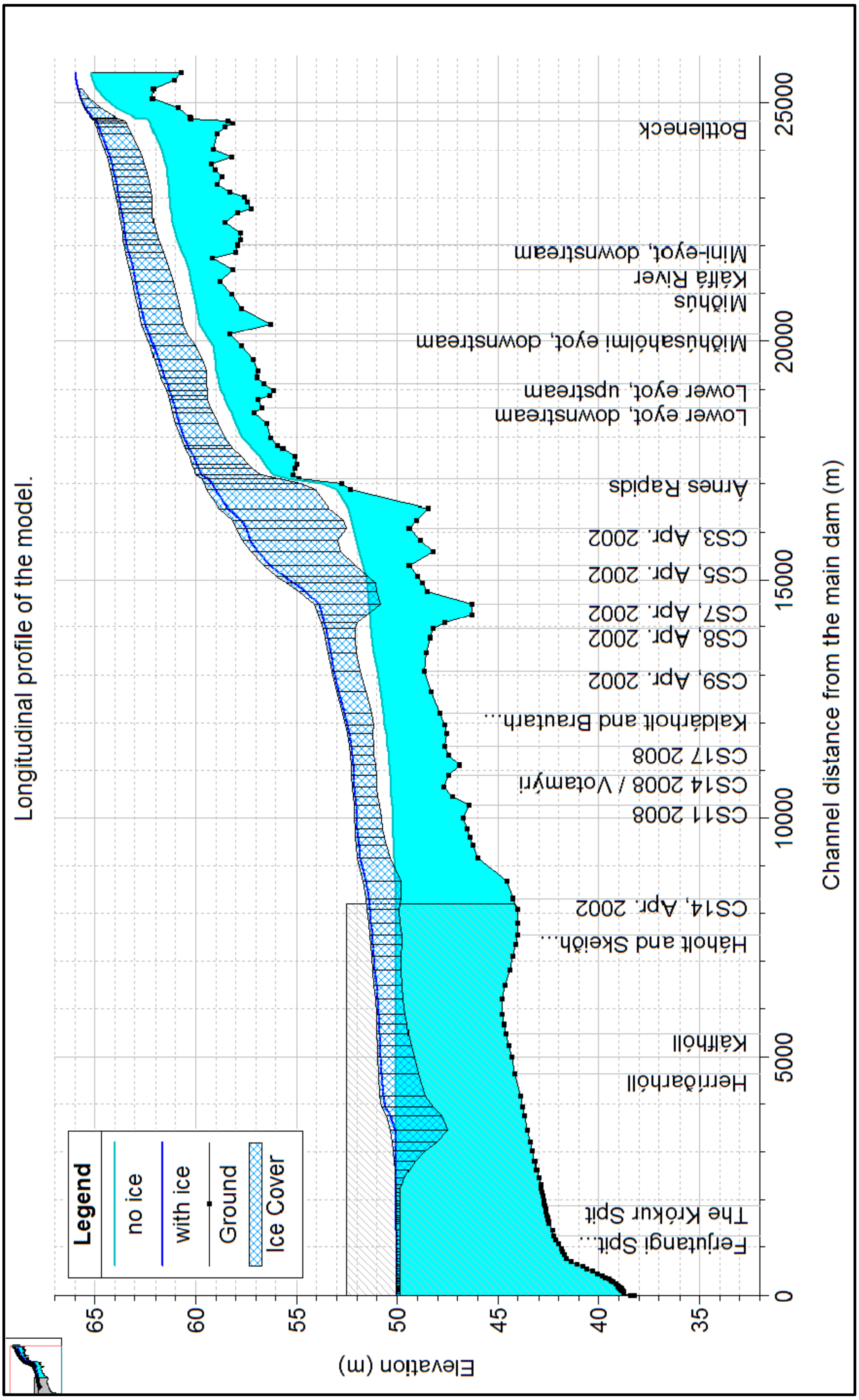

Figure 7.12 *The longitudinal profile of the expected equilibrium state of the Heiðarlón Ice Jam if allowed to reach all the way upp to the pool below Búði Fall. The profile for open surface flow included for comparison. The discharge is 300 m^3/s.*

Given enough ice flow the ice jam might grow more than this but as the calibration of Urriðafoss Ice Jam showed, the ice jam would change from a wide river ice jam to a combination of hanging dam and a wide river ice jam after it has reached the pool below the waterfall. So the model only works up to the pool below the waterfall. Later in this chapter the possibility of a bigger ice jam will be addressed based on possible ice formation in the reach above and the formation of a hanging dam in the reach below Búði Fall.

The minimum ice cover thickness in the model was set to 0,2 m in the whole river reach. Ice jam formation was allowed everywhere except in the lowest and highest cross-sections simply due to limitations in HEC-RAS. As the influence or the ice jam dies out in the reservoir quite a distance upstream of the dam, this limitation in the down stream end has no effect on the ice jam calculation. At the upper end the possibility of the formation of a hanging dam has to be kept in mind.

Manning's roughness factor, n_i, had to be iterated and the values ended in the range of 0,02-0,096 with the average value of 0,049. The water level rise due to the ice jam formation was on average 2,4 m, not including the part of the intake pond where there was almost no waterlevel rise. The highest water level rise was calculated as 6,0 m. The ice cover thickness got the average value of 2,1 m, the thickest part reached 5,5 m and the thinnest got the minimum value given beforehand.

The volume of ice in the calculated ice jam was about 22 Mm^3 if all is included, but about 10 Mm^3 if only the ice in the main channel is counted. Figure 7.13 shows how far the water can spread due to higher waterlevel caused by the ice jam.

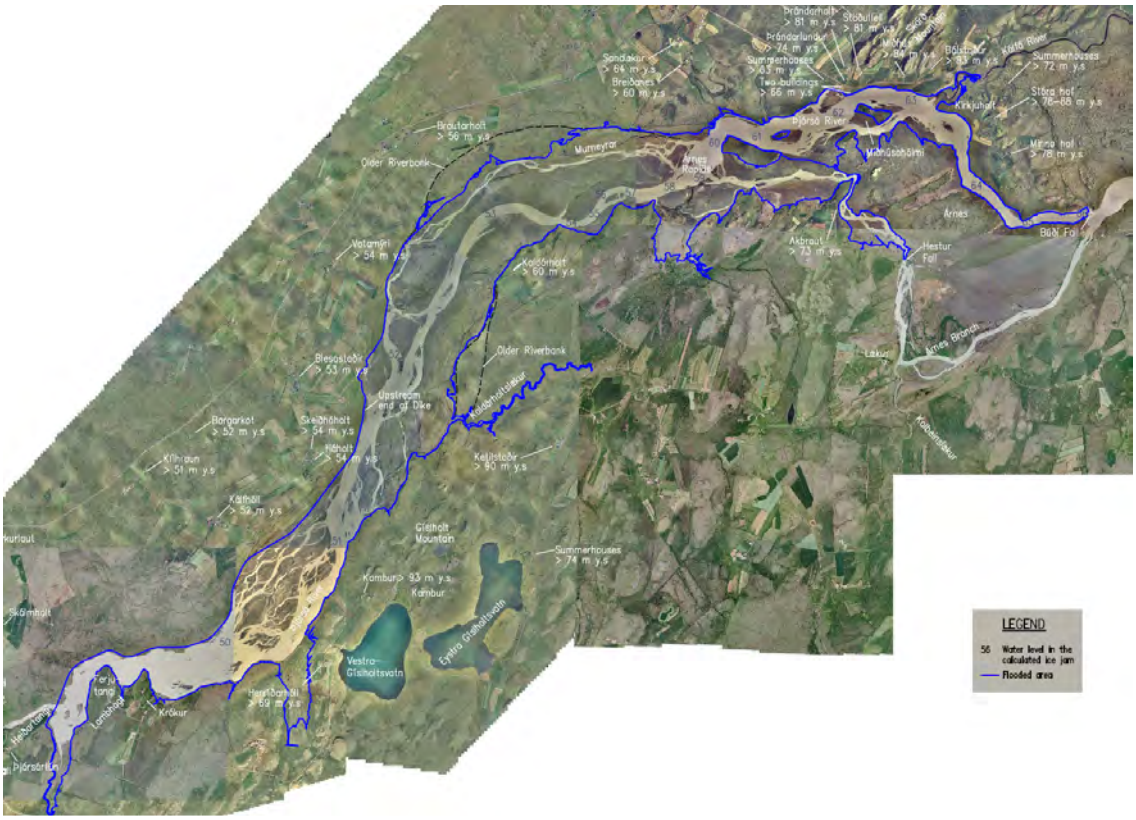

Figure 7.13 *Overview of how high the water can rise due to a continuous wide river ice jam reaching all the way up to the pond below Búði Fall. Discharge 300 m^3/s. An A3 version of this figure can be found at the end of this report before the Appendixes.*

7.4.1.3 Events

Table 7.2 gives examples of ice production capability of the reach above the upper end of the Heiðarlón Pond during four periods if the surface would stay open the whole time. The heat loss was taken from a report on ice survey in Upper Þjórsá River (Sigmundur Freysteinsson, 1972). The periods picked were severe cold periods.

Table 7.2 *Examples of calculated ice production during cold spells.*

	Ice production over the whole period in Mm^3		
	per 0,9 km^2.	per 3,8 km^2.	per 8,7 km^2.
21. Feb. – 27. Marz 1965	3	12	26
6. Dec. 1962 – 22. Feb. 1963	7	29	67
4. Dec. 1957 – 14. Marz 1958	12	52	119
8. Nov. 1950 - 20. April 1951	18	74	169

Assuming current construction order, chapter 7.4.1.1, and that the ice diverted into the Þjórsá River Branch at Árnes stays above Árnes Rapids, the open water surface producing ice for the Heiðarlón Ice Jam could only come from an area of approximately 1 km^2. Column two in Table 7.2 shows how much ice that area could produce during the four events, if the surface would stay open the whole time. The amount is of similar order as the ice in the calculated ice jam. The development of the ice jam would then be fast in the beginning, when the open water surface is bigger, and then slower and slower until it would reach a location where no ice would form in the water coming from Holt Powerstation. In this case the severity of the ice production period would not matter as the open water surface would be closed down with time and the growth of the ice jam would stop. The severity of the cold period would only influence how fast the ice jam would develop.

If the ice skimmed and diverted at Búði Diversion structure would not stop upstream of Árnes Rapids, more ice would be added to the ice jam and it could possibly grow up Árnes Rapids and further.

If only Hvammur and Urriðafoss Hydroelectric Projects would be constructed, the open surface area above Heiðarlón Pond would be approximately 3,8 km^2. Column three in Table 7.2 shows how much ice could be produced if the open water surface would stay the same the whole time. The lowest numbers are similar to the ice in the calculated ice jam, see chapter 7.4.1.2, but the highest one is much higher. In the other scenarios, already covered in this report, the difference in magnitude between the volume of possible ice production and ice volume in the calculated ice jams has not been important. The reason is that the model covered the whole reach contributing to ice production. This meant that:

a) If the production volume was higher than the volume of the calculated ice jam, the open area would soon be covered with ice thus stopping the ice production and the reach in question would be in equilibrium.
b) If the volume of the calculated ice jam was higher, then the ice jam would stop growing when the cold spell lifted and the event was over. Thus again reaching an equilibrium state.

In this case, however, the model does not cover the whole reach contributing ice to the ice jam. When the calculated ice jam has reached the pool below Búði Fall we simply stopped calculating. In reality the open surface from the tailrace from Hvammur Powerstation down to Búði Fall would continue producing more ice that would have no alternative other than flowing down Búði Fall creating a hanging dam. In that case the possibility of a bigger ice jam in the reach between Árnes Rapids and Búði Fall is very relevant. The ice jam would most probably change from a wide river ice jam to a hanging dam and would be able to rise much higher than in the figure shown, probably up to and slightly above the edge of the waterfall and from there upstream to Þjórsárholt. How high the ice jam might rise under these circumstances has to be estimated by other means than with a model in HEC-RAS, as the software can not model a hanging ice dam.

If only Urriðafoss Hydroelectric Project would be constructed, the open surface area above Heiðarlón Pond would be approximately 8,7 km^2. Column four in Table 7.2 shows how much ice could be produced if the open water surface would stay the same the whole time. Almost the same applies for this case as for the case only with Hvammur and Urriðafoss Hydroelectric Projects. The only difference is that as the open water surface area is larger without Hagalón Pond, the ice jam would grow much faster, leading to higher possibility of the ice jam exceeding the calculated ice jam in Figure 7.12.

7.4.2 Structures or things of interest close to the river

The west bank dike is a part of the Urriðafoss Hydroelectric Project, shown on all the profile figures as gray hatched area. Its location has been changed from its originally planned location since the model was made. The difference can be seen in Figure 7.1 where the cross section lines for the model pass over the dike in stead of ending there. This could change the results slightly but shouldn't change much. Its design height is 52,5 m a.s.l. Figure 7.14 and Figure 7.15 show the longitudinal profile of the modelled river reach where the banks have been added as reference as well as the design flood for the Hydroelectric Project. In Figure 7.14 the west bank has been added as two lines. The lower one represents the current riverbank while the upper one shows the older riverbank, see Figure 7.16 for the location of the upper and older riverbank. The reason for this division between upper and lower banks is that the river has been utilised and its flow regulated for powerstations. Before, it was very alluvial and as such had a very wide channel with many constantly changing branches. Dams in the upper reaches have limited the sediment flow. This triggered erosion in the downstream reaches. In Lower Þjórsá the degradation has created a relatively stable, usually single, channel into its former alluvial riverbed. Some parts of its former channel have not been flooded for a long time or very seldom in recent years and are now vegetated. These parts do no longer look like a river channel.

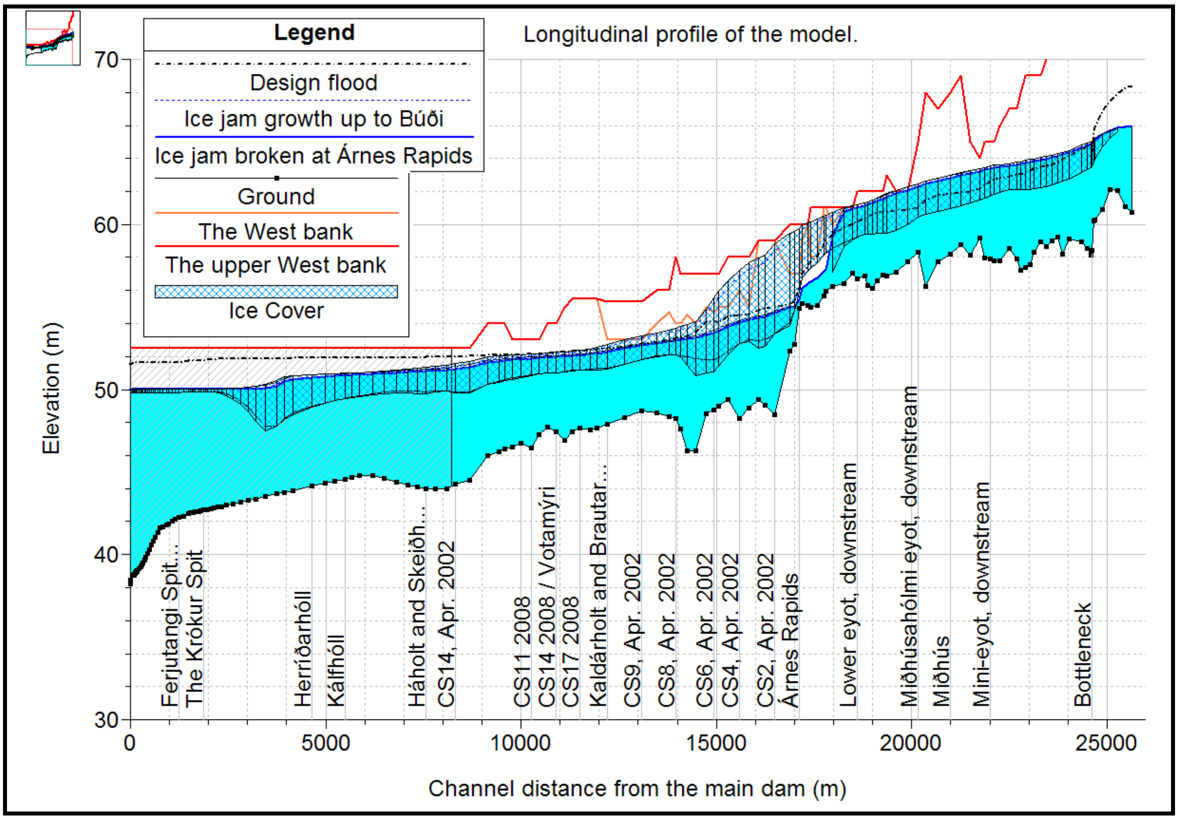

Figure 7.14 *The West Bank of the river with the longitudinal profile of two freeze-up ice jams and the design flood as a comparison.*

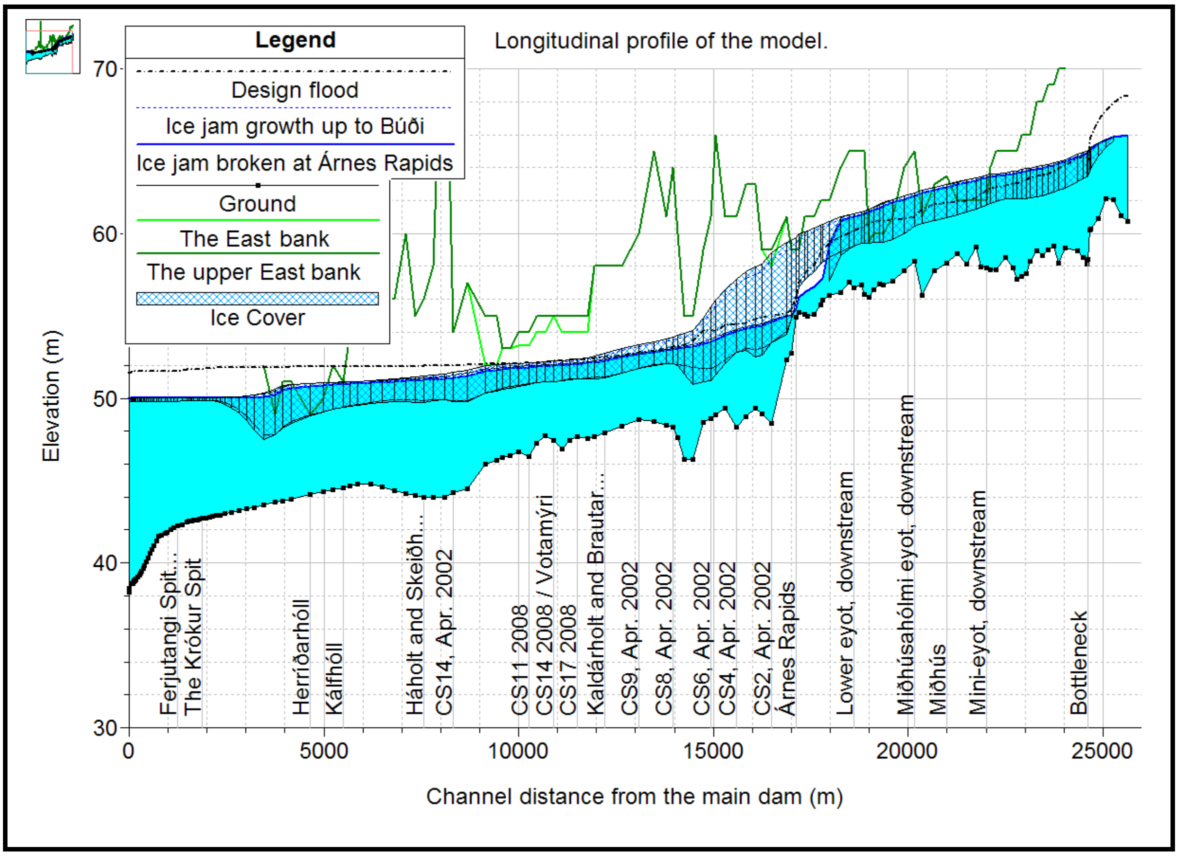

Figure 7.15 *The East Bank of the river with the longitudinal profile of two freeze-up ice jams and the design flood as a comparison.*

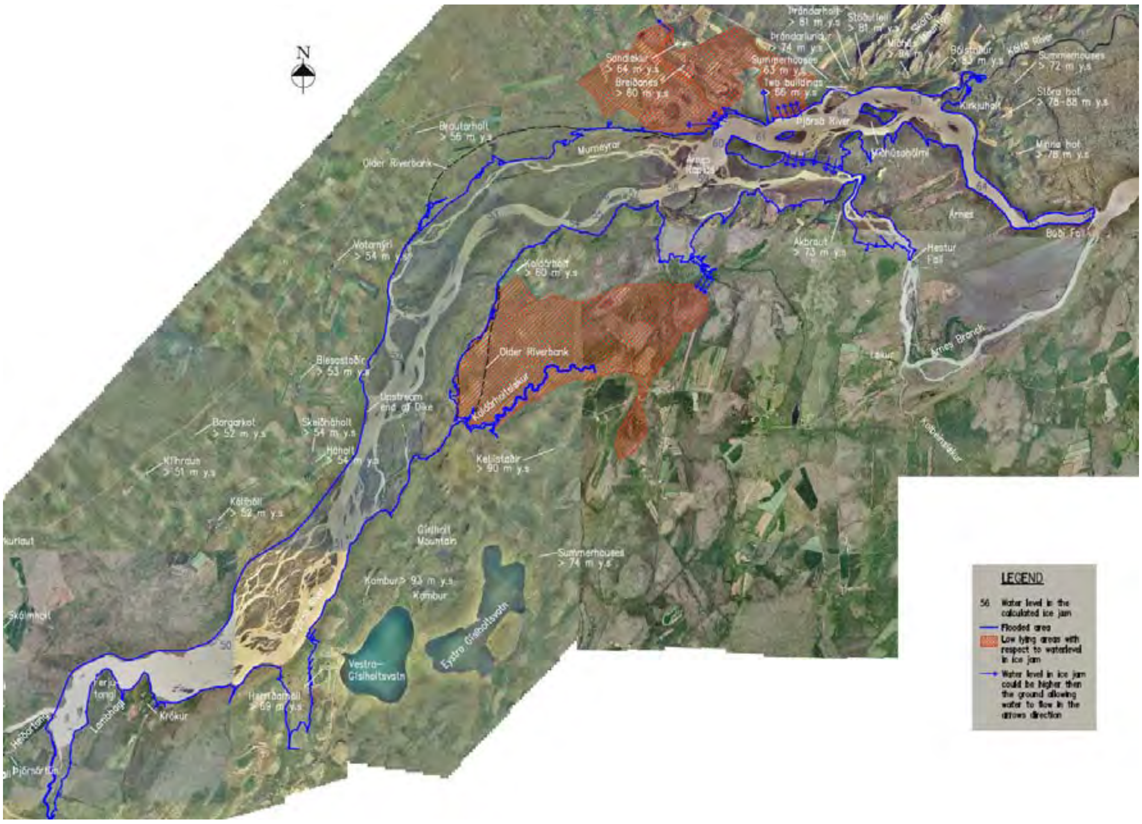

Figure 7.16 *Possible location of overflow. An A3 version of this figure can be found at the end of this report before the appendixes.*

The waterlevel within the ice jam shown in Figure 7.10 would, in all locations, be below the banks. The waterlevel in Figure 7.12, on the other hand, is critical in some places. In figures 7.14 and 7.15 the banks have been added to Figure 7.12. Additionally the design flood was added as well as the ice jam that would form if the ice jam in figure 7.12 would be divided at Árnes Rapids, i.e. ice retention works stopping most of the ice above Árnes Rapids dividing the ice jam into two less severe parts.

In Figure 7.16, arrows show where the water might flow over the banks. Behind some of the arrows areas lower than the point of flooding are marked. Those areas do not represent flooded areas as very little water is expected to flow over the banks and that water would always run down hill and soon find some draining canals or small brooks to flow in. At the west bank water would flow over the lower banks at Murneyrar, but not over the upper bank. Above Árnes Rapids water would flow into draining canals. The main draining canal opens into the river there but the canal has a gate so as long as the gate is fully closed, water would only flow into the smaller canals. At two locations, between Miðhúsahólmi Island and Árnes Rapids the height of the banks could be critical but it is more likely that the land is some 20-40 cm higher.

At the upstream end of the dike the waterlevel in the ice jam is less than a meter below the top of the dike.

At the east bank, water would flow into the low area below Herríðarhóll Farm. This area might be sealed of with a dike. A short distance upstream from Kaldárholtslækur water can flow over the lower bank but not over the upper bank. At Árnes Rapids and upstream of the rapids, water can flow over the Árnes Island at some locations, see the arrows, and in some cases small parts of the island can be flooded.

Both calculated freeze-up ice jams should not cause any flooding problems assuming the ice is adequately represented by the model and the parameters used. Ice retention above Árnes Rapids would be beneficial. All new building plans close to the river should take the possibility of ice jams into account, especially at Árnes Island.

The location of farms and summer houses close to the river can be seen on Figure 7.16. All the buildings were above the waterlevel in the ice jam. Above Árnes Rapids most farms were well above the waterlevel in the ice jam. Close to Miðhúsahólmi there is a summer house that lies a little over a meter above the bigger calculated ice jam. Breiðanes Farm is the only farmhouse in this area that lies relatively low compared to the waterlevel in the big ice jam. Additionally it is located close to the area where water might both flow over the bank and into the draining canals. On the other hand a brook runs past the farm that might possibly carry excess water.

The location of possible ice retention structures above Árnes Rapids has to take the location and height of this farm into account, i.e. has to be located above the place were water might flow over the banks.

Below Árnes Rapids both Votamýri farm and Blesastaðir farm lie little over a meter above the waterlevel in the possible ice jam. This might indicate the need of adding to the dike and making it higher at its upstream end or at least a good surveyance to start with.

8 Conclusions

Calibration of the Urriðfoss Ice Jam showed that the ice jam feature in HEC-RAS software can be used to model wide river ice jams in Þjórsá River as long as the river reach modelled does not include waterfalls or too steep parts.

The model for the Hagalón Ice Jam gave an average waterlevel rise of 90 cm due to the freeze-up ice jam with discharge steady at 300 m^3/s. The highest waterlevel rise reached 1,5 m. A break up ice jam was also tested with an underlying flood of 1500 m^3/s. The waterlevel rise in this case was much higher than in the freeze-up ice jam, but still similar to the waterlevel rise due to the design flood. In this case the water level rise at the upstream end of the dike is only one meter lower than the top of the dike. It has to be considered whether this is acceptable or not. Additionally the highway is designed too low over about 3 km and should be lifted higher or it might be flooded in the case of break-up ice jam. This problem might be limited by using an ice boom.

The model for the Heiðarlón Ice Jam up to Árnes Rapids gave an average water level rise of 1 m based on freeze-up ice jam with discharge steady at 300 m^3/s. The highest value calculated was 1,3 m. A break up ice jam was not tested.

The reach up to Búði Fall was then added to the model. Model-runs were made assuming that the upper powerstations were not constructed first, and that the Árnes Branch would freeze over forcing all water to run down the Þjórsá River at Árnes. The calculated ice jam was much bigger than the one for the lower branch only. The average water level rise was 2,4 m with the highest reaching 6 m just below the Árnes Rapids. As the rapids are a steep portion in the river the question rises whether or not the ice jam is still a wide river ice jam below the rapids. The waterlevel rise of 6 m just below the rapids is the same as noted on a map in an article by Sigurjón Rist (Sigurjón Rist, 1962), but downstream of that location the map gives 4 m water level rise while the model calculates around 2 m. It is quite possible that below the rapids the ice jam might change from being a wide river ice jam into a hanging dam. This can be avoided if the ice is trapped in the river above the rapids.

Similarly, in the channel from the Árnes Rapids up to Búði Fall, the ice jam can be modelled as a wide river ice jam as it grows up to the pond below the waterfall but then it might change its character and start to behave like a hanging ice dam. This could also be avoided if ice would be trapped at some location upstream of the waterfall.

The models, for both locations, give good information about what can be expected but their limitations have to be kept in mind.

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Figures in A3

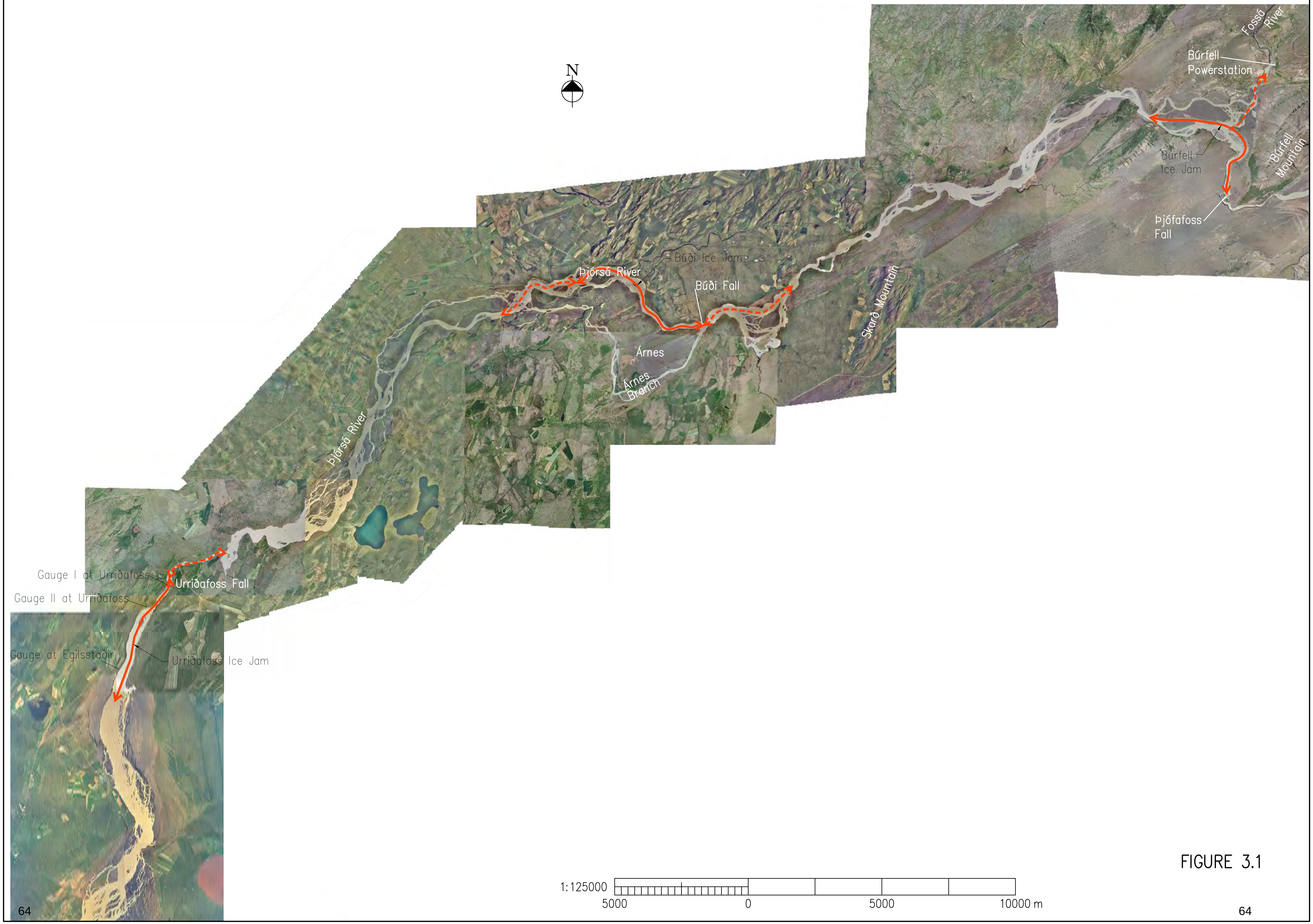
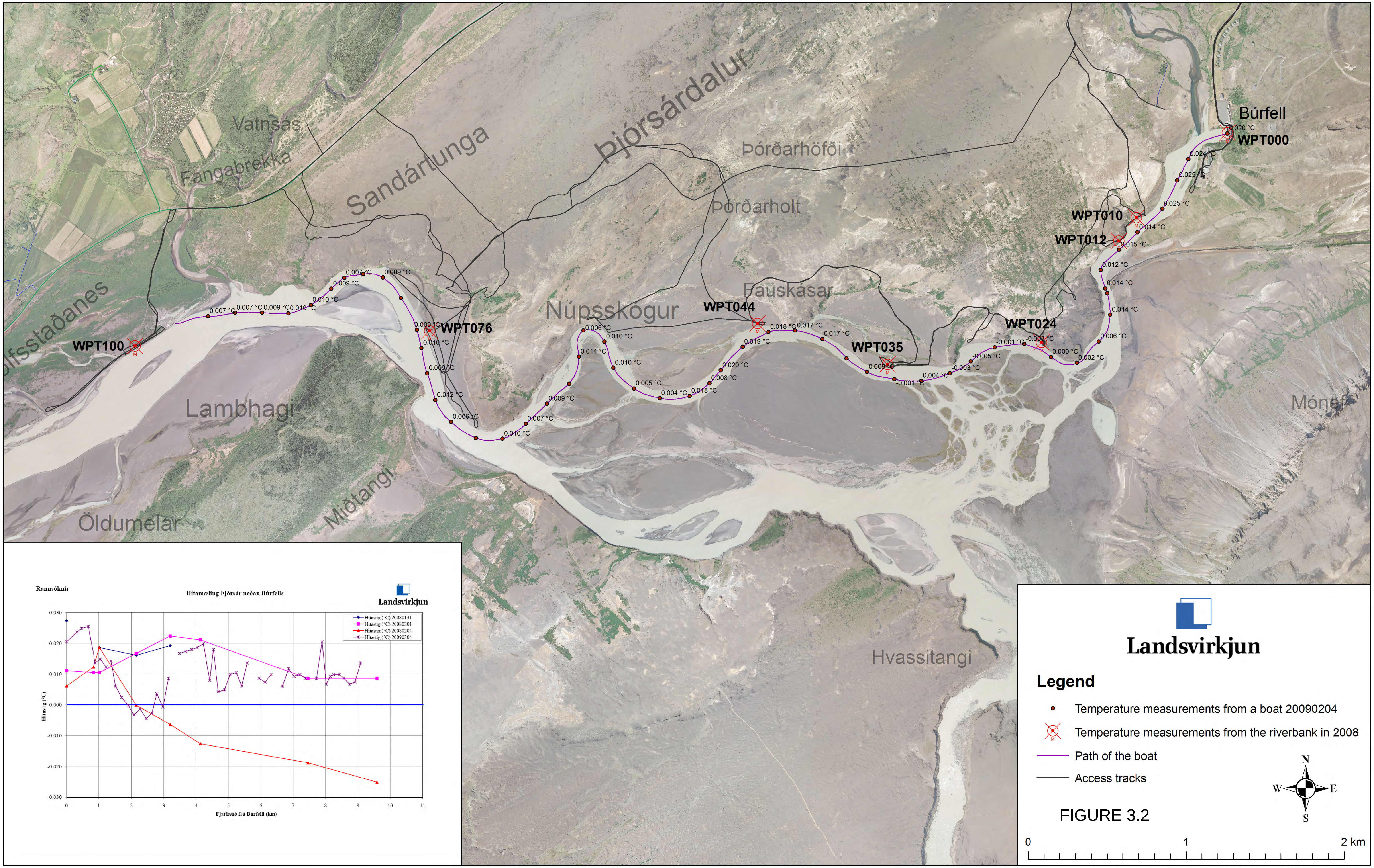

N
Fossá River
Búrfell Powerstation
Búrfell Ice Jam
Búrfell Mountain
Þjófafoss Fall
Búði Ice Jam
Þjórsá River
Búði Fall
Skarð Mountain
Árnes
Árnes Branch
Þjórsá River
Gauge I at Urriðafoss
Urriðafoss Fall
Gauge II at Urriðafoss
Gauge at Egilsstaðir
Urriðafoss Ice Jam
1:125000
5000
0
5000
10000 m

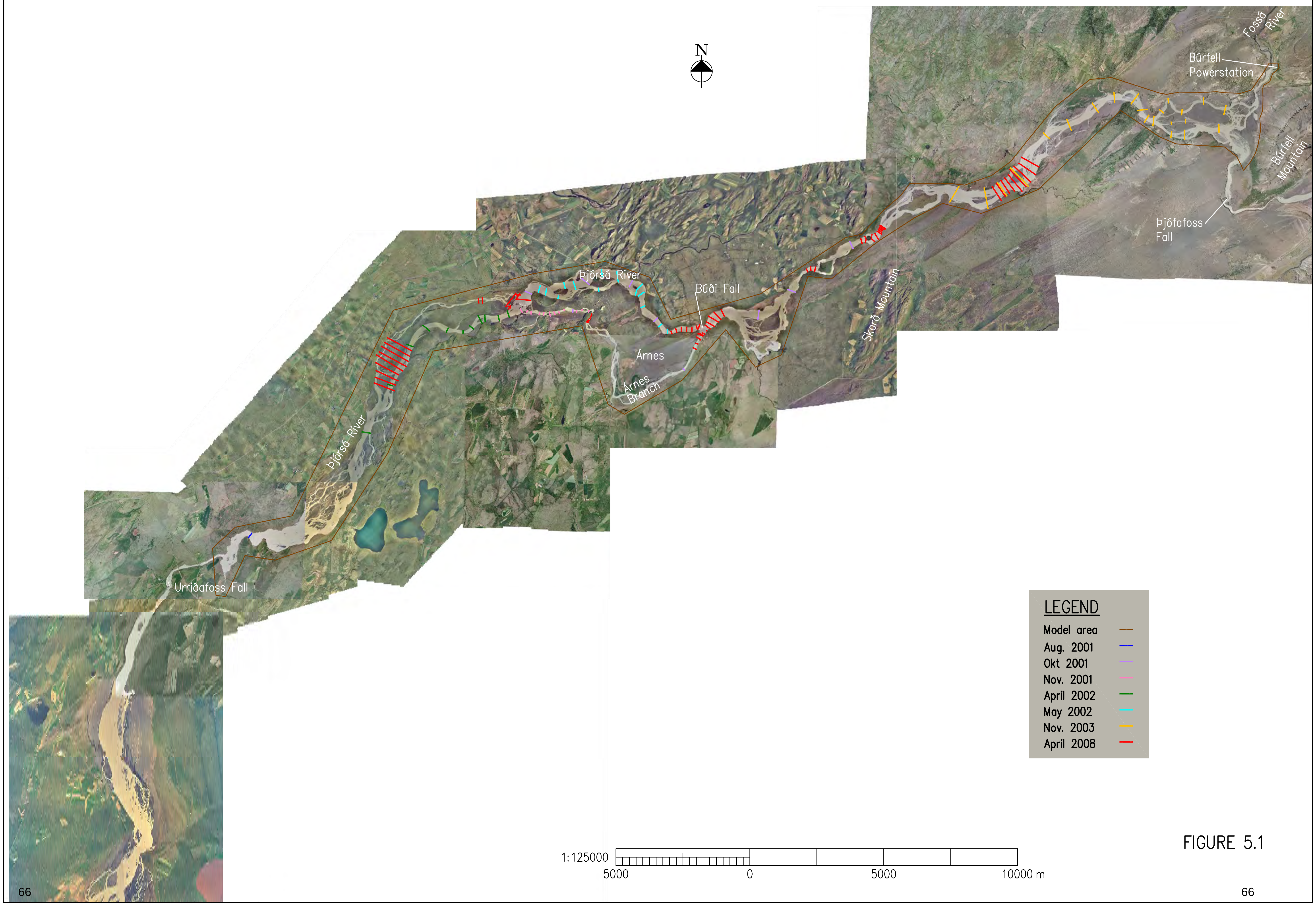
FIGURE 3.1

64

Temperature measurements in Þjórsá downstream of Búrfell



Map Document: (F:\LUK\Victor\Thjorsa\Isamal\Hitam i Thjorsa nedan Burfells_2009 e.mxd)
9.1.2010 -- 12:19:58


N
Fossá River
Búrfell Powerstation
Búrfell Mountain
Þjófafoss Fall
Skarð Mountain
Þjórsá River
Búði Fall
Árnes
Árnes Branch
Þjórsá River
Urriðafoss Fall
LEGEND
Model area
Aug. 2001
Okt 2001
Nov. 2001
April 2002
May 2002
Nov. 2003
April 2008
1:125000
5000
0
5000
10000 m
FIGURE 5.1

66

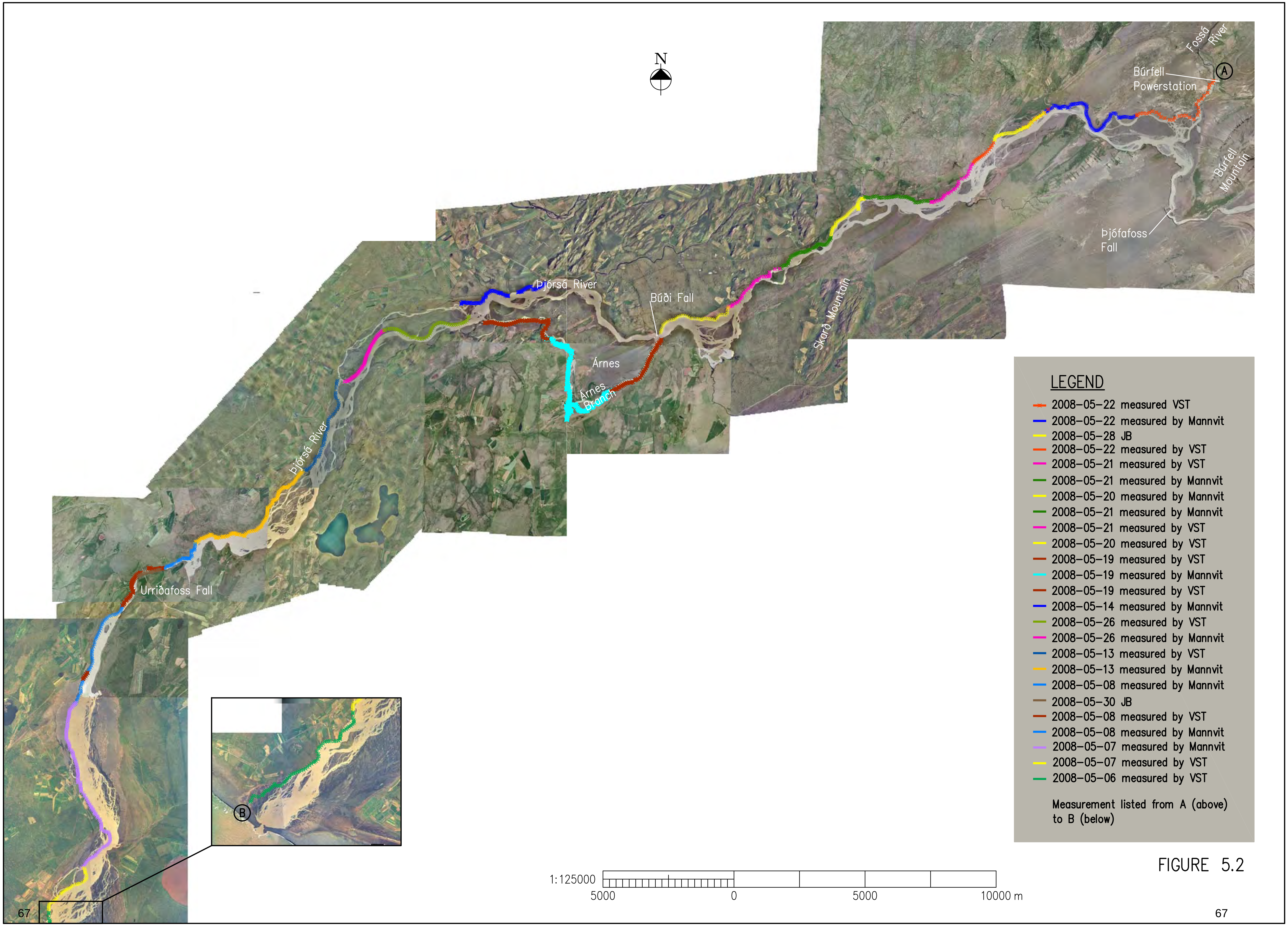

N
Fossá River
Búrfell Powerstation
A
Búrfell Mountain
Þjófafoss Fall
Skarð Mountain
Búði Fall
Þjórsá River
Árnes
Árnes Branch
Þjórsá River
Urriðafoss Fall
B
LEGEND
2008–05–22 measured VST
2008–05–22 measured by Mannvit
2008–05–28 JB
2008–05–22 measured by VST
2008–05–21 measured by VST
2008–05–21 measured by Mannvit
2008–05–20 measured by Mannvit
2008–05–21 measured by Mannvit
2008–05–21 measured by VST
2008–05–20 measured by VST
2008–05–19 measured by VST
2008–05–19 measured by Mannvit
2008–05–19 measured by VST
2008–05–14 measured by Mannvit
2008–05–26 measured by VST
2008–05–26 measured by Mannvit
2008–05–13 measured by VST
2008–05–13 measured by Mannvit
2008–05–08 measured by Mannvit
2008–05–30 JB
2008–05–08 measured by VST
2008–05–08 measured by Mannvit
2008–05–07 measured by Mannvit
2008–05–07 measured by VST
2008–05–06 measured by VST
Measurement listed from A (above) to B (below)
1:125000
5000
0
5000
10000 m
67

FIGURE 5.2

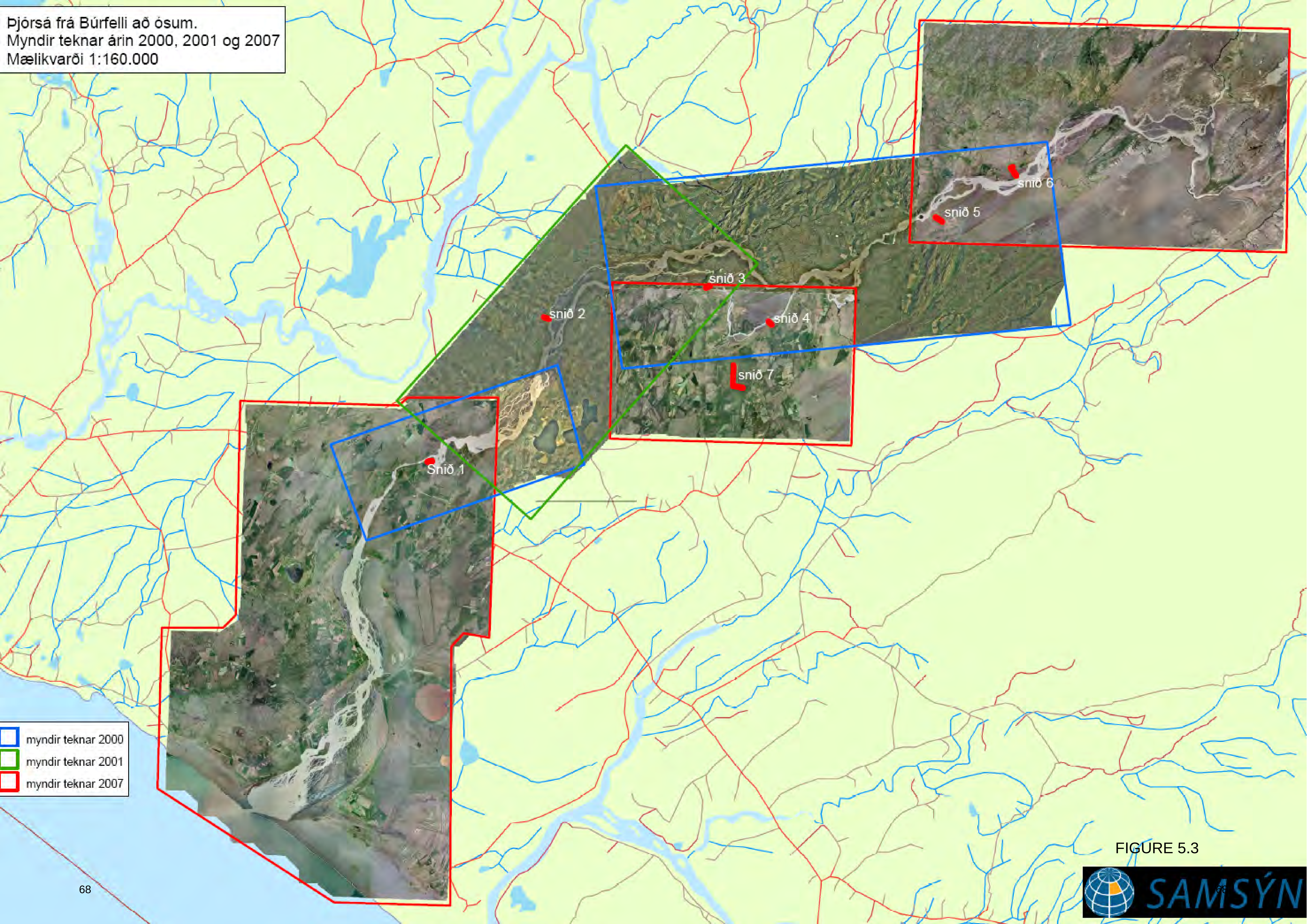

Þjórsá frá Búrfelli að ósum.
Myndir teknar árin 2000, 2001 og 2007
Mælikvarði 1:160.000
snið 6
snið 5
snið 3
snið 2
snið 4
snið 7
Snið 1
myndir teknar 2000
myndir teknar 2001
myndir teknar 2007
SAMSÝN

FIGURE 5.3

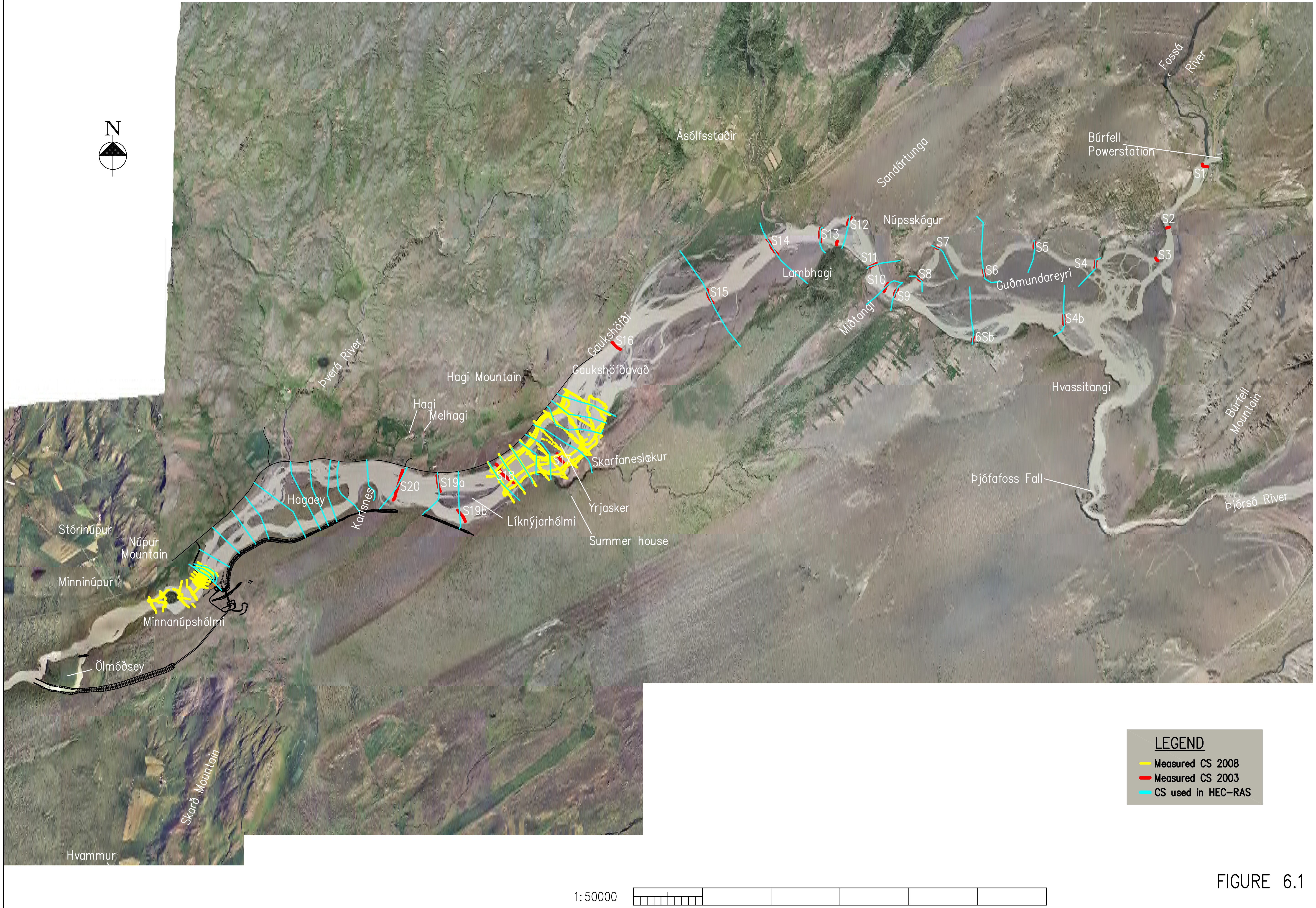

N
Fossá River
Búrfell Powerstation
Ásólfsstaðir
Sandártunga
Núpsskógur
S1
S2
S3
S4
S4b
S5
S6
6Sb
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
S19a
S19b
S20
Lambhagi
Guðmundareyri
Miðtangi
Gaukshöfði
Gaukshöfðavað
Hvassitangi
Búrfell Mountain
Þjófafoss Fall
Þjórsá River
Þverá River
Hagi Mountain
Hagi
Melhagi
Skarfaneslækur
Yrjasker
Summer house
Líknýjarhólmi
Karlsnes
Hagaey
Stórinúpur
Núpur Mountain
Minninúpur
Minnanúpshólmi
Ölmóðsey
Skarð Mountain
Hvammur
LEGEND
Measured CS 2008
Measured CS 2003
CS used in HEC-RAS
1:50000
1000
0
1000
2000
3000
4000
5000 m

FIGURE 6.1

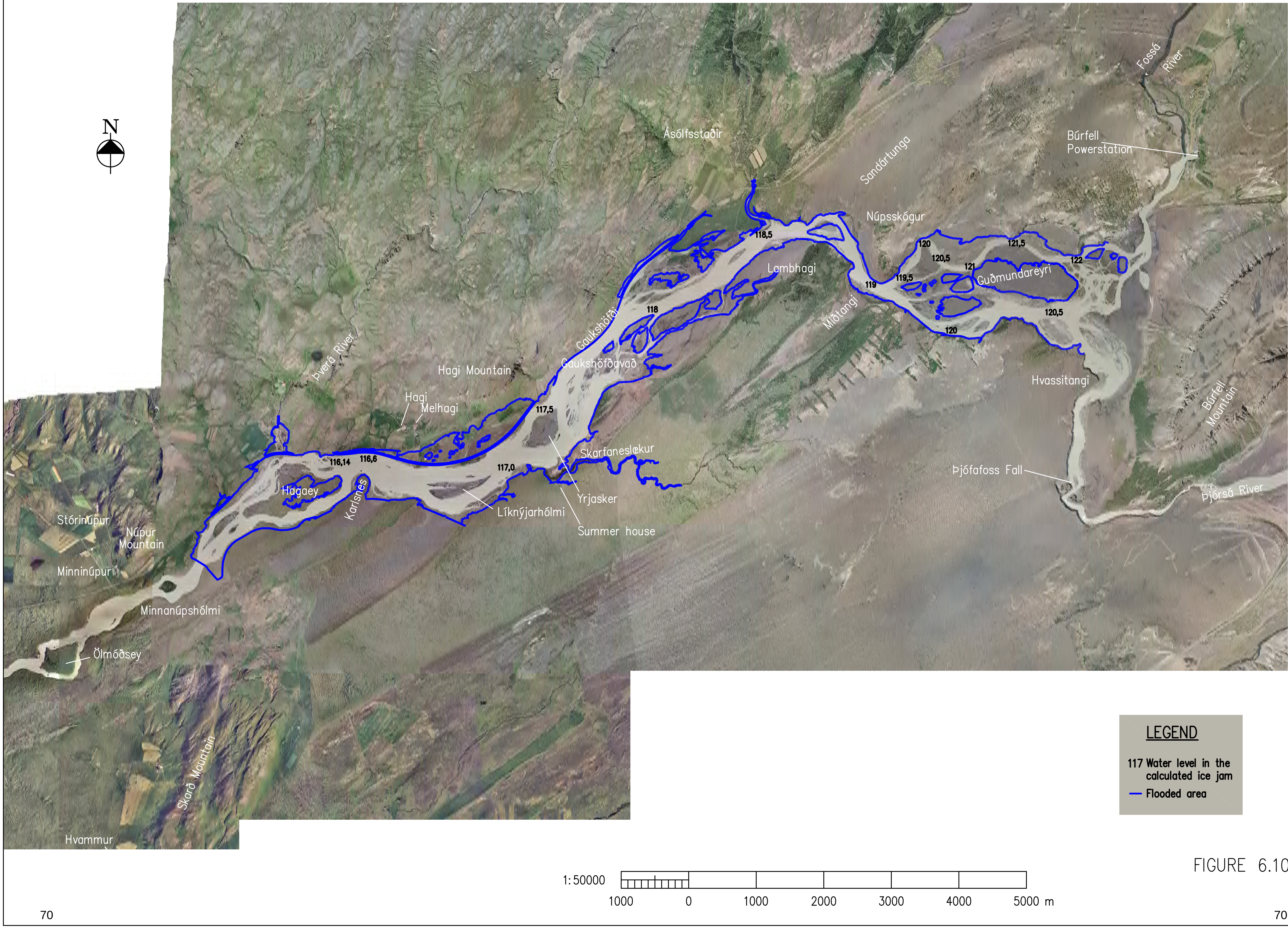


FIGURE 6.10

70

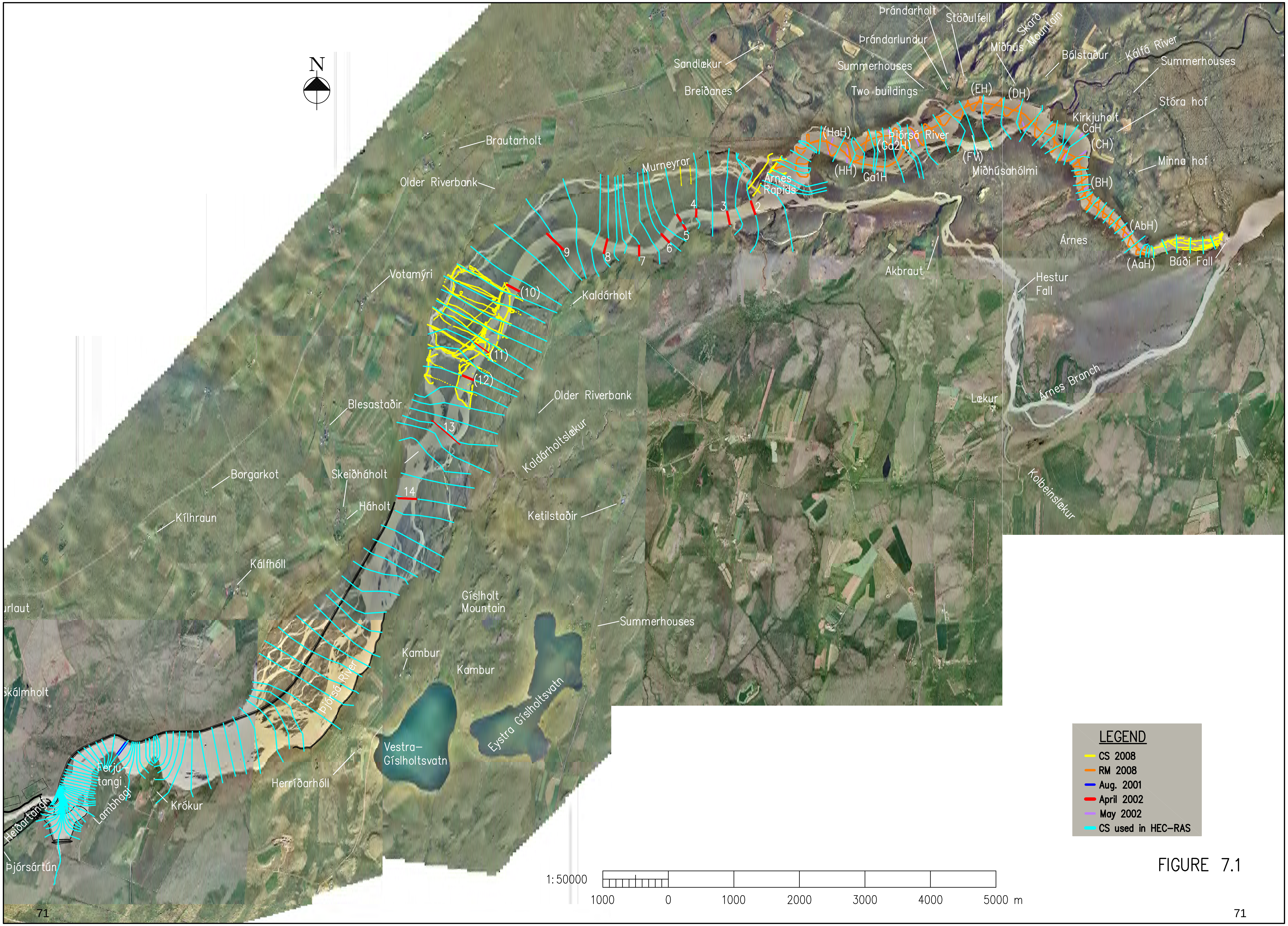
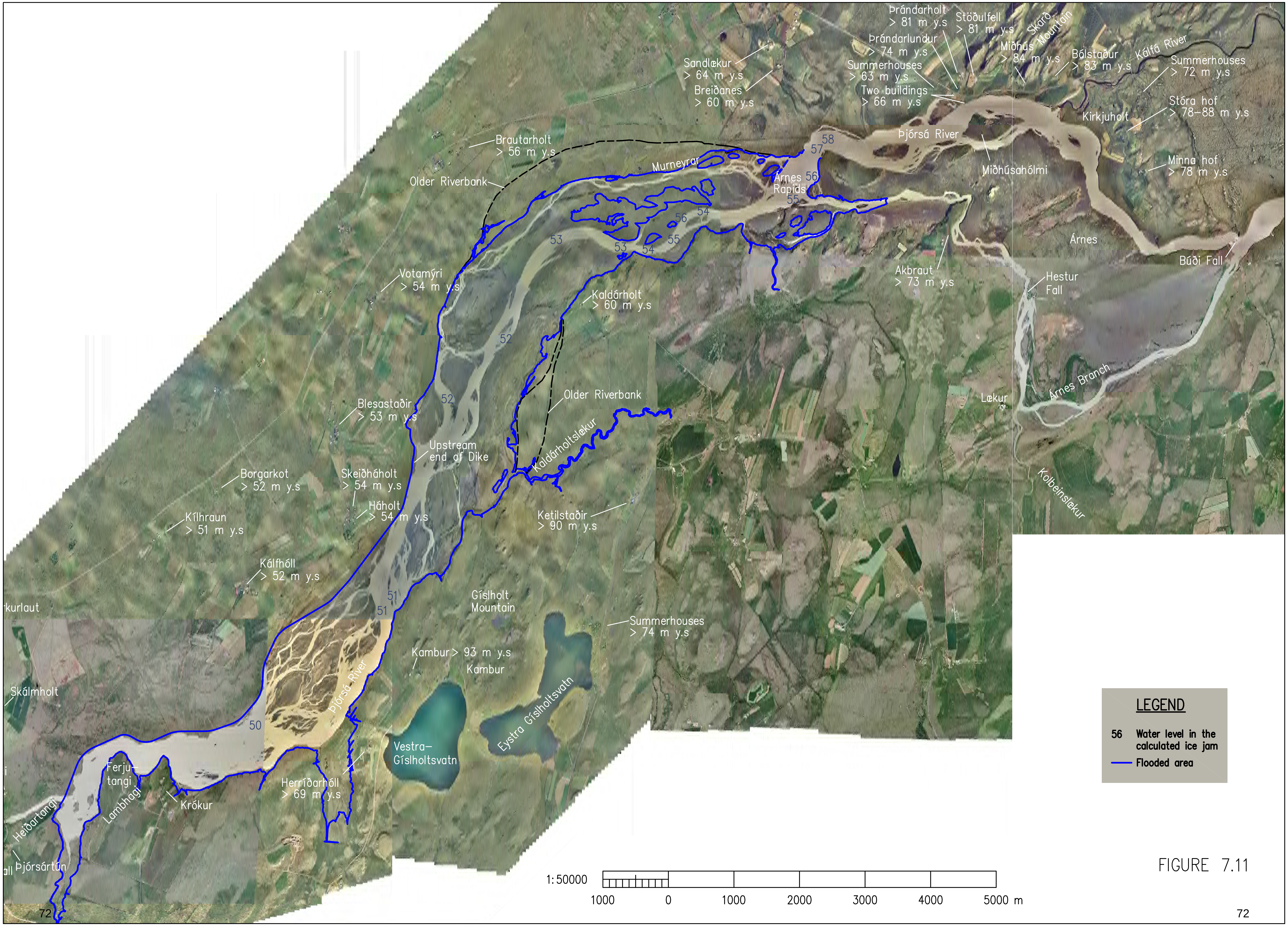

N
Þrándarholt
Stóðulfell
Skarð
Miðhús
Mountain
Þrándarlundur
Sandlækur
Summerhouses
Bólstaður
Kálfá River
Summerhouses
Breiðanes
Two buildings
(EH)
(DH)
Stóra hof
Kirkjuholt
CaH
(CH)
(HaH)
Þjórsá River
(Ga2H)
(FV)
Miðhúsahólmi
Minna hof
Brautarholt
Murneyrar
(HH)
Ga1H
Árnes
Rapids
(BH)
Older Riverbank
4
3
2
5
6
7
8
9
(AbH)
Árnes
(AaH)
Búði Fall
Akbraut
Hestur
Fall
Votamýri
(10)
Kaldárholt
(11)
(12)
Older Riverbank
Blesastaðir
Lækur
Árnes Branch
13
Kaldárholtslækur
Borgarkot
Skeiðháholt
Kolbeinslækur
14
Háholt
Kílhraun
Ketilstaðir
Kálfhóll
urlaut
Gíslholt
Mountain
Summerhouses
Kambur
Kambur
Skálmholt
Þjórsá River
Eystra Gíslholtsvatn
Vestra–
Gíslholtsvatn
Ferju-
tangi
Herríðarhóll
Lambhagi
Krókur
Heiðartangi
Þjórsártún
LEGEND
CS 2008
RM 2008
Aug. 2001
April 2002
May 2002
CS used in HEC-RAS
1:50000
1000
0
1000
2000
3000
4000
5000 m

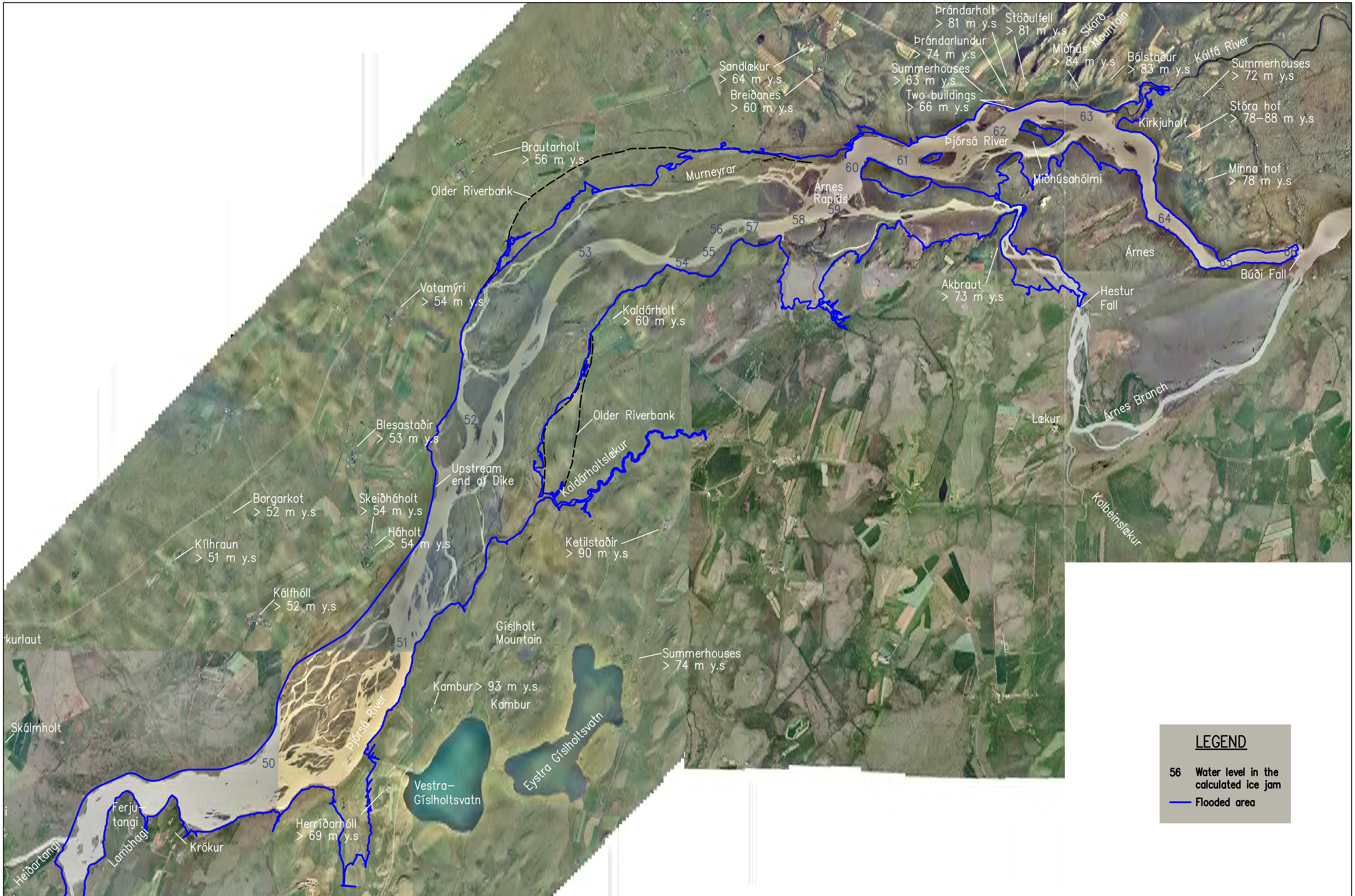
FIGURE 7.1

71



Þrándarholt
> 81 m y.s
Stóðulfell
> 81 m y.s
Þrándarlundur
> 74 m y.s
Skarð Mountain
Miðhús
> 84 m y.s
Bólstaður
> 83 m y.s
Kálfá River
Summerhouses
> 72 m y.s
Sandlækur
> 64 m y.s
Summerhouses
> 63 m y.s
Breiðanes
> 60 m y.s
Two buildings
> 66 m y.s
Kirkjuholt
Stóra hof
> 78–88 m y.s
Þjórsá River
Minna hof
> 78 m y.s
Brautarholt
> 56 m y.s
Murneyrar
Árnes Rapids
Miðhúsahólmi
Older Riverbank
Árnes
Búði Fall
Votamýri
> 54 m y.s
Kaldárholt
> 60 m y.s
Akbraut
> 73 m y.s
Hestur Fall
Older Riverbank
Lækur
Árnes Branch
Blesastaðir
> 53 m y.s
Kaldárholtslækur
Upstream end of Dike
Borgarkot
> 52 m y.s
Skeiðháholt
> 54 m y.s
Kolbeinslækur
Háholt
> 54 m y.s
Kílhraun
> 51 m y.s
Ketilstaðir
> 90 m y.s
Kálfhóll
> 52 m y.s
kurlaut
Gíslholt Mountain
Summerhouses
> 74 m y.s
Kambur > 93 m y.s
Kambur
Skálmholt
Þjórsá River
Eystra Gíslholtsvatn
Vestra-Gíslholtsvatn
Ferju-tangi
Lambhagi
Krókur
Herríðarhóll
> 69 m y.s
Heiðartangi
Þjórsártún
LEGEND
56 Water level in the calculated ice jam
Flooded area
1:50000
1000 0 1000 2000 3000 4000 5000 m

FIGURE 7.11



Þrándarholt > 81 m y.s
Stóðulfell > 81 m y.s
Skarð Mountain
Þrándarlundur > 74 m y.s
Miðhus > 84 m y.s
Bólstaður > 83 m y.s
Kálfá River
Summerhouses > 72 m y.s
Sandlækur > 64 m y.s
Summerhouses > 63 m y.s
Breiðanes > 60 m y.s
Two buildings > 66 m y.s
Stóra hof > 78–88 m y.s
Kirkjuholt
Þjórsá River
Minna hof > 78 m y.s
Miðhúsahólmi
Brautarholt > 56 m y.s
Murneyrar
Árnes Rapids
Older Riverbank
Árnes
Búði Fall
Akbraut > 73 m y.s
Hestur Fall
Votamýri > 54 m y.s
Kaldárholt > 60 m y.s
Older Riverbank
Lækur
Árnes Branch
Blesastaðir > 53 m y.s
Upstream end of Dike
Kaldárholtslækur
Borgarkot > 52 m y.s
Skeiðháholt > 54 m y.s
Kolbeinslækur
Háholt > 54 m y.s
Kílhraun > 51 m y.s
Ketilstaðir > 90 m y.s
Kálfhóll > 52 m y.s
Gíslholt Mountain
Summerhouses > 74 m y.s
Kambur > 93 m y.s
Kambur
Skálmholt
Þjórsá River
Eystra Gíslholtsvatn
Vestra-Gíslholtsvatn
Ferju-tangi
Lambhagi
Herríðarhóll > 69 m y.s
Krókur
Heiðartangi
Þjórsártún
LEGEND
56 Water level in the calculated ice jam
Flooded area
1:50000
1000 0 1000 2000 3000 4000 5000 m

FIGURE 7.13

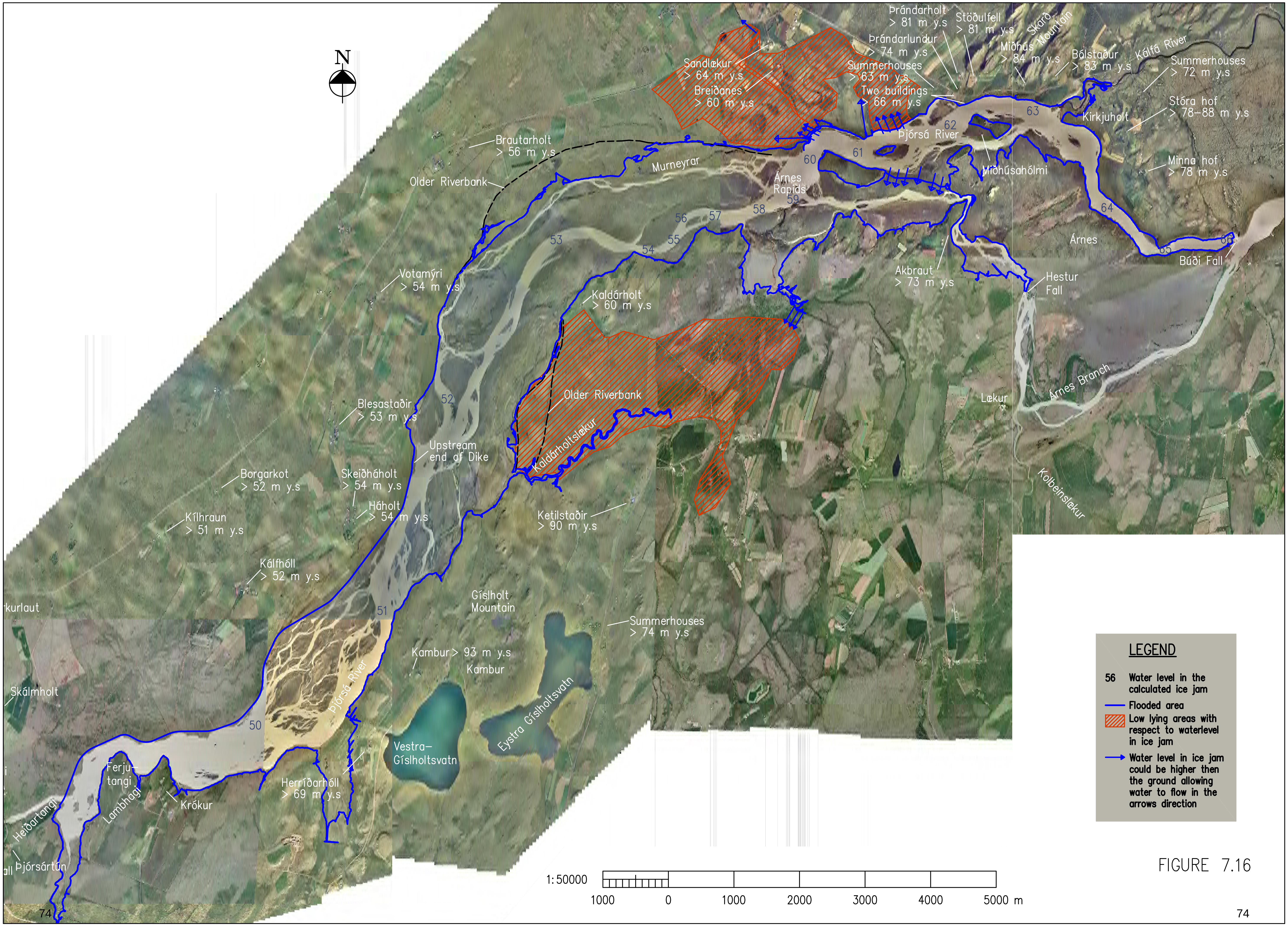

N
Þrándarholt
> 81 m y.s
Stóðulfell
> 81 m y.s
Skarð Mountain
Þrándarlundur
> 74 m y.s
Miðhús
> 84 m y.s
Bólstaður
> 83 m y.s
Kálfá River
Sandlækur
> 64 m y.s
Summerhouses
> 63 m y.s
Summerhouses
> 72 m y.s
Breiðanes
> 60 m y.s
Two buildings
> 66 m y.s
Stóra hof
> 78–88 m y.s
Kirkjuholt
Þjórsá River
Brautarholt
> 56 m y.s
Murneyrar
Árnes Rapids
Miðhúsahólmi
Minna hof
> 78 m y.s
Older Riverbank
Árnes
Búði Fall
Akbraut
> 73 m y.s
Hestur Fall
Votamýri
> 54 m y.s
Kaldárholt
> 60 m y.s
Older Riverbank
Árnes Branch
Lækur
Blesastaðir
> 53 m y.s
Kaldárholtslækur
Upstream end of Dike
Borgarkot
> 52 m y.s
Skeiðháholt
> 54 m y.s
Kolbeinslækur
Háholt
> 54 m y.s
Ketilstaðir
> 90 m y.s
Kílhraun
> 51 m y.s
Kálfhóll
> 52 m y.s
Gíslholt Mountain
kurlaut
Summerhouses
> 74 m y.s
Kambur > 93 m y.s
Kambur
Skálmholt
Þjórsá River
Eystra Gíslholtsvatn
Vestra-Gíslholtsvatn
Ferjutangi
Lambhagi
Krókur
Herríðarhóll
> 69 m y.s
Heiðartangi
Þjórsártún
LEGEND
56 Water level in the calculated ice jam
Flooded area
Low lying areas with respect to waterlevel in ice jam
Water level in ice jam could be higher then the ground allowing water to flow in the arrows direction
1:50000
1000 0 1000 2000 3000 4000 5000 m

FIGURE 7.16

Appendices

Appendix 1 – Correspondence with experts

E-mail 1 to Dr. Spyros Beltaos

From: Hörn Hrafnsdóttir [mailto:hhr@verkis.is]
Sent: Thursday, March 26, 2009 1:09 PM
To: Beltaos,Spyros [Burlington]
Subject: Ice properties to use in a HEC-RAS model of a reach in Lower Thjórsá River, Iceland.

Dear Dr. Spyros Beltaos,

Ice properties to use in a HEC-RAS model of a reach in Lower Thjórsá River, Iceland.

My name is Hörn Hrafnsdóttir and I am a civil engineer specialized in water resources engineering. I am working for the Consulting Engineering Company, Verkís, in Iceland and Mr. Sigmundur Freysteinsson is working with us as a private consultant on matters concerning ice. We are currently working on a possible ice jam problem upstream of a proposed hydropower station in Iceland and we would appreciate your advice or your reference to new reports on the above mentioned matter if you know of any. Following is a short description of what we are looking at.

In the Upper reaches of Thjórsá River there are already many hydropower plants and diversions which have led to very regulated flow in the Lower Thjórsá River. At the moment 3 Hydropower Stations are planned in the Lower Thjórsá River, all benefitting from the highly regulated flow and reduced ice flow due to the retention of ice in upper reservoirs and reduced open water for ice production. But even though ice flow has been reduced we still might have considerable amount of ice production above each of the three proposed power plants. In two of the power plants the intake ponds are located in the river itself and that will cause ice accumulation upstream of the ponds.

At the moment we are looking at the Hvammsvirkjun Hydropower Station which is the most upstream one of the three. You can see its layout; intake pond and the river reach above it up to Búrfell Hydropower Station on picture 1, see attachment. Also marked on the picture are measured cross-sections and on picture 2 you can see part of the HEC-RAS model I have made for this river reach from the dam up to where the two branches come together. On the picture I have put the banks on either site, water level with no ice and with ice (using n_i=0,08, p=0,4 and φ=45). The intake pond is 4,3 km^2 and the open water above it up to Búrfell Hydropower Station has been estimated to be about 2 km^2 after full formation of border ice.

We are assuming this would be a freezup jam as it usually is in Lower Thjórsá. And as the reach is not very long the frazil will probably be frazil slush or very un-matured pancake ice. **Now the big question is what parameters would be most suited for this site.**

Other parameters of interest: Discharge during cold spells will be around 300 m^3/s. The slope is in the range of 0,001-0,0001.

Sincerely,
Hörn Hrafnsdóttir, Consulting Eng., M.Sc.

Hörn Hrafnsdóttir

Vatnsauðlindaverkfræðingur | Water-Resources Engineer
+354 569 4912 | +354 -

Ármúla 4 | 108 Reykjavik | +354 422 8000 | www.verkis.is

E-mail 1 from Dr. Spyros Beltaos

From: Beltaos,Spyros [Burlington] [mailto:Spyros.Beltaos@ec.gc.ca]
Sent: Friday, March 27, 2009 3:43 PM
To: Hörn Hrafnsdóttir
Cc: Tang, Pat (ENV); Steven Daly
Subject: RE: Ice properties to use in a HEC-RAS model of a reach in Lower Thjórsá River, Iceland.

Dear Hörn Hrafnsdóttir:

I have reviewed the information in your attachment and can offer the following comments:

(a) The parameters you have used for HEC-RAS seem reasonable, though one cannot be assured that they correctly represent local conditions without some actual measurements to check against. In your application, it may be desirable to run a few scenarios with different parameters and chose a "conservative" output. For breakup jams, detailed calibrations on a Canadian river are described in the attached paper (see full citation below). One of our findings was that use of the roughness-thickness relationship, rather than of constant-ice jam roughness, gave better results. Freezeup jams that comprise ice blocks and ice pans may have different parameters.

(b) I am copying this message to Patrick Tang (co-author of the attached paper); and to Steve Daly who has developed the ice routines in HEC-RAS and has extensive experience with their use

(c) You mentioned that the ice in the jam is likely to mostly consist of slush. This entails the possibility of forming a hanging dam, which is a very different, and potentially more dangerous, type of jam than the type simulated by HEC-RAS ("wide-channel jam", formed by collapse and shoving). Hanging dams form by under-ice transport and deposition. Depending on frazil-generation potential in upstream reaches, this process may go on for a long time, leading to much thicker accumulations than jams formed by collapse and shoving, and thence to higher water levels. I am not aware of any public-domain models that simulate hanging dams. If you are interested in proprietary models, I could provide one or two contacts. For general information on hanging dams, see Ashton (1986, "River and Lake Ice Engineering") and/or Beltaos (1995, "River Ice Jams"). Both are textbooks - published by Water Resources Publications.

I trust this information is helpful. The citation to the attached article is: Tang, P. and Beltaos, S. 2009. Modelling of River Ice Jams for Flood Forecasting in New Brunswick. Proceedings, 65th Eastern Snow Conference, Fairlee (Lake Morey), Vermont, USA (in press).

With best regards,

Dr. Spyros Beltaos, P.Eng., FCSCE
Research Scientist
Aquatic Ecosystem Impacts Research Division
National Water Research Institute
Environment Canada
867 Lakeshore Rd.
Burlington, ON L7R 4A6
Canada
Tel. 905-336-4898 Fax 905-336-4420 email spyros.beltaos@ec.gc.ca

E-mail 2 to Dr. Spyros Beltaos

From: Hörn Hrafnsdóttir [mailto:hhr@verkis.is]
Sent: Thursday, April 02, 2009 7:27 AM
To: Beltaos,Spyros [Burlington]
Cc: Tang, Pat (ENV); Steven Daly; 'Sigmundur Freysteinsson (sigmundu@simnet.is)'
Subject: RE: Ice properties to use in a HEC-RAS model of a reach in Lower Thjórsá River, Iceland.

Dear Dr. Spyros Beltaos,
Cc. Patrick Tang and Steven Daly.

Thank you so much for your reply. I really appreciate it.

I have already run a few scenarios with different parameters and I have tried out Nezhikhovskiy's relationship between the ice thickness and n_i as it is given in HEC-RAS as I understand that his results are based on freezup jams. I think though that HEC-RAS must use the relationship for ice floes rather than for slush resulting in too high roughness in the case of the reach in question. But I need to get confirmation on that. If I'm right I have been thinking of trying to use Nezhikhovskiy's relationship in HEC-RAS manually by using the loose or dense slush relationship and endless iterations.

The porosity has little effect when the friction angle is high but as I lower the friction angle the porosity has more effects. I have already tested porosity from 0,4 up to 0,6.

The friction angle is a problem. Firstly I don't find much about it like reports or measurements, secondly it can have major effect in this reach and thirdly as the ice is probably frazil slush I'm assuming the friction angle might be lower than the values used by many for breakup jams. So this parameter is of major concern. I have tested values from 60 down to 30.

I also realize that HEC-RAS is based on breakup jams with no cohesion but it seemed to be alright as an indication to the possibility of a problem or not, as I don't know of any handy software for freezeup jams.

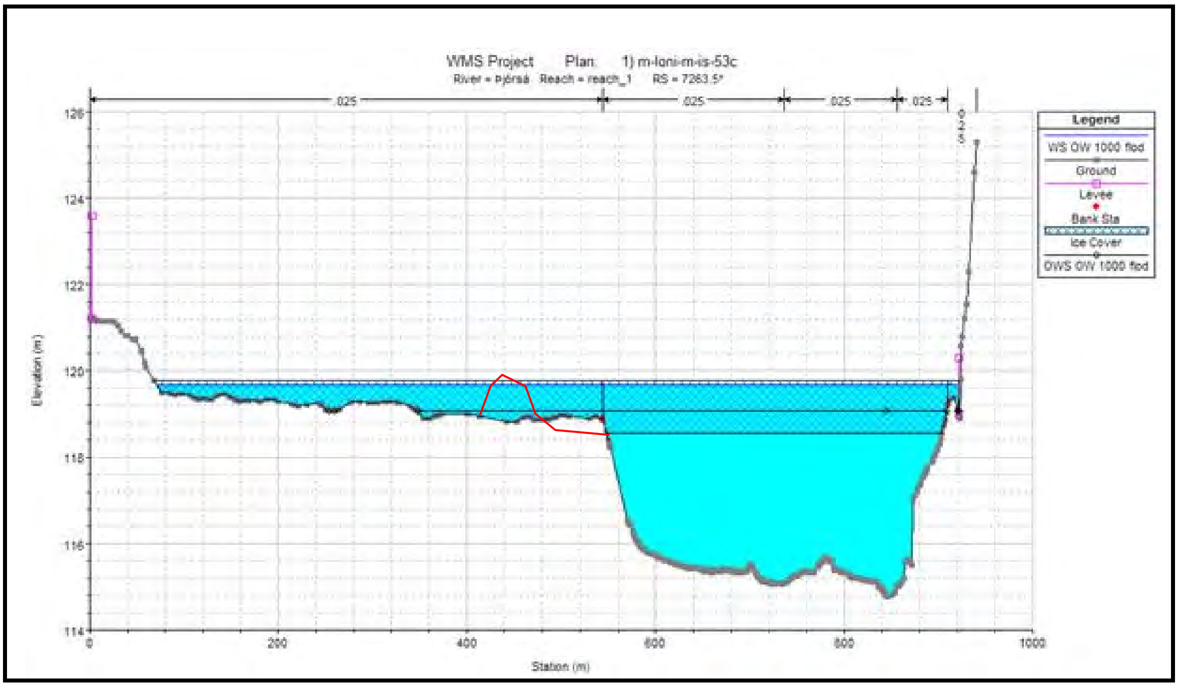
Regarding the problem of finding reasonable parameters I have been wondering if it might be possible to test the site with an ice-net, thus producing similar effect as the intake pond would do. Relying on the active part of the frazil in the beginning of cold spells to form an ice sheet in a location slightly above the end of the proposed intake pond (approximately in station 7610 as the slope is favorable there) and see if we can get an ice jam formation from there. But this is quite difficult as the banks are made of a mixture of gravel and sand (the river used to be alluvial in this part but after the damming upstream it has formed a relatively stable channel in the alluvial bedmaterial) and the river is about 200 m in width. That means that it will both be difficult to put the nets in place and also to monitor water level changes and other relevant parameters.

Another approach I am working on for all the above parameters is trying to calibrate them to a know ice jam location much further downstream, the socalled Urridafoss ice jam. The down site is that there the ice will be more matured so its properties might be different both because it has been disposed to the cold for a longer time and also because between the two sites there are rapids and two waterfalls so the shape of the particles should be different. At the site we are looking at there are no rapids. But we will try this just to get some indication.

I agree with you that as the ice is probably mostly frazil ice or slush that the formation of the hanging dam is possible. That possibility needs to be looked at and taken seriously, so all additional knowledge, research, modeling possibilities and connections is appreciated. I attached some pictures of iceflow at the site.

Regarding the modeling in HEC-RAS, I have been wondering whether I will have to change some things in my model to account for some complications in the bathymetry of the river, so I added some questions for Steven Daly:

1. How does HEC-RAS deal with ice jam calculations in cross-sections with an island in the middle? Can it handle that or would I have to split up the flow?
2. How does HEC-RAS deal with ice jam calculations at junctions?
3. How does HEC-RAS deal with cross-sections like this one? I am wondering whether I will have to tick out the jam formation in the overbank area in this section and if so does HEC-RAS know that there is no bank in the main channel to push against on the left side above approximately 119 m asl. Or do you recommend any other tricks for cross-sections like this one? Then of course, in real life, the bank material, as it is gravel and sand in this case on the left side, would probably be pushed by the ice reforming the channel so maybe some modifications to the cross-section (like the red line) would be most appropriate.



Regarding the pictures I sent in my last e-mail. I have some additional explanations.

The red dashed lines are around a known location of an ice jam that formed yearly before any hydropower plants were built upstream. But nowadays it does not form as the ice flow is stopped in reservoirs upstream of this location and the reach above it, which is a narrow and steep canyon, is now nearly empty during cold spells as the water flows through the Búrfell Power plant. The ice jam used to be in the order of 15-40 Mm^3 and the waterlevel rise could be as high as 10-15 m.

The cross-sections in picture 1 start in station 58.122 and the first one equivalent to station 0 in picture 2, that is, at the dam. Furthermore, picture 2 only goes up to where the river branches come together behind the old ice jam site. The reason for not showing the river all the way up is that the narrow, deep reach in the bend just downstream of the former ice jam site seems to break the jam into two. So, ice jam formed upstream of that site does not influence the formation downstream of the bend. That seems logical keeping in mind that the old ice jam used to start in the bend and formed upstream from there. But then on the other hand I would like to know how well HEC-RAS models river ice where two river reaches come together, just to be sure that the modeling has nothing to do with these results.

Sincerely,
Hörn Hrafnsdóttir, Consulting Eng., M.Sc.

E-mail 2 from Dr. Spyros Beltaos

From: Beltaos,Spyros [Burlington] [mailto:Spyros.Beltaos@ec.gc.ca]
Sent: Thursday, April 02, 2009 6:39 PM
To: Hörn Hrafnsdóttir
Cc: Tang, Pat (ENV); Steven Daly; sigmundu@simnet.is

Subject: RE: Ice properties to use in a HEC-RAS model of a reach in Lower Thjórsá River, Iceland.

Just a few quick comments – am off to a week's field trip tomorrow and attending to last-minute details.

I agree with your comments on the Nezhikhovskiy relationships – so far, only the one with the ice blocks has been tested by others (e.g. attached article). The relationship with dense slush may be the best for your application…the loose slush values seem a bit low to me; also, the dense-loose distinction may be subjective.

Porosity is almost always taken as 0.4. There are few data, and we have no idea as to its potential variability. By fixing it, we are in effect making other parameters compensate for errors in porosity.

Friction angle is not known very well, and is not universally defined by different modelers. There is some evidence suggesting that it should be more than 45 degrees, and that it is so large because of cohesion, which is not a constant (as in soils), but increases with normal effective pressure in the jam.

Your idea about calibrating on the downstream site (Urridafoss) seems the most practical to me, despite the drawbacks.

Hanging dam modelling: I was recently involved in a Canadian study where the engineering consultant was Mr. Rick Carson (KGSGROUP; rcarson@kgsgroup.com) a well-known and experienced Canadian ice engineer. He used a 1-D model that could simulate the progressive growth of the hanging dam. Also, the 2-D model CRISSP (http://www.ceati.com/success1.php) may have a hanging dam routine; am not certain. There may well be other proprietary models, but that's all I know.

Regards,

Spyros

Dr. Spyros Beltaos, P.Eng., FCSCE
Research Scientist
Aquatic Ecosystem Impacts Research Division
National Water Research Institute
Environment Canada
867 Lakeshore Rd.
Burlington, ON L7R 4A6
Canada
Tel. 905-336-4898 Fax 905-336-4420 email spyros.beltaos@ec.gc.ca

E-mails to Andrew M. Tuthill, P. E.

Similar or the same as to Dr. Spyros Beltaos and not repeated here.

E-mail 1 from Andrew M. Tuthill, P. E.

From: Tuthill, Andrew M ERDC-CRREL-NH
[mailto:Andrew.M.Tuthill@usace.army.mil]
Sent: Tuesday, June 09, 2009 2:07 PM
To: Hörn Hrafnsdóttir
Cc: White, Kathleen D ERDC-CRREL-NH; sigmundu@simnet.is
Subject: RE: Ice properties to use in a HEC-RAS model of a reach in Lower Thjórsá River, Iceland.

Dear Ms. Hrafnsdóttir

I am very sorry for the late reply. I have been swamped by a number of projects and deadlines. I hope this is not too late to be of use. I re-read your correspondence with Dr. White and have a pretty good idea of the situation and the ice modeling issues. One thing that would be helpful would be the pictures 1 and 2 of the river layout and HEC RAS model info. These graphics did not come through in the messages I received. I do have the three photographs which are excellent. Below are responses to your specific questions.

A. As the ice jam that will most likely form is a freezeup jam (we know HEC-RAS is based on breakup jams but it seemed to be alright as an indication to the possibility of a problem or not, as I don't know of any handy software for freezeup jams) and will probably be made of loose frazil it is very difficult to speculate what the properties will be like. And as the river reach is open during wintertime as it is, we have very little hope of measuring anything except what I have already mentioned in my former letter.

Response: From your description of the river and ice processes, it seems reasonable to use HEC-RAS to model the ice the ice covers upstream of the intake ponds as a freezeup ice jams. The frazil slush and pans will accumulated on the free flowing sections of river above the intake ponds and progress upstream, thickening due to the downstream forces of water drag and gravity.

I made a few basic calculations of equilibrium ice jam thickness using the attached excel spreadsheet and the hydraulic data you provided for the lower Thorsa River. The calculations assume normal flow conditions upstream of the backwater effects of the intake ponds. Most ice jam profiles have a mid-section of relatively uniform thickness called the equilibrium section.
This equilibrium ice thickness can be calculated from White(1999)TR99-11 equation 19. I calculated ice thicknesses for slopes of 0.001 and 0.0001 using a bed Mannings nb of 0.033 for coarse gravel and a first-guess ice underside roughness ni of 0.04. This seemed reasonable based on Fig. 7 of White (1999) and also past modeling efforts involving freezeup ice jams.

Often the ice is roughest at the time of ice jam formation followed by smoothing of the jam underside and declining stage with time. This is advantageous in terms of reduced head losses for hydro production once the freezeup ice cover has formed.

In my experience, ice roughness is the primary calibration tool in the HEC-RAS model. The second most important parameter is the maximum under ice water velocity which is usually set at about 1.5 m/s. Angle of internal friction phi, and ice accumulation porosity e, are usually left at their "default" values of 45 degrees and 0.4 respectively. I have had instability problems using the option of allowing HEC-RAS calculating ice roughness as a function of ice thickness. I usually select a reasonable ice roughness based on expected ice accumulation type and thickness, then run HEC-RAS with a fixed ice roughness. I then re-check the ice roughness to see if it's reasonable, based on the calculated ice accumulation thickness.

For nb=0.033, ni=0.04, phi=45 degrees, e=0.4, Discharge Q=300 cms, Width = 200m and Slope = 0.001 I get an equilibrium ice thickness of 2.9 m, an under ice flow depth of 1.5 m and an under-ice water velocity of 1.0 m/s.

Decreasing the slope to 0.0001, with all other values kept the same gives an equilibrium ice thickness of 0.67 m, an under ice depth of 2.4 m and an under-ice flow velocity of 0.6 m/s.

These initial calculations suggest that stable freezeup ice accumulations will exist upstream of the proposed intake ponds for the given range of hydraulic conditions. Under ice water velocities are well below the default

threshold for ice erosion of 1.5 m/s.

B. I have though been wondering if it might be possible to test the site with an ice-net. Relying on the active part of the frazil in the beginning of cold spells to form an ice sheet in a location slightly above the end of the proposed intake pond (approximately in station 7610) and see if we can get an ice jam formation from there. But this is quite difficult as the banks are made of a mixture of gravel and sand (the river used to be alluvial in this part but after the damming upstream it has formed a relatively stable channel in the alluvial bed material) and the river is about 200 m in width.

Response: From the above calculations, it appears that ice retention in the upper part of the intake ponds would be feasible. The time-tested criteria for ice retention are water velocity < about 0.67 m/s and Froude number < about 0.08 (USACE, 2008). So, for the slope = 0.0001 case, ice retention would be possible, while for the slope = 0.001 the water velocity would probably be too high for ice nets or a boom to stop the drifting frazil. If the boom were located a section of river that met the retention criteria, the ice cover could still progress up through steeper upstream sections.

USACE (2006) Engineering and Design-Ice Engineering. US Army Engineer Manual 1110-2-1612.

http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1612/toc.htm

To my knowledge, the use of ice nets to promote ice retention and ice cover formation is fairly rare. The attached CRREL Special Report SR-95-19, pp.

13-14 describes several applications. Much more widely-used are ice booms.

Modern ice retention booms, constructed of steel pipes, are quite effective, robust and relatively inexpensive. Razek Abdelnour of Fleet Technology in Canada has designed many successful ice boom projects.

http://media.bmt.org/bmt_media/bmt_services/41/BoomEngineeringServices.pdf

C. Regarding Manning n for the underside of the ice, I have speculated whether to use Nezhikhovskiy's relationship between the ice thickness and ni.

I have already tried that out in the model but I think that HEC-RAS must use the relationship for ice floes rather than for slush resulting in too high roughness. But I need to get confirmation on that (have already gotten a contact to Mr. Steven F. Daly through Mr. Spyros Beltaos). If I'm right I have been thinking of trying to use Nezhikhovskiy's relationship in HEC-RAS manually by using the loose or dense slush relationship and endless iterations.

Response: As discussed above, I recommend inputting a fixed roughness. I also have had instability problems with the calculated ice roughness option in HEC-RAS.

D. Regarding the friction angle, I have big concerns about this parameter.

Firstly I don't find much about it like reports or measurements, secondly it can have major effect in this reach and thirdly as the ice is probably frazil slush I'm assuming the friction angle might be lower than the values used by

many for breakup jams. So this parameter is of major concern. I have

tested values from 45 down to 30.

Response: You are probably correct that an accumulation of loose frazil slush has a lower internal strength than a breakup ice jam composed of larger floes. I don't know of any research or experiments that have measured this though. Another complication is that freezeup ice accumulations form at below-freezing air temperatures, so cohesion of floes may increase internal strength in an unpredictable way. For simplicity sake, I usually leave the angle of internal friction at it's default value of 45 degrees and the cohesion at zero and calibrate the model with the ice roughness.

E. The porosity has little effect when the friction angle is high but as I lower the friction angle the porosity has more effects. I have already tested porosity from 0,4 up to 0,6.

Response: I am sure that porosity varies as you suggest, depending on ice jam type and floe size. For lack of a better strategy, I usually leave the porosity at 0.4, for both breakup and freezeup ice jams.

Again, dong this is possible since influence of ice roughness has a much bigger effect on model results.

1. How does HEC-RAS deal with ice jam calculations in cross-sections with an island in the middle? Can it handle that or would I have to split up the flow?

Response: That's a good question. If the island is within the main channel, I do not think HEC-RAS treats the island as two channels (two sub-widths, two sub-flow areas etc.) I think the model just blocks off that portion of the main channel flow area. One way to test this would be to set the channel bank stations in such a way that one side of the island is overbank flow and the other is the main channel flow. Steve Daly would be the better person to ask about this.

2. How does HEC-RAS deal with ice jam calculations at junctions?

Response: HEC-RAS can handle junctions okay. I usually model the mainstem river and the upstream tributaries as separate reaches. The model solves the ice jam force balance from downstream to upstream, so the conditions of the upper-most cross section (water surface elevation and ice thickness) of the lower reach become the downstream boundary for each tributary. If the channel separates around a large island and rejoins downstream, that might be more of a problem. I've never modeled that particlual case, so would have to look into it.

3. How does HEC-RAS deal with cross-sections like this one? I am wondering whether I will have to tick out the jam formation in the overbank area in this section and if so does HEC-RAS know that there is no bank in the main channel to push against on the left side above approximately 119 m asl.

Or do you recommend any other tricks for cross-sections like this one? Then of course, in real life, the bank material, as it is gravel and sand in this case on the left side, would probably be pushed by the ice reforming the channel so maybe some modifications to the cross-section (like the red line) would be most appropriate.

Response: I see the cross section with flow and an ice cover in the left overbank, but I can't see the red line. Deciding how to deal with ice jamming in the overbank areas can be difficult. The user has the option of modeling the overbank area as an ice jam, a fixed thickness ice cover or open water.

If the main channel is modeled as an ice jam HEC-RAS assumes that the user-input bank station is the main channel boundary and treats the bank station location as the river bank, even in cases where the water level is above bankfull.

Please feel free to call if you have further questions or would like to discuss.

Sincerely,

Andy

Andrew M. Tuthill, P. E.
U S Army Cold Regions Research and Engineering Laboratory
72 Lyme Rd.
Hanover, NH 03755
603-646-4225

Appendix 2 – Calibration of ice variables using the Urriðafoss Ice Jam

Introduction

The Urriðafoss Ice Jam has formed for as long as people in the area can remember, both before changes in the upper reaches and today. This reach, in Þjórsá River, had already been modelled in HEC-RAS for dam break analysis. There are not many measured cross sections in the modelled reach and the modelling was made before the new measured longitudinal profile of the river was measured. For this reason the model did not represent the river bed as well as the model used for modelling the ice jams in this report, chapters 6 and 7. Nevertheless as this is the only location with a known ice jam that can be used for calibration, the decision was made to use the model for calibration purposes. Another drawback in using this site is that it is located much further downstream than Hagalón Pond so the ice in the river at that location will be more developed than in the short reach above Hagalón Pond. Nevertheless this is the best option available. Figure A2.1 shows an overview of the river reach within the model that was used for ice jam calibration.

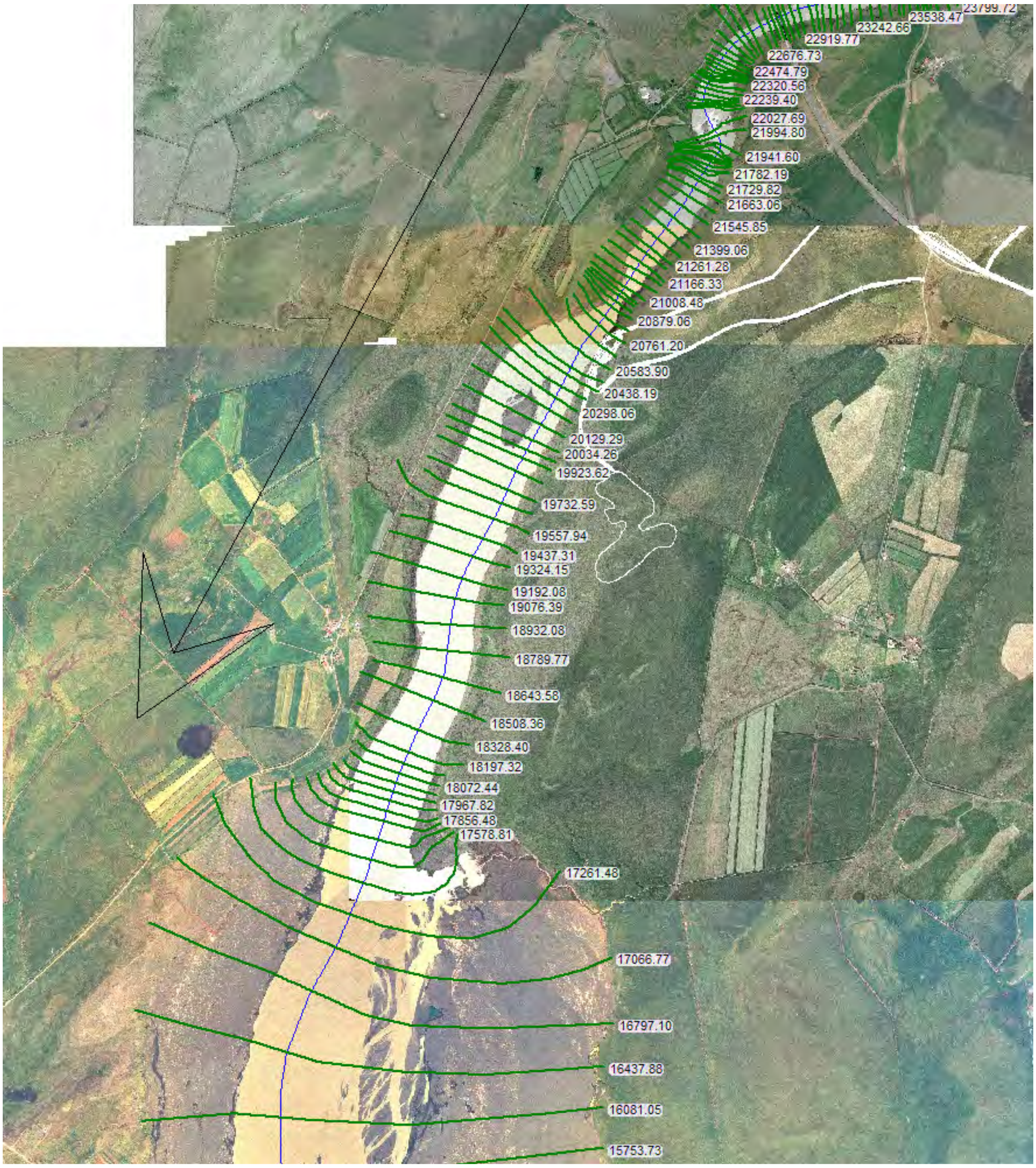


Figure A2.1 *Overview of the reach within the model that was used for ice jam calibration.*

As soon as the calibration work started it became obvious that the reach where the bulk of the ice jam formed and where we have the water level measurements, needed to be calibrated for discharge without ice using the measurements of the longitudinal profile of the river form 2008. The calibration method was very simple. As there are no measured cross sections in this area the channel was assumed to be trapezoidal (almost rectangle) and the riverbed was lowered until a good fit was found for a realistic Manning's n for the riverbed. Figure A2.2 shows how well the measured water surface fitted the calculated profile at the end of the calibration for this river reach. There were two datasets to calibrate. Firstly, the measurements of the longitudinal profile in 2008 and secondly, the three waterlevel measurement sites. The former is shown as red dots and the calculated waterlevel shown in blue (two lines as the discharge was in between 400 and 450 m^3/s). This dataset gave good results. The second is shown with green dots and marine blue line (at the top of the blue shaded area) for the calculated water level for a discharge of 260 m^3/s. This dataset did not fit the calculations very well as can be seen. The location of the gauges is also shown on the figure. But this is as good as it got.

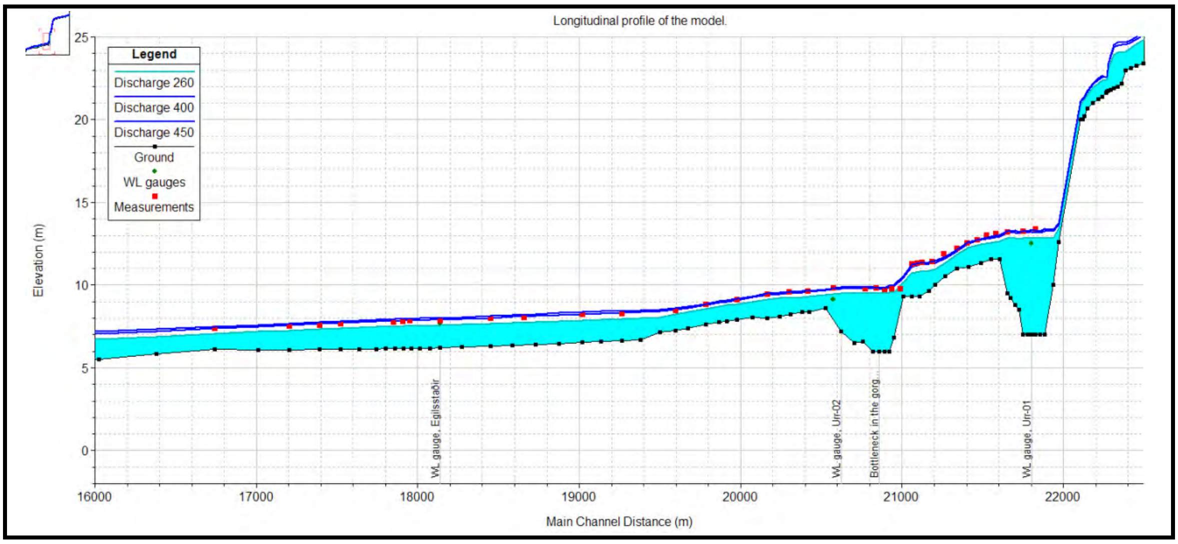


Figure A2.2 *Calibration of the reach without ice.*

Caribration of the ice variables

Measurements of the ice jam exist, both new and old. According to Sigurjón Rist (1962) the maximum waterlevel rise within the ice jam was normally about 13 m and in extreme cases it rose 18 m. On the 31st of January and the 3rd of February in 2004 the ice jam profile was measured (Victor and Gunnar, 2006). Figures 9.3 and 9.4 show the results of two unsuccessful attempts to calibrate the ice variables to the measured ice jam data. In figure A2.3 the values for n_i and p_i are realistic, but ϕ has been lowered to unrealistic values. The two most downstream measurements from 31 st of January are reached but all other data are far above the calculated ice jam. In figure A2.4 all the variables are pushed to their most unfavourable values but still the ice jam can not be mached over the whole length of the ice jam. In addition to these unfavourable values, the maximum allowable velocity in HEC-RAS, above wich no ice jam can form, had to be brought up to unrealistic values in order to get the ice jam to form a unity, i.e. not break up at the edge of the waterfall. As these values seem very high and unrealistic, photographs were examined in order to shed a light on what might be going on in the ice jam.

Figure A2.5 shows the formation of Búrfell Ice Jam just below Þjófafoss Fall. Even though this ice jam does not form any longer, due to the changes in the upstream reaches of the river, this photograph gives a vital clue to what might be happening below Urriðafoss Fall. It seems quite obvious on the picture that the ice is being lifted up, not shoved together, indicating the formation of a hanging dam below the waterfall. The ice jam part in HEC-RAS has not been designed to model the formation of a hanging dam so if the same happens below Urriðafoss Fall the explenation might be found. No photographs, as clear as this one, were found for Urriðafoss Ice Jam but there might be some other indications.

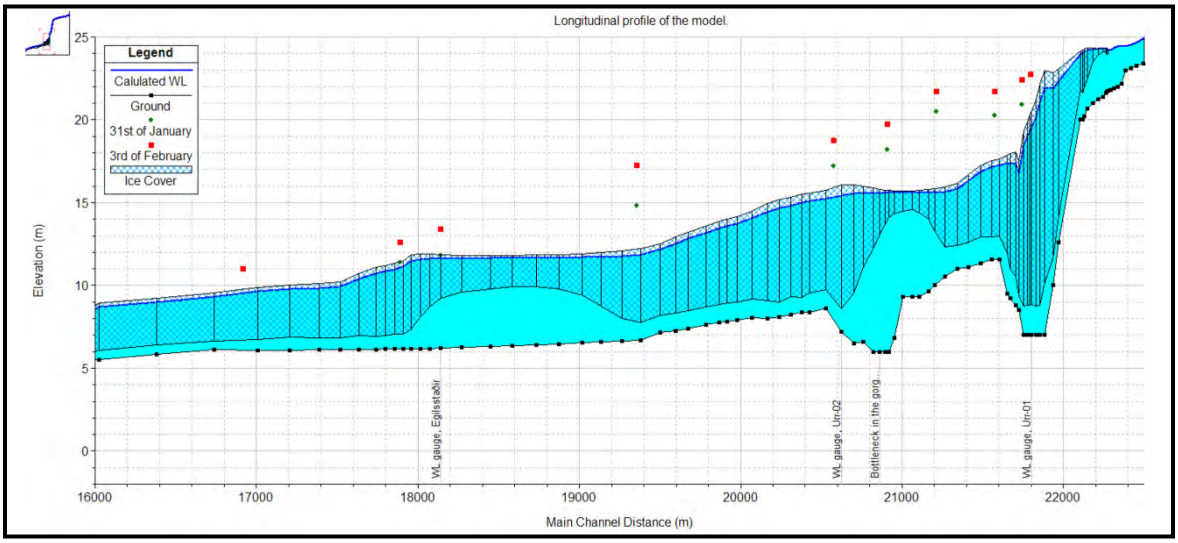


Figure A2.3 *Test using n_i = dense slush, ϕ = 25°-30° and p_j = 0,5 in order to calibrate the model to the extremes in 2004.*

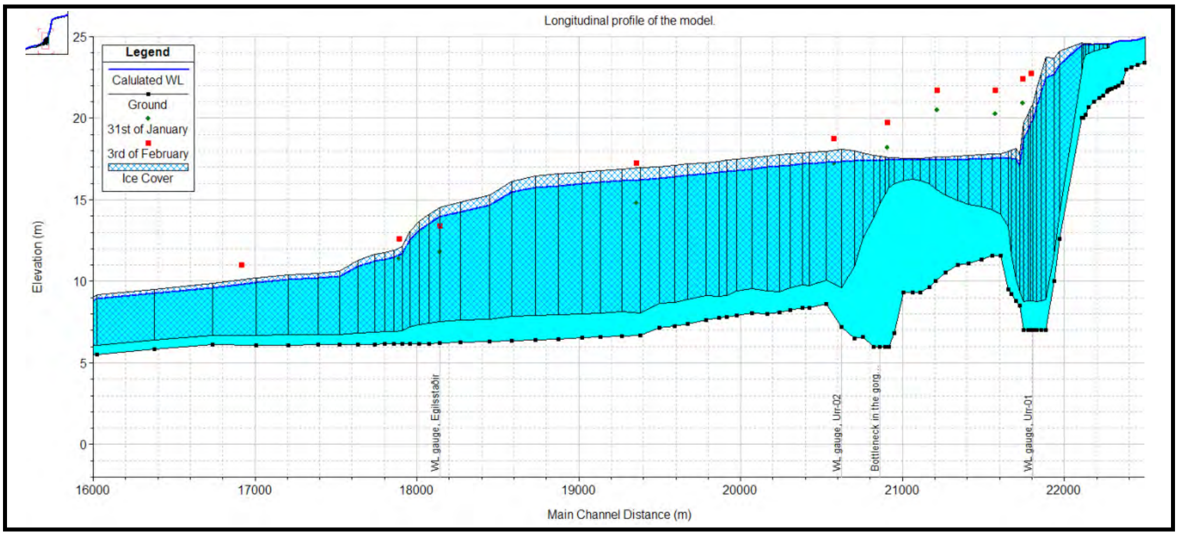


Figure A2.4 *Test using n_i = 0,12, ϕ = 20° and p_j = 0,6 in order to calibrate the model to the extremes in 2004.*

The figures from Figure A2.6 to 11 show the upper part of the Urriðafoss Ice Jam site focusing on the reach just above and below the waterfall all the way down to the second bottleneck in the gorge. The figures may indicate the formation of a hanging dam from the pool below the waterfall all the way down to the second bottleneck in the gorge. Indicating that ice jam formation in this part of the river can not be modelled in HEC-RAS. The sites in question also fall into the framework described in chapter 2.1.2 on hanging dams. Thus it was concluded that the Urriðafoss Ice Jam, in all its glory, can not be modelled in HEC-RAS. Nevertheless it is possible to use the first stages of the ice jam formation as indication for the ice jam variables, i.e. before the ice jam develops into a hanging dam, as the reach below the waterfall, all the way up to the pool below it, is not very steep and the ice jam formed within it should start as a wide river ice jam.

Figure A2.5 *Picture of the formation of the Búrfell Ice Jam just below the Þjófafoss Fall on the 25th of March 1965 (Sigmundur Freysteinsson, 1965, pic. 36-1965-03-25 Þjófafoss).*

Figure A2.6 *Overview of the upper part of the ice jam site. At the top is the Urriðafoss Fall. Below it is the waterfall pool followed by a bottleneck in the gorge. At the bottom is the downstream bottleneck opening from there into the wider part of the gorge and further down stream the wider gorge opens onto the plains, see Figure A2.1.*

In two of the reports on ice investigation in the area (Gunnar & Victor, 2003 & 2006) there are graphs showing the measured waterlevels below Urriðafoss Fall during the formation of the Urriðafoss Ice Jam. Figure A2.12 shows these graphs (copied from the reports) and they show that in the early stages of ice jam formation, waterlevel at Egilsstaðir gauge rose (the waterlevel rise in winter 2003-04 is missing on the graph) without any real rise at Urriðafoss 01 gauge until the waterlevel had risen up to about 10-11 m a.s.l. at Egilsstaðir gauge. Then Urriðafoss 01 started to rise and in most cases the waterlevel at Egilsstaðir gauge stayed almost the same during the first rise at Urriðafoss 01. After waterlevel at Urriðafoss 01 gauge had risen to about 18-20 m a.s.l. the waterlevel at Egilsstaðir gauge started to rise again and also the one at Urriðafoss 01 gauge except if there was a thaw in between. This behaviour might be due to the two phased formation of the ice jam. In the first stage, the wide river ice jam forms, with waterlevel rise due to upstream growth of the ice jam and some shoving. Then the second phase takes over where the hanging dam starts to form from the pool below the waterfall and in the trough between the bottlenecks in the gorge. After some limit has been reached a hybrid of the two formations forms the rest of the ice jam.

The gauge Urriðafoss 02 is located a short distance downstream of the second bottleneck. This gauge seems prone to damages and is not always in operation, but in some winters it was working the whole time. It seems to rise and fall in phase with Urriðafoss 01 gauge but with lower water levels.

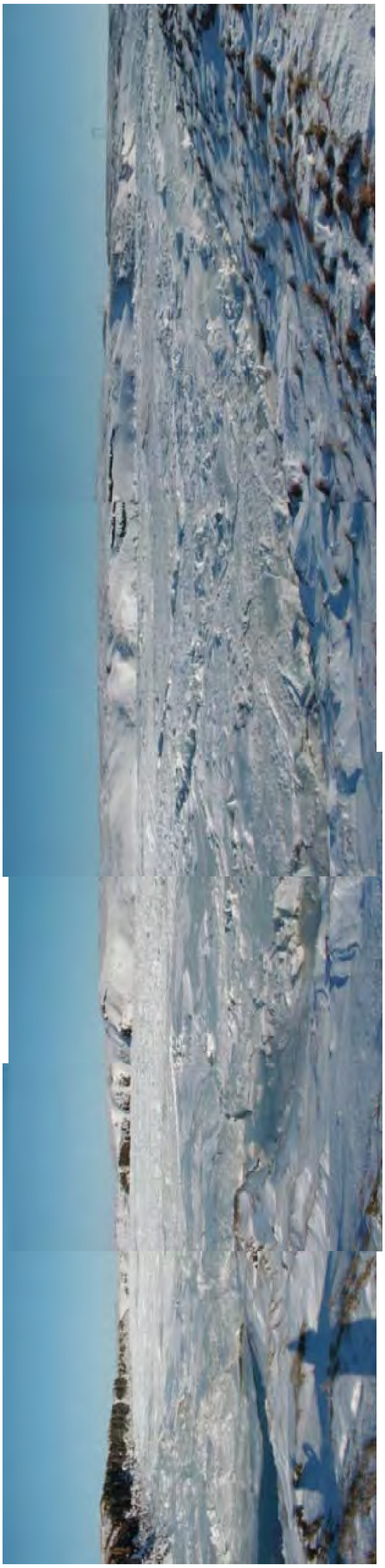


Figure A2.7 *Combined pictures of Urriðafoss Ice Jam on the 28th of February 2002 (Victor Kr. Helgason, 2002b, pic. P2280013-16). To the far left is the brook Kambholtskelda (the brook just below Urriðafoss Farm) and the upstream view above the Urriðafoss Fall. To the right is the downstream view below the waterfall and in the middle is the waterfall with the thickest part of the ice jam. Flow is from left to the right.*

Figure A2.8 *Combined pictures of Urriðafoss Ice Jam little further down stream below the waterfall on the 28th of February 2002 (Victor Kr. Helgason, 2002b, pic. P2280039-40). Flow is from left to the right.*

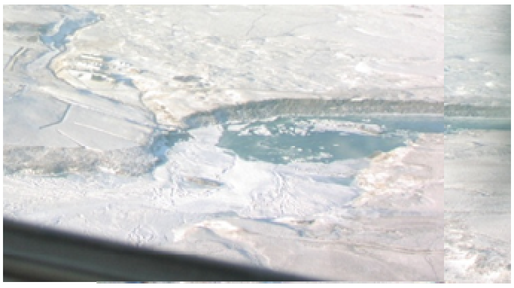


Figure A2.9 *Above, aerial photograph of the Urriðafoss Ice Jam formation at Urriðafoss Fall on the 11th of February 2002 (Victor Kr. Helgason, 2002b, pic. P2110136-137).*

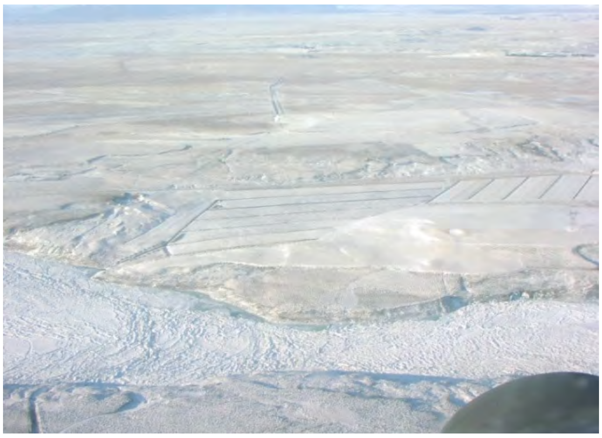


Figure A2.10 *Above, aerial photograph of the Urriðafoss Ice Jam at the upper bottleneck on the 11th of February 2002 (Victor Kr. Helgason, 2002b, pic. P2110138). Flow is from right to left showing shoving in the upstream direction?*

Figure A2.11 *To the left, a photograph of the lower bottleneck on the 28th of February 2002 (Victor Kr. Helgason, 2002b, pic. P2280059). Flow is from right to the left showing shoving in the downstream direction.*

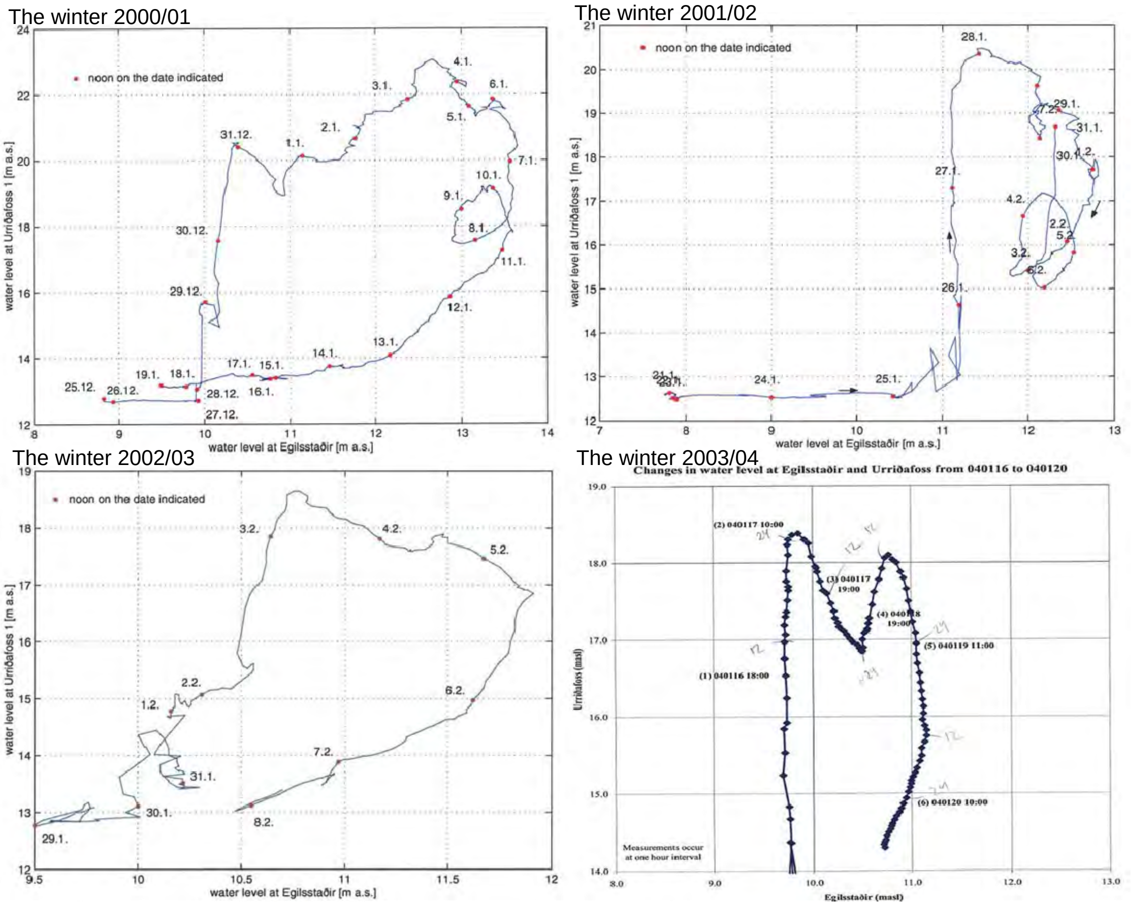


Figure A2.12 *Copies of graphs from two reports by Gunnar and Victor (2003 & 2006). Showing the relationship between the waterlevel at Egilsstaðir gauge and Urriðafoss 01 gauge.*

Based on this the early phases of the formation of the Urriðafoss Ice Jam was calibrated. Figure A2.13 shows the final result. It was found by using

- the Nezhikhovskiy's relationship between ice jam thickness and ice roughness for dense slush, $n_i = 0,0302 * \ln(t) + 0,0445$,
- $\phi = 45°$ and
- $p_j = 0,4$.

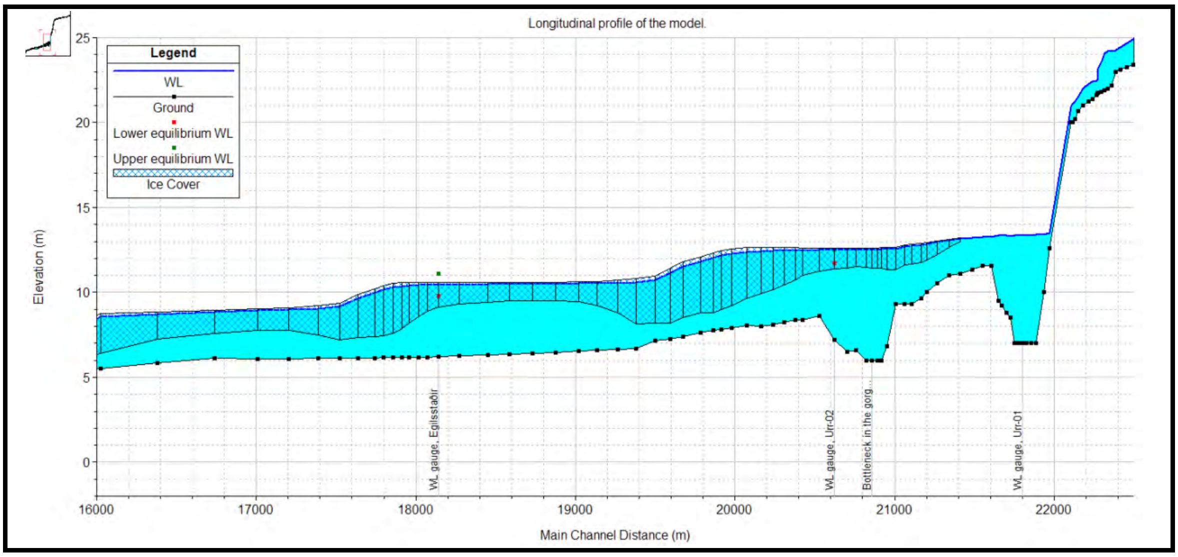


Figure A2.13 *Calibration of the early stages of Urriðafoss Ice Jam.*

Appendix 3 – The development of the Hagalón Ice Jam

In this appendix the expected development of the ice jam is shown starting with an ice formation on the intake-pond. On each figure there are two graphs. The upper one shows the mean velocity in the cross section at each location in the model and the lower one shows the water surface profile and the ice formation. On both graphs there are two lines (plus the ice in the lower), one for ice free conditions and the other one for the river with ice jam formed.

At the first one the ice formation has started but not gone on for long. On each additional figure time has been added and more ice formed adding to the ice jam. In reality it would be difficult to predict how far up the ice jam would form each time as that depends on the length of the cold spells and its severity. Also the formation could be broken up with warmer periods and breakup to some degree or fully. The model does not account for that.

In the text for each figure the volume of the ice mass is given.

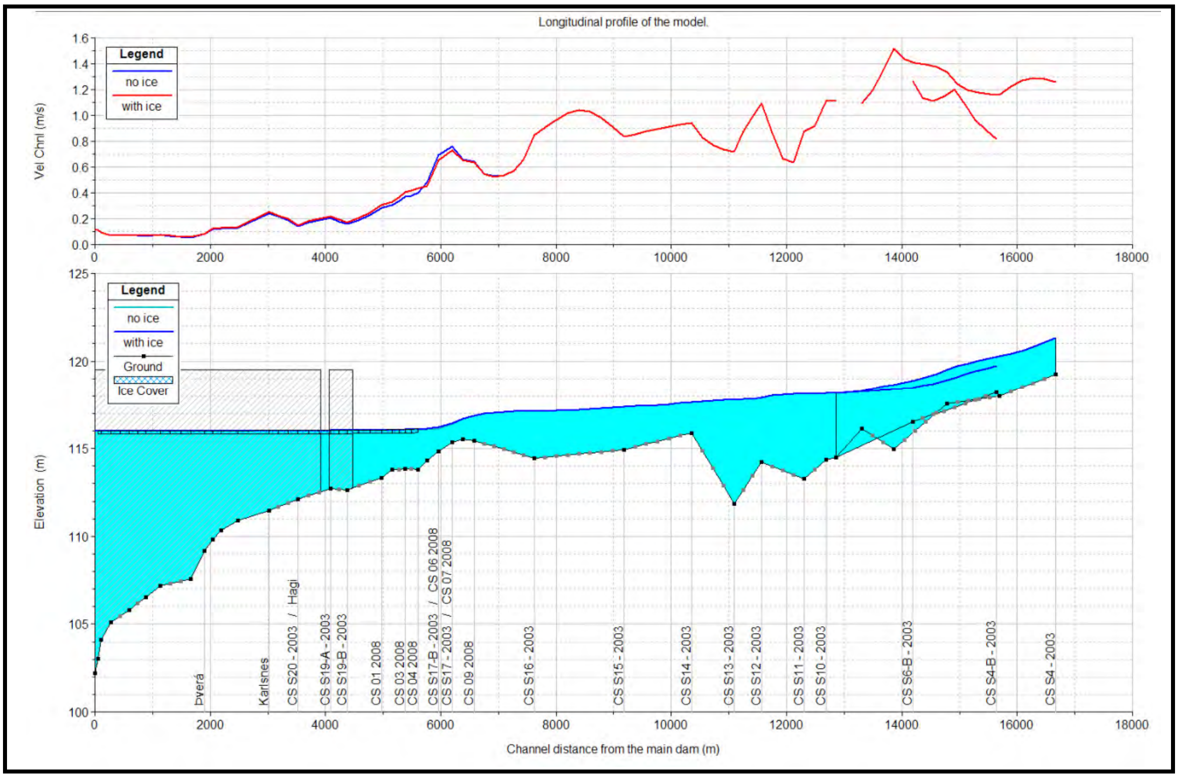


Figure A3.1 *Ice volume 0,4 Mm³.*

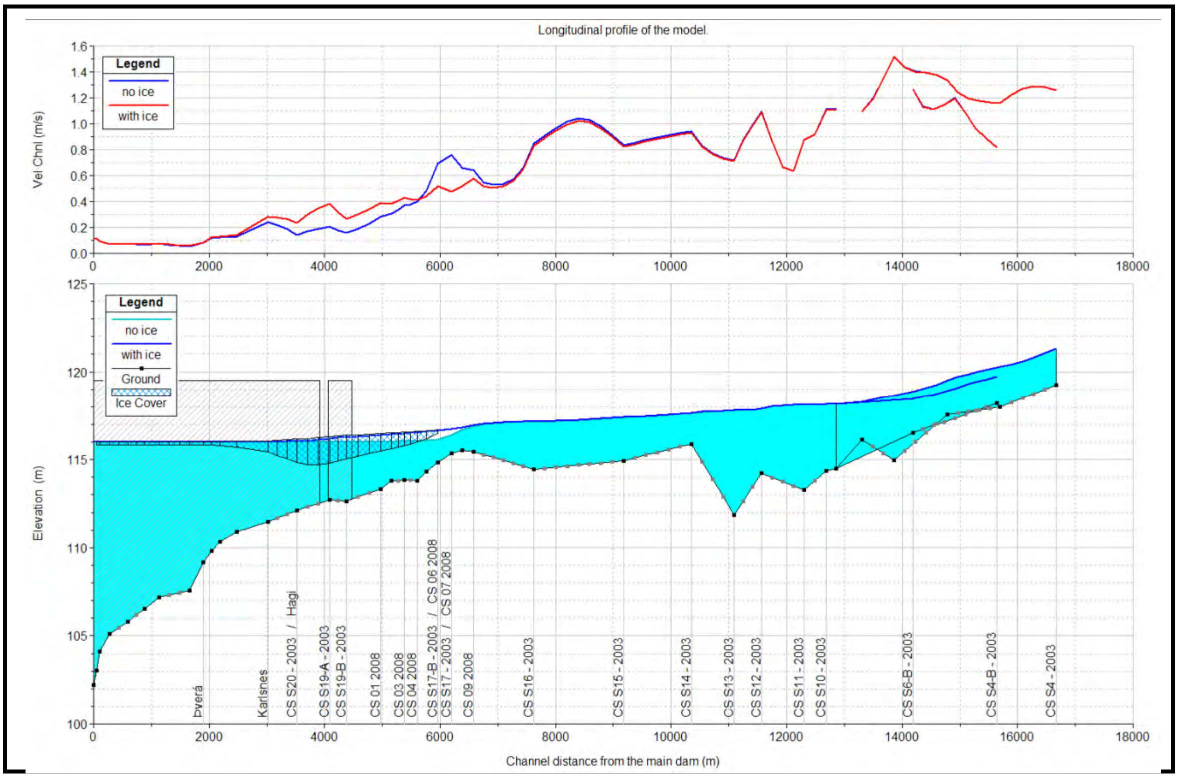


Figure A3.2 *Ice volume 1,5 Mm^3.*

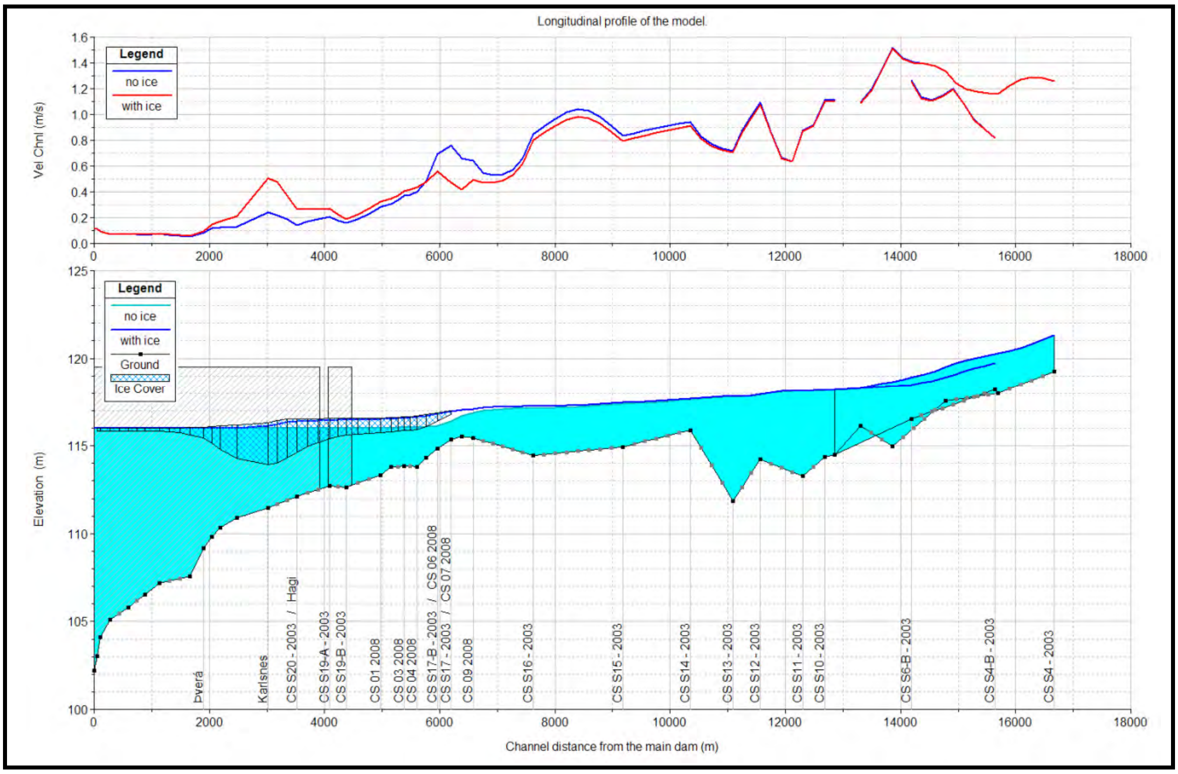


Figure A3.3 *Ice volume 2,0 Mm^3.*

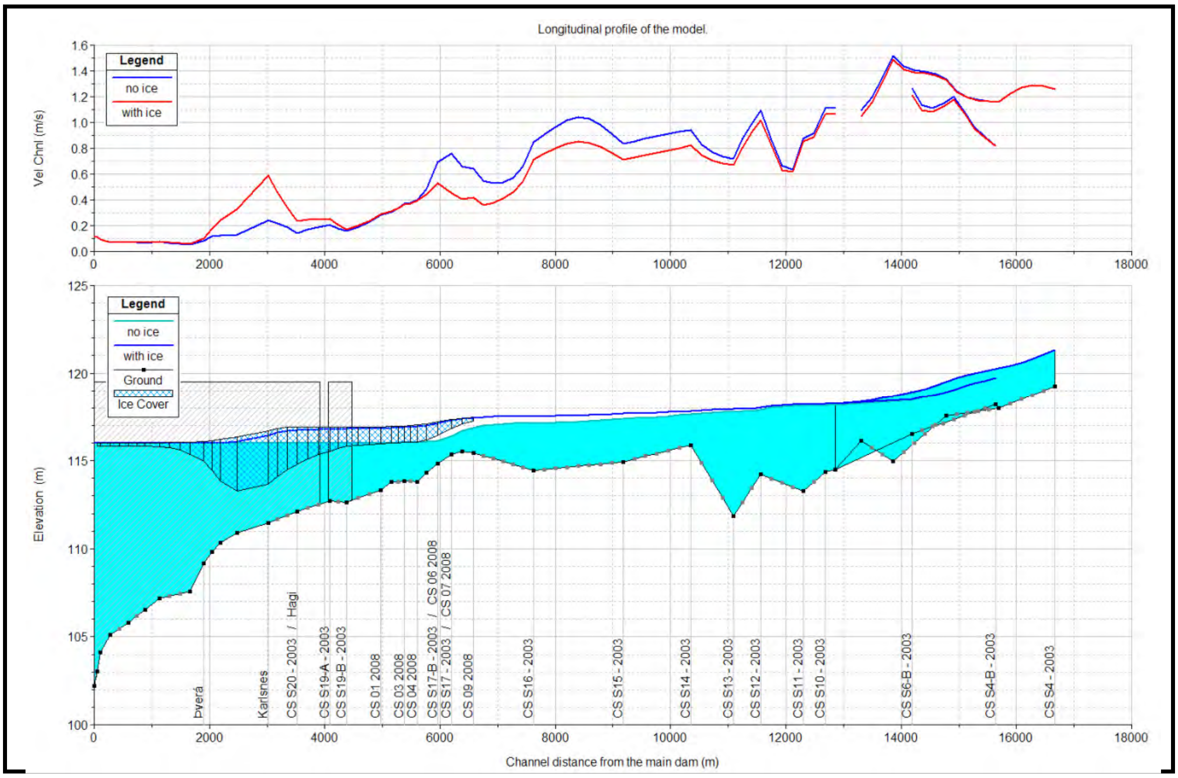


Figure A3.4 *Ice volume 2,7 Mm³.*

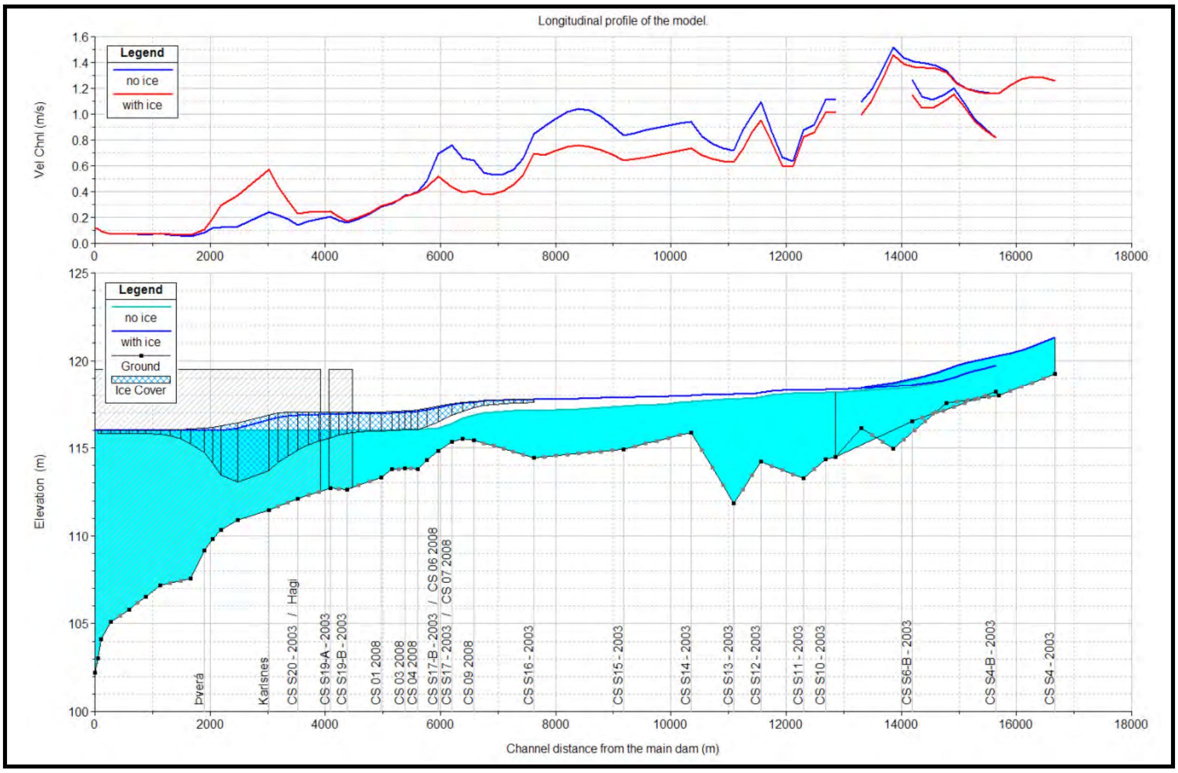


Figure A3.5 *Ice volume 3,1 Mm³.*

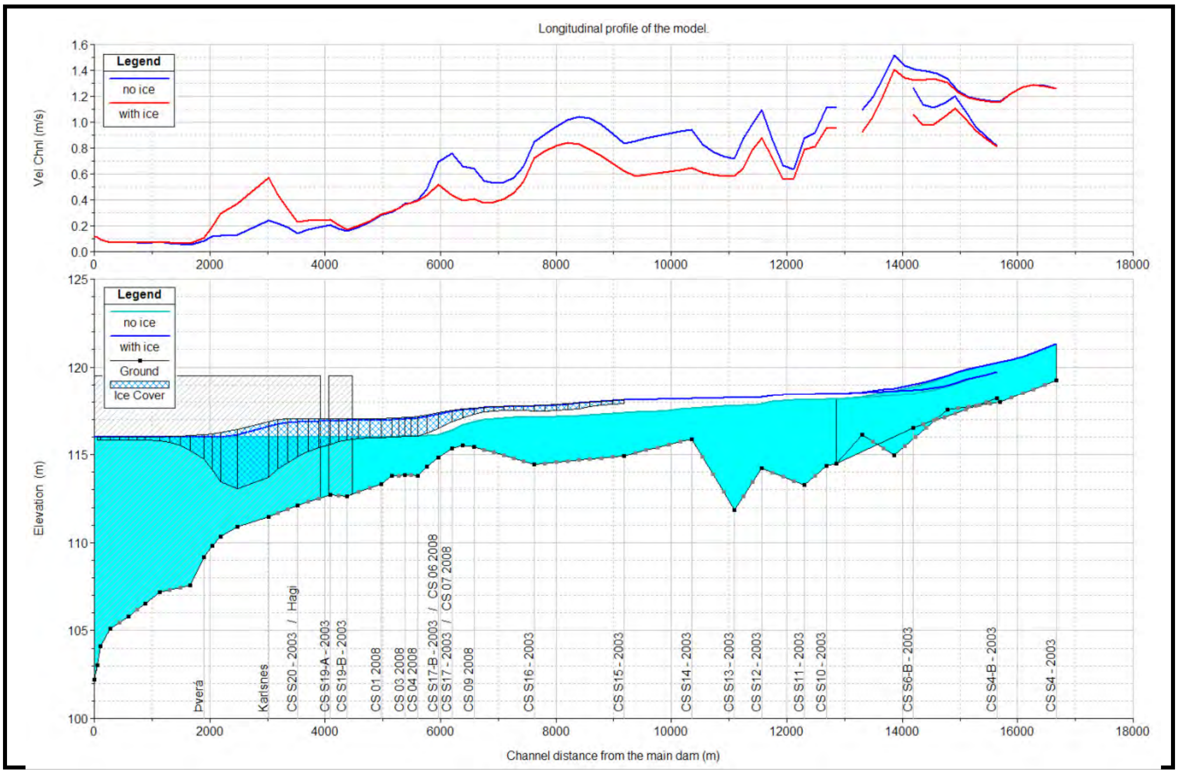


Figure A3.6 *Ice volume 3,2 Mm³.*

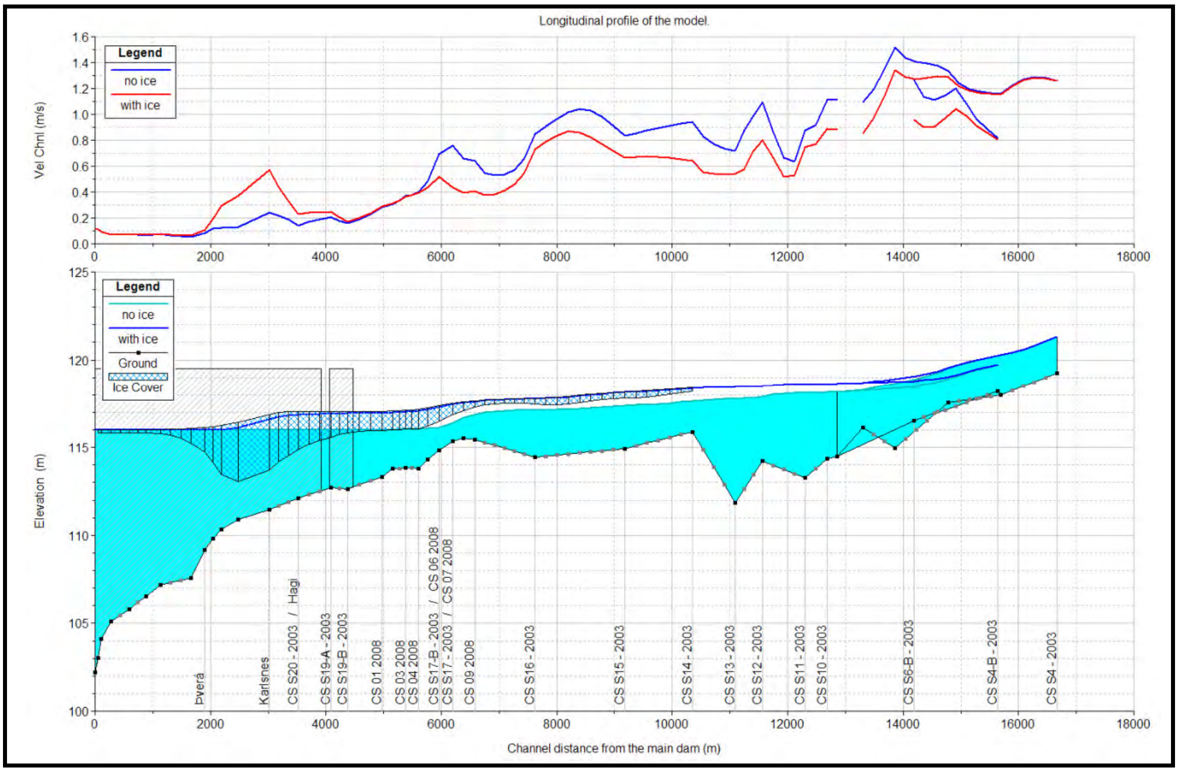


Figure A3.7 *Ice volume 3,3 Mm³.*

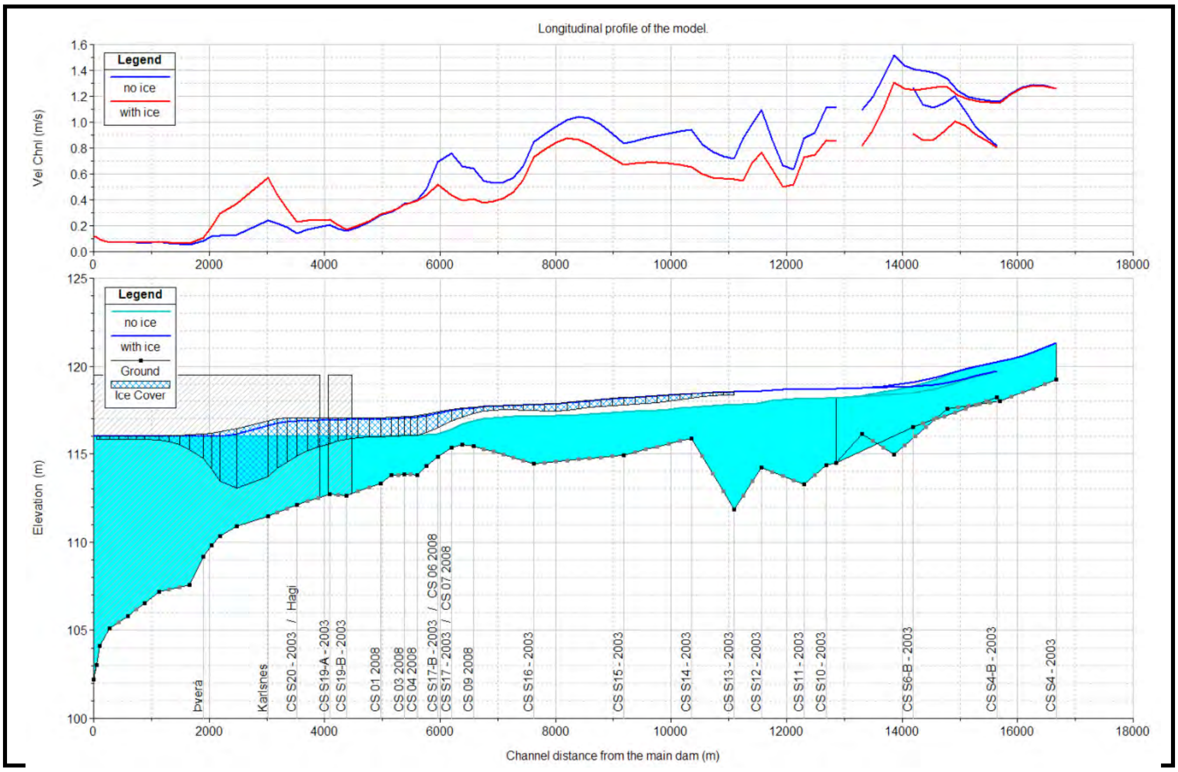


Figure A3.8 *Ice volume 3,3 Mm^3.*

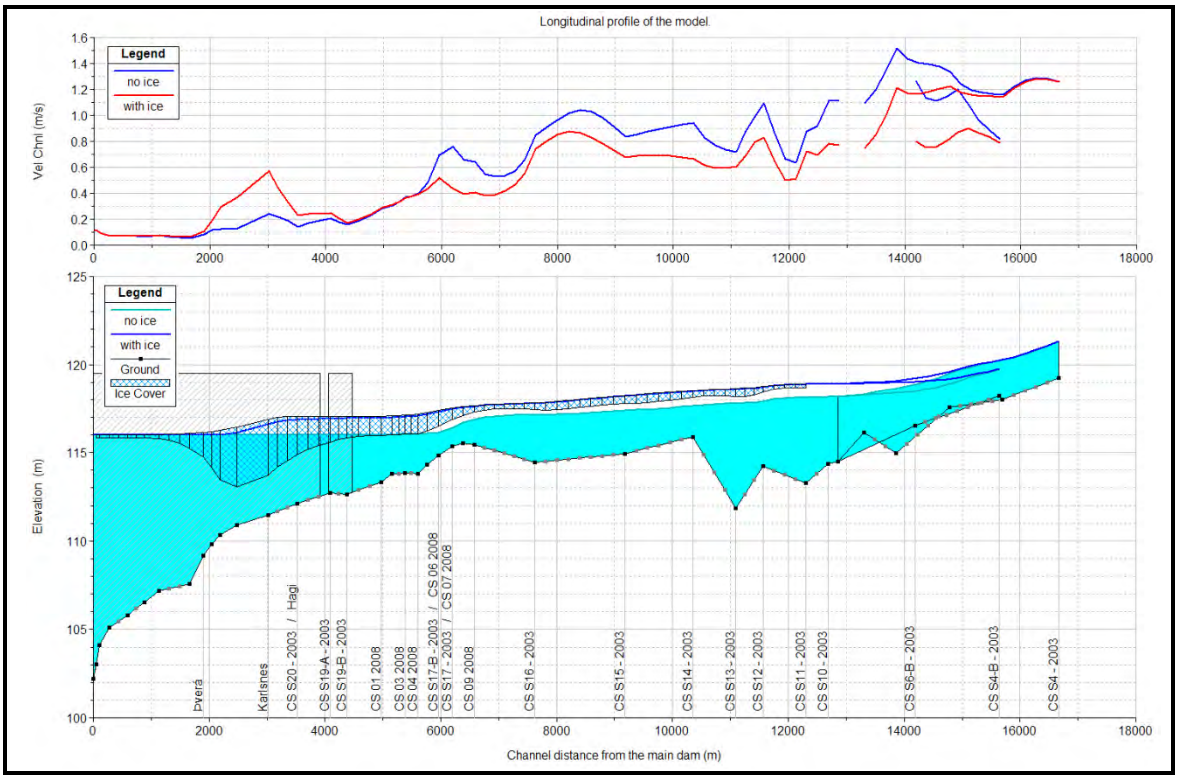


Figure A3.9 *Ice volume 3,4 Mm^3.*

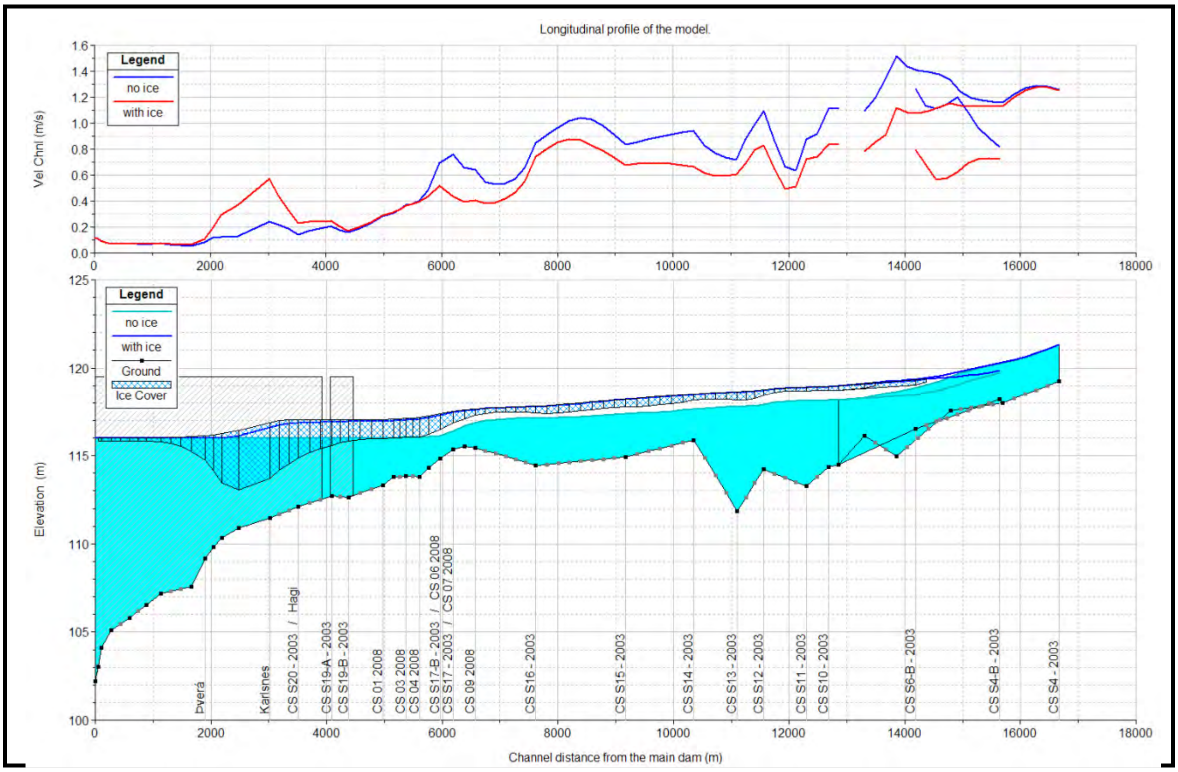


Figure A3.10 *Ice volume 3,5 Mm^3.*

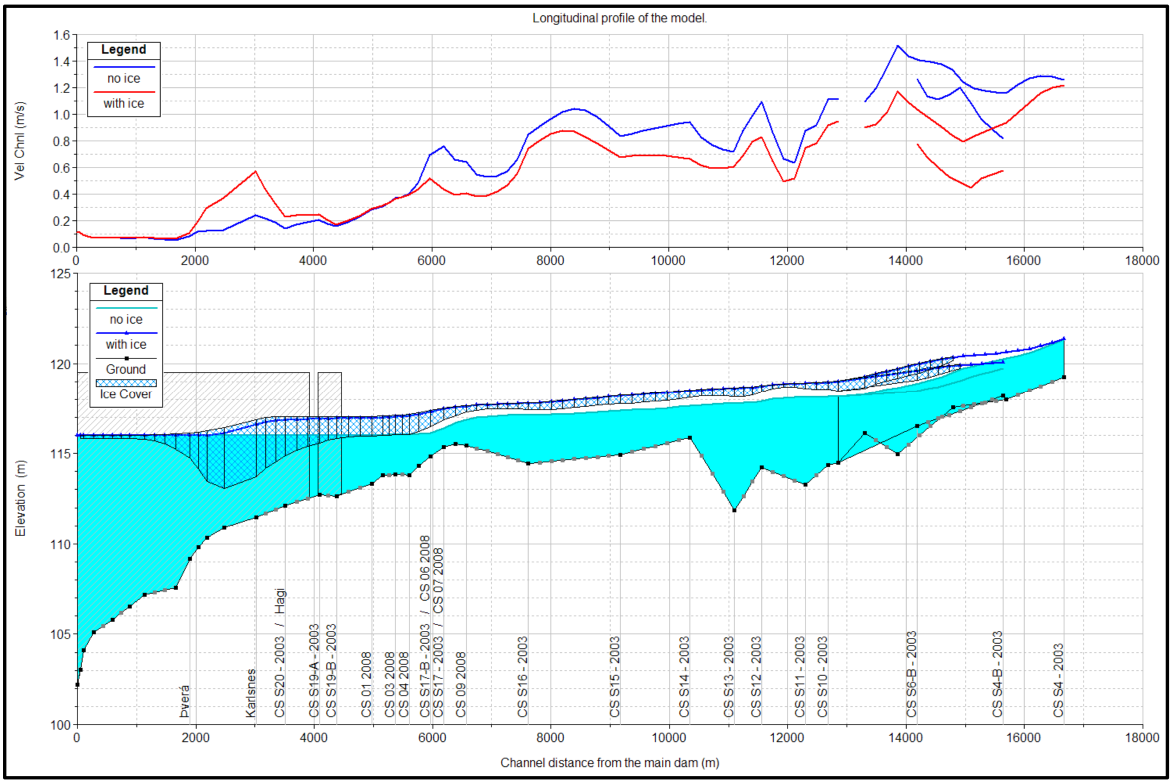


Figure A3.11 *Ice volume 3,6 Mm^3.*

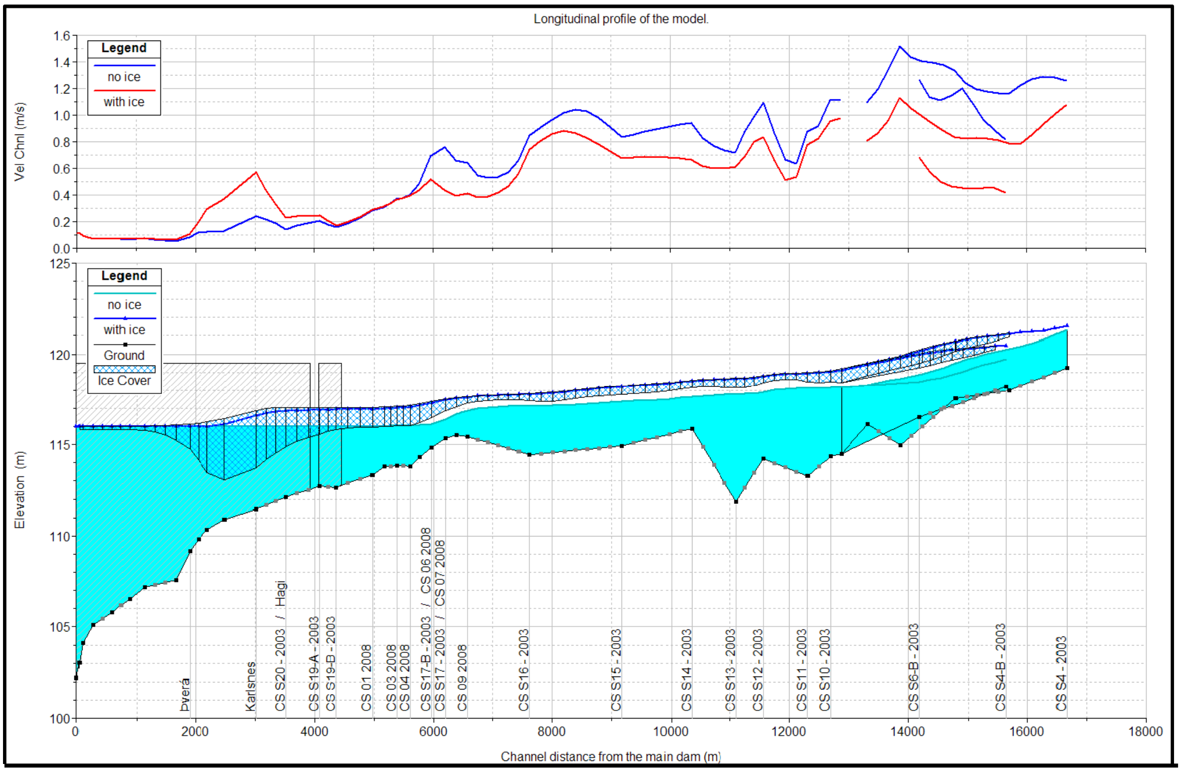


Figure A3.12 *Ice volume 3,8 Mm^3.*

Appendix 4 – Effects of possible dredging operations – Hagalón Pond

See chapter 6.4.5 for more information.

Yrjasker Reef

First version, Yrjasker 1.

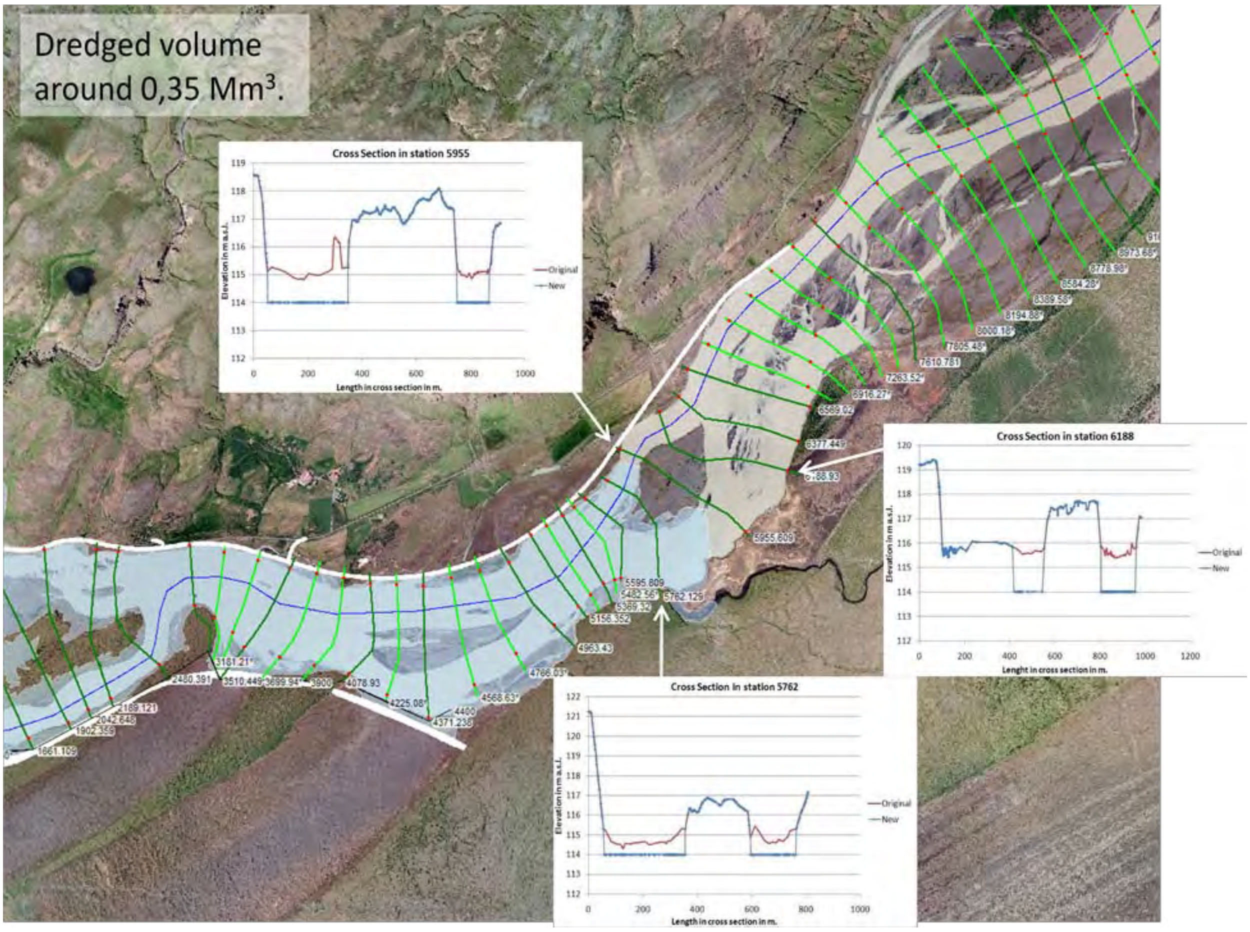


Figure A4.1 *The bathymetry of the river on either side of the reef is lowered down to 114 m a.s.l. in three cross-sections.*

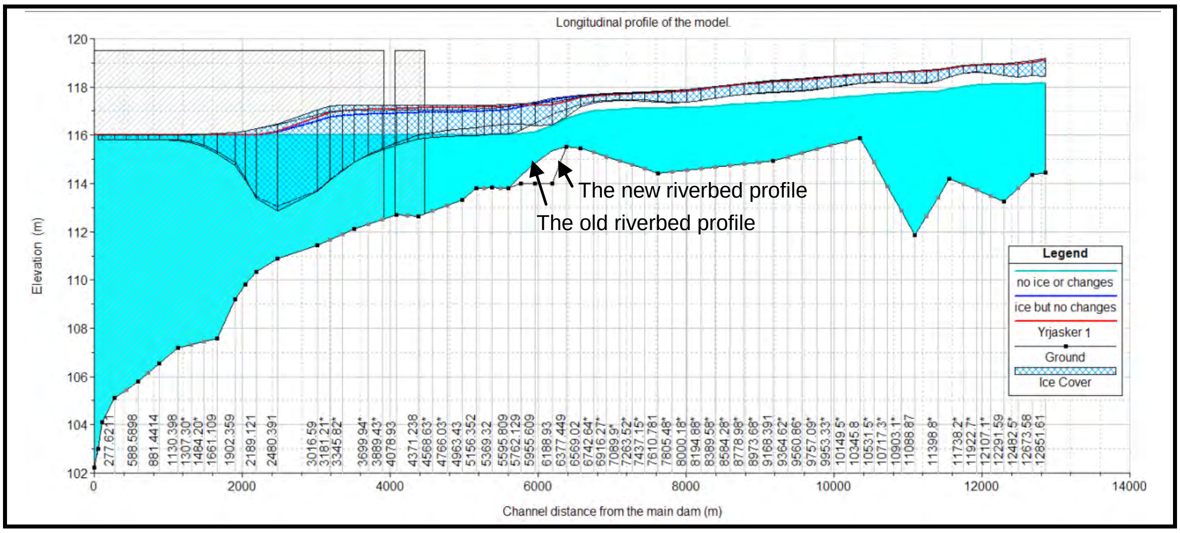


Figure A4.2 *The changed longitudinal profile is the red one. Very small changes. Above the junctions there are no changes so only the lower part of the model is shown.*

Second version, Yrjasker 2.

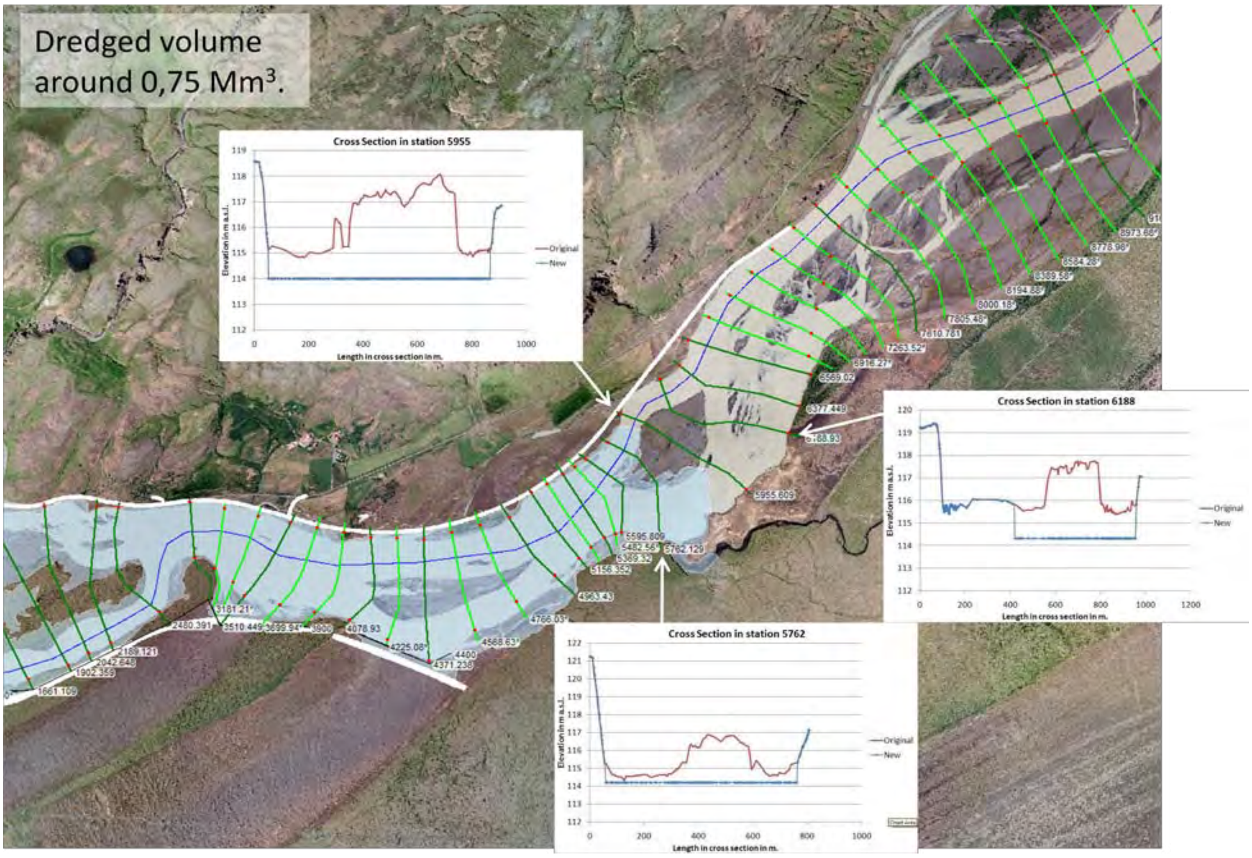


Figure A4.3 *The bathymetry of the river on either side of the reef is lowered down to 114 m a.s.l. in three cross-sections as before and the reef is removed.*

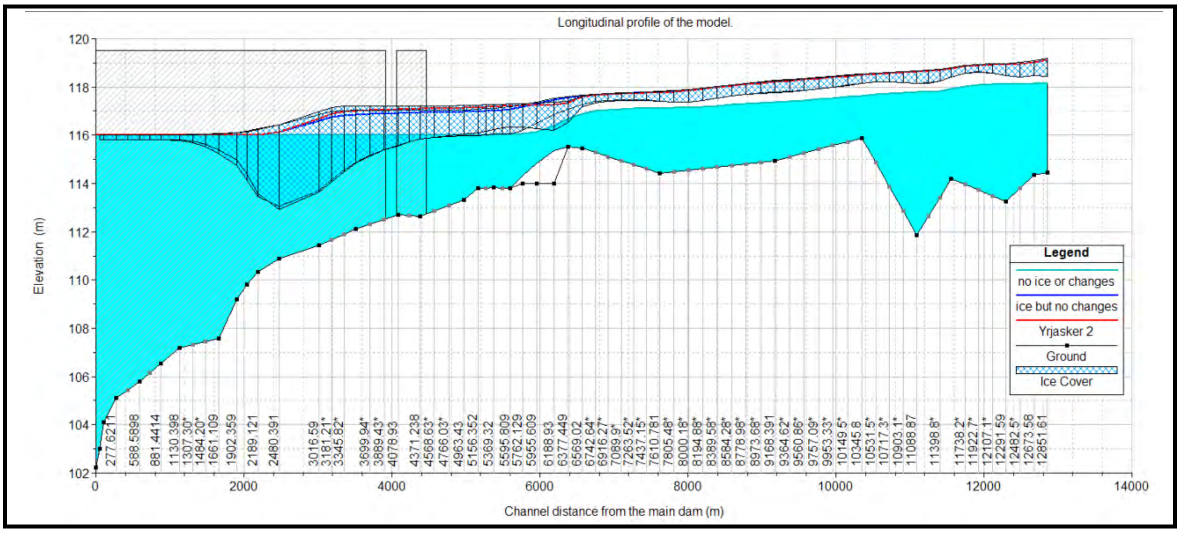


Figure A4.4 *The changed longitudinal profile is the red one. Very small changes. Above the junctions there are no changes so only the lower part of the model is shown.*

Third version, Yrjasker 3.

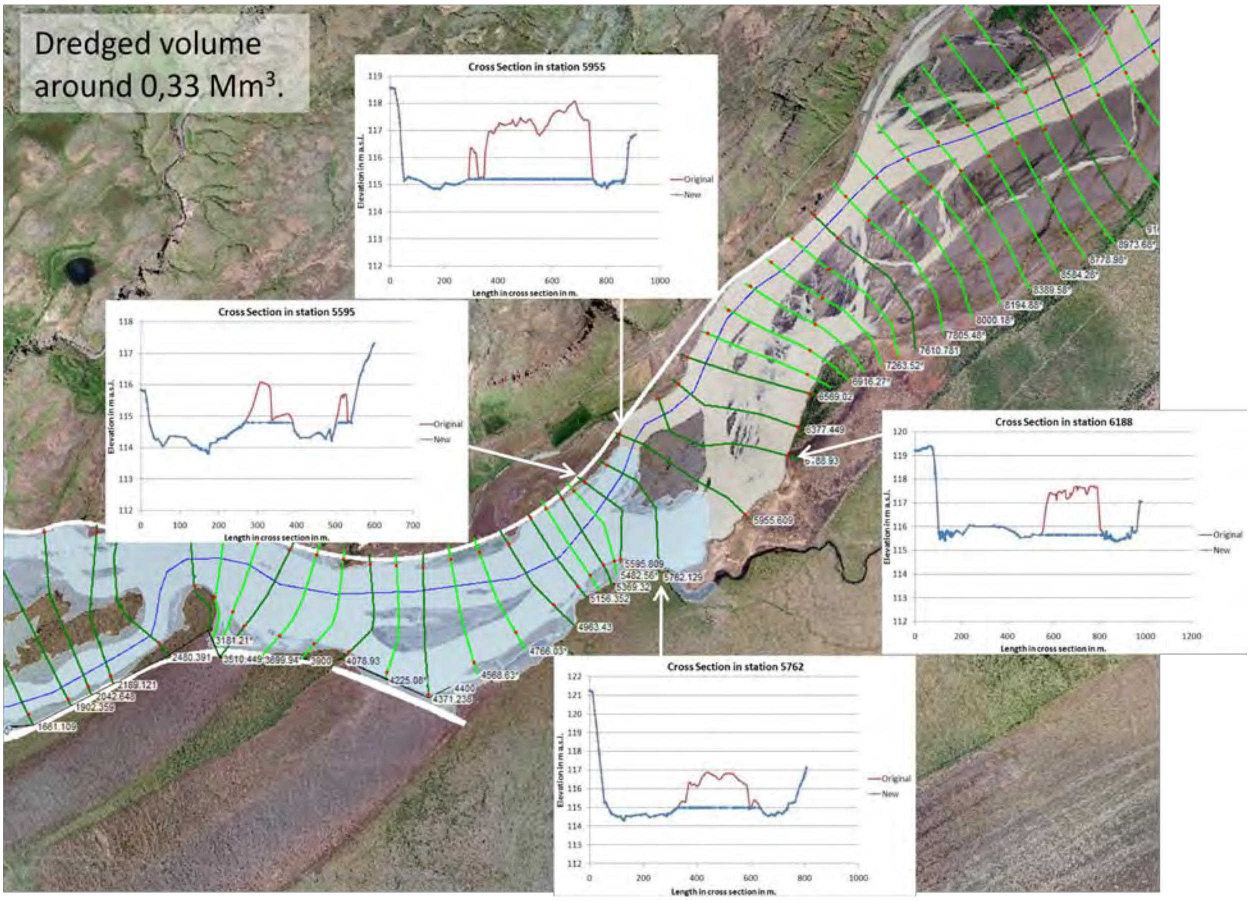


Figure A4.5 *The bathymetry of the river is changed by removing the reef.*

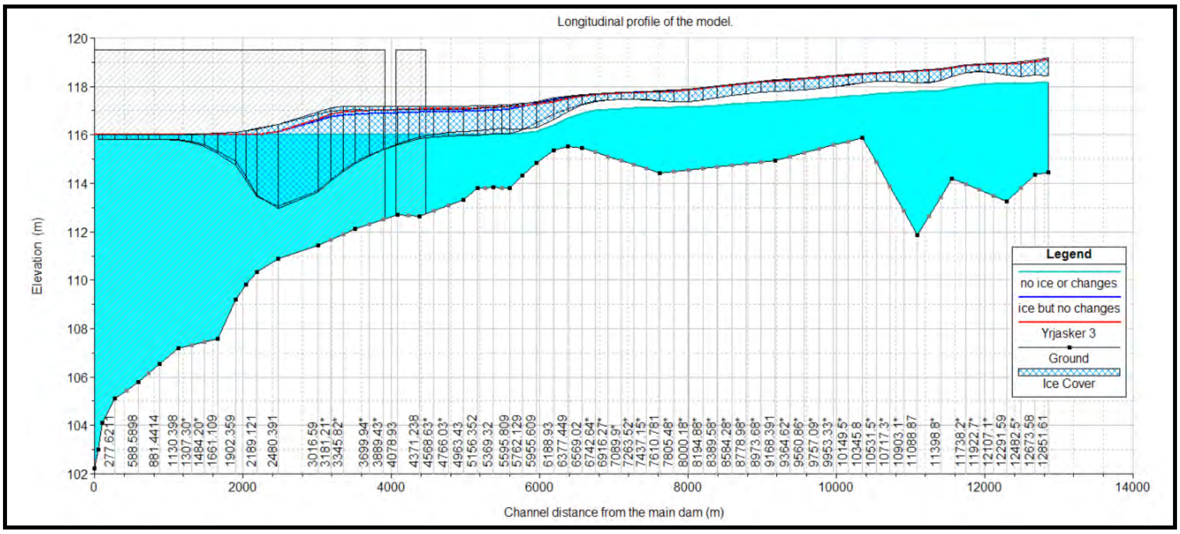


Figure A4.6 *The changed longitudinal profile is the red one. Very small changes. Above the junctions there are no changes so only the lower part of the model is shown.*

The shallows caused by the lava removed

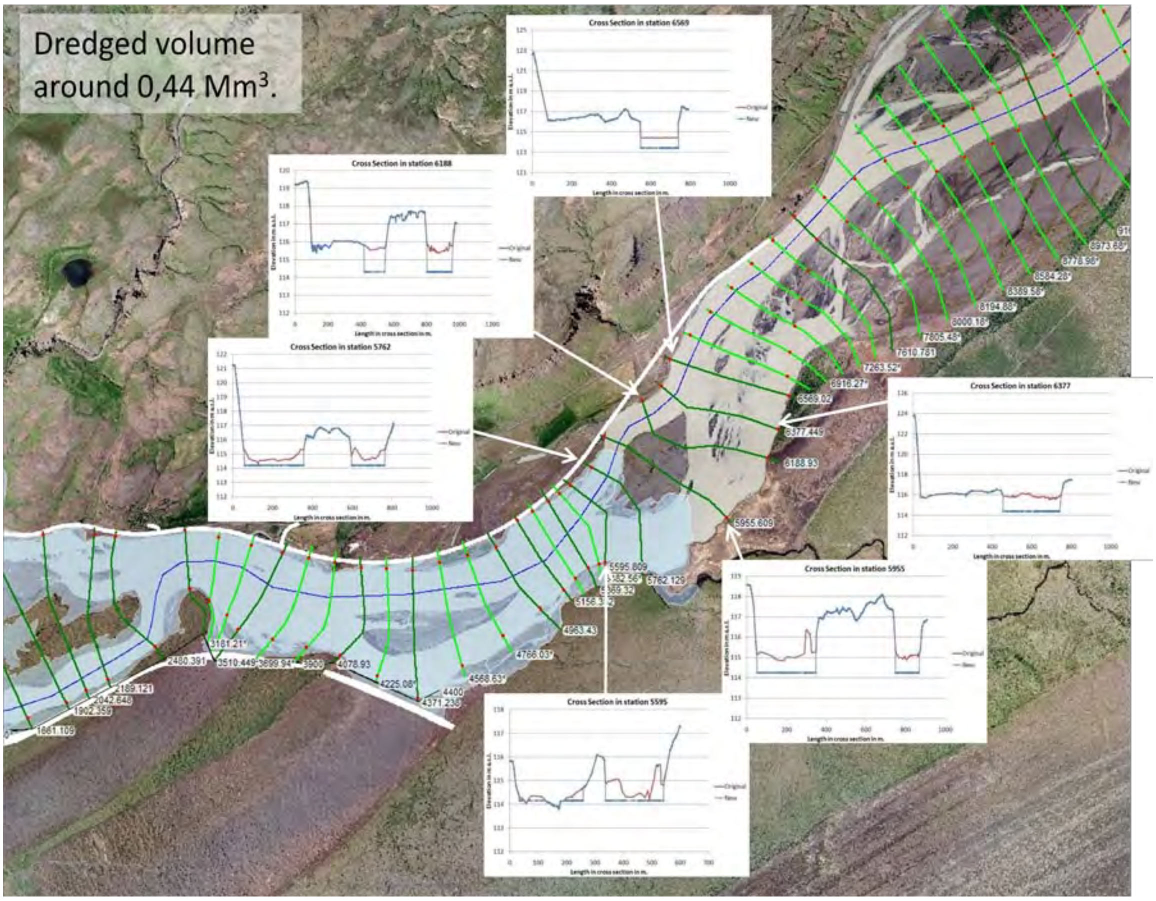


Figure A4.7 *The bathymetry of the river is changed by removing the shallows.*

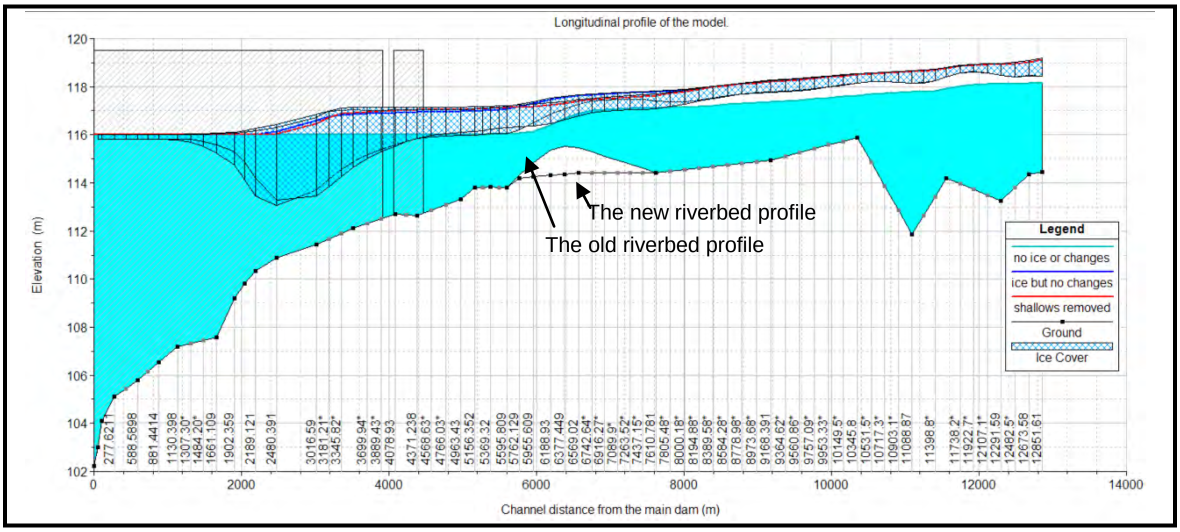


Figure A4.8 *The changed longitudinal profile is the red one. Again small changes. Above the junctions there are no changes so only the lower part of the model is shown.*

The upper part (shallow part) of the intake pond lowered

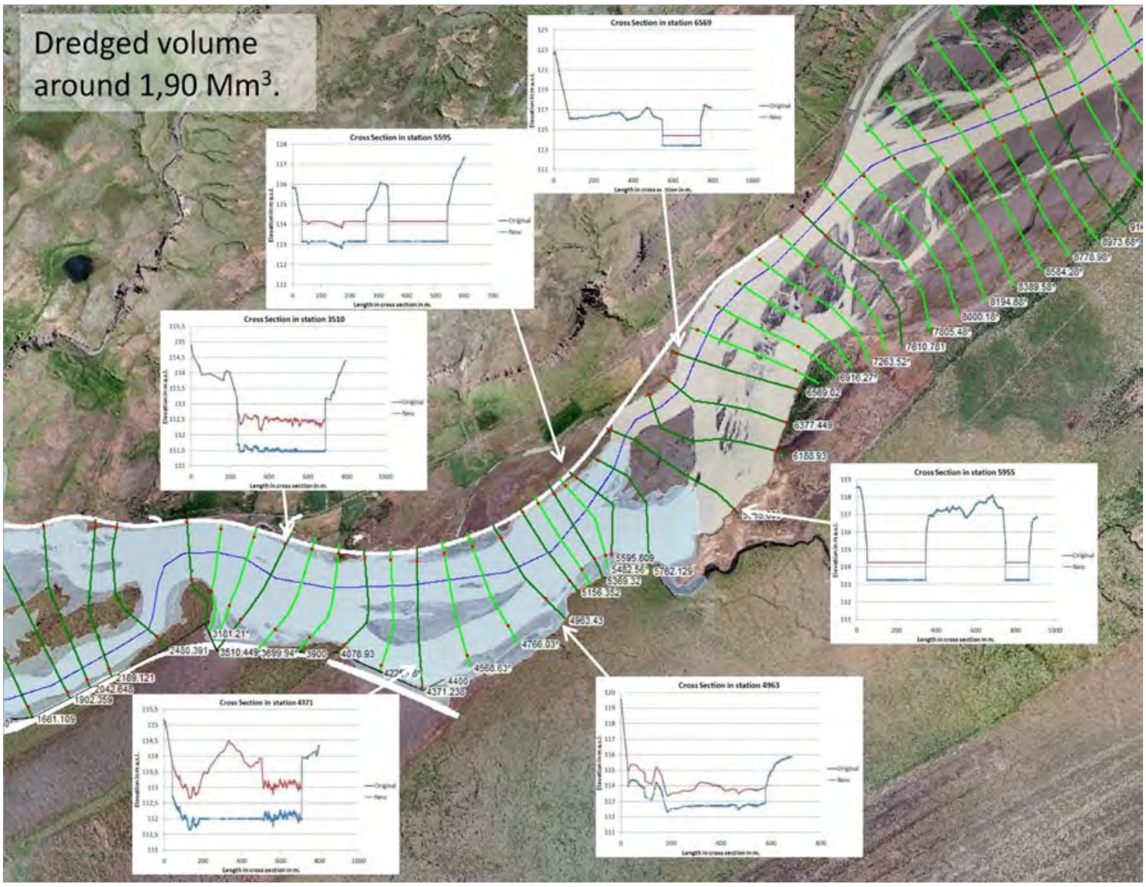


Figure A4.9 *The bathymetry of the river is changed by lowering the upper part of the intake pond. Only a few of the cross sections are shown as indication of how they were changed, as they are too many to show them all.*

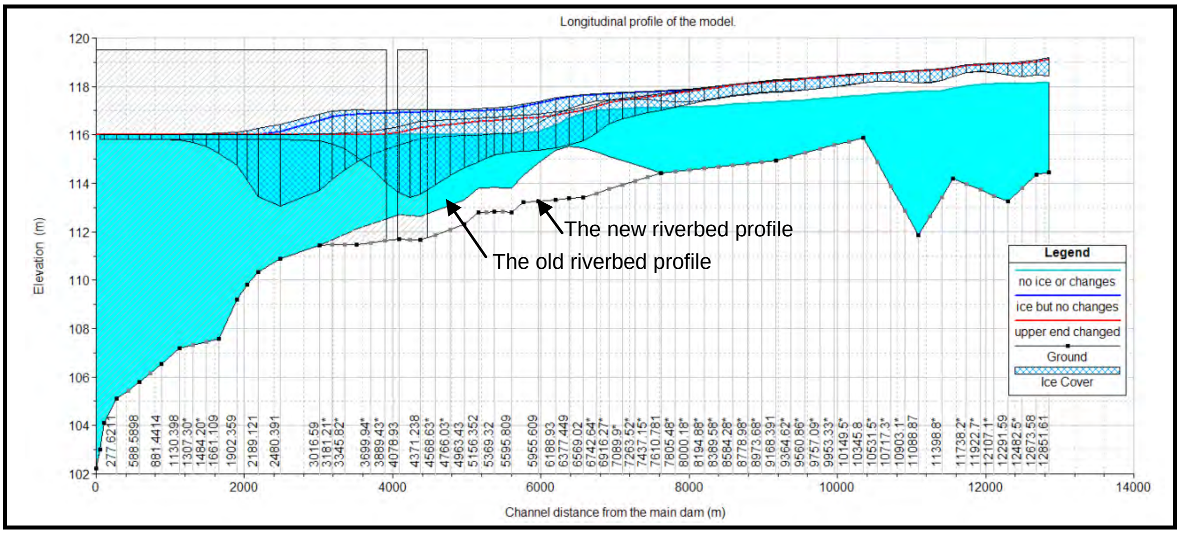


Figure A4.10 *The changed longitudinal profile is the red one. Above the junctions there are no changes so only the lower part of the model is shown.*