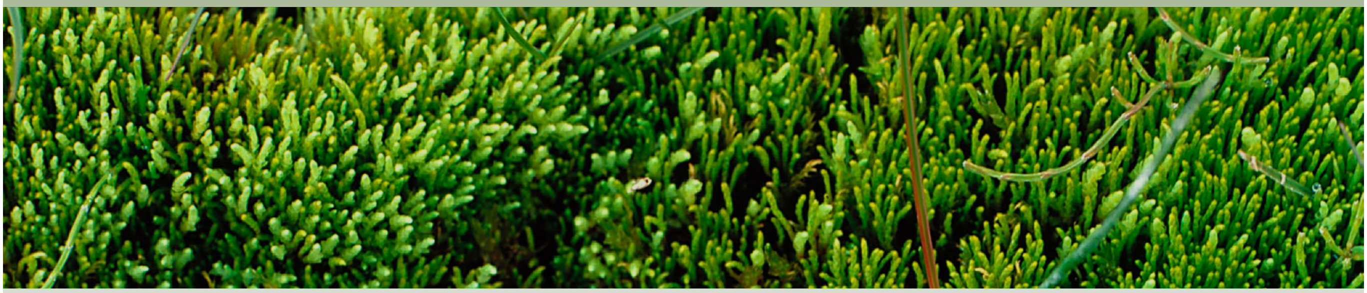
LV-2018-088

Landsvirkjun



The Laxá
Hydrology and sediment transport

Changes caused by the hydropower stations

Lykilsíða

Landsvirkjun

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Útdráttur: This report is a part of a research plan intended to shed light on how the Laxá Stations have affected salmon in the Laxá. It covers the topics of flow and sediment transport with the focus on possible changes in daily flow pattern, floods, sediment transport and settling. Additionally, removal of material from the river is addressed and the effects on the substrate.
The main results were: the Laxá Stations have almost no effect on flow, floods and transport of alluvial material due to the small sizes of the intake ponds. The transport of larger material is likely to have been affected.
The structures in the Geirastaðir branch has affected the flow in the Laxá. The effects are: more steady flow in the Laxá, less water level fluctuations in Mývatn and less ice formations in the Laxá.
Improvements include: a) A safe passage of sediment material. b) A plan to transport some material to the Laxá downstream of the Laxá Stations.

Lykilorð: Laxá, rennslissveiflur, flóð, aurburður, setmyndun, botnefni, ísmyndanir, íshrannir, útskolun úr lónum.

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AUTHOR(S):	PROJECT MANAGER:
Hörn Hrafnsdóttir	Hörn Hrafnsdóttir

CLIENT:	CO-OPERATORS:
Landsvirkjun	
SUPERVISION:	
Sveinn Kári Valdimarsson	

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Improvements include: a) A safe passage of sediment material. b) A plan to transport some material to the Laxá downstream of the Laxá Stations.

KEYWORDS (ENGLISH):	KEYWORDS (ICELANDIC):
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PROJECT MANAGER´S SIGNATURE:	REVIEWED BY:
Hörn Hrafnsdóttir	Sveinn Kári Valdimarsson (LV) Helgi Jóhannesson (LV) Þórhildur Guðmundsdóttir (Verkís)

LV-2018-088

The Laxá
Hydrology and sediment transport

Changes caused by the hydropower stations

December 2018

Abstract

Landsvirkjun and the angling clubs are working together on a research plan that is intended to shed light on how the Laxá Hydropower Stations have affected salmon in the Laxá. This report is a part of this work and covers the topics of flow and sediment transport.

Besides looking into the natural behaviour of the river, regarding flow and sediment transport, the focus was on the following:

- Has the daily flow pattern changed?
- Have floods changed?
- Has the balance of transport and settling within the system changed?
- Has removal of material affected the substrate material in the river?
- Can some improvements be made?

The results were that the Laxá Stations have almost no effect on flow, floods and transport of alluvial material due to the small sizes of the intake ponds. The transport of larger material, cobbles and rocks, is likely to have been affected somewhat. Additionally, the access between the source of material and the river has been restricted within the Laxá canyon due to constructions and changes made within the canyon. Quantifying the effect is very difficult.

The main changes on flow in the Laxá are caused by the structures in the Geirastaðir branch just below Mývatn. The effects are:

- more steady flow from Mývatn to the Laxá,
- less water level fluctuations in Mývatn and
- less ice formations in the Laxá.

Improvements include a safe passage of sediment material, the whole range from sand to rocks, past the Laxá Stations. This is already in the first phase where a new construction with sediment sluicing equipment is being tested. The results are promising but only cover the part from upstream of the intake tunnel for Laxá III to the downstream of the dam for Laxá III. It is foreseen that if this proves to be successful the pipes will be elongated to the downstream end of Laxá II. If that works, the equipment and pipes should pass material safely from upstream of the stations to the downstream. The operation of the equipment is also crucial as the material should be passed as naturally as possible.

To compensate for missing material from the canyon, the plan is to transport some material to the Laxá downstream of the Laxá Stations. The location has to be carefully chosen and it is suggested that the river itself is trusted to redistribute the material further downstream in wintertime with ice formations of various kind.

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1 Introduction

The purpose of this report is to shed light on the effects the Laxá Hydropower Stations have on the natural flow patterns of the river and sediment transport. Both Landsvirkjun and the angling clubs are working together on a research plan that is intended to shed light on how the stations have affected salmon in the Laxá. A draft of a research plan from the angling clubs can be found in appendix 2. At a meeting on the 13th of November 2015 between all parties, it was agreed that the angling clubs would handle the research covered under items 1, 4, and 5 while Landsvirkjun would cover points 2 and 3, see appendix 2. Additionally, Landsvirkjun expressed interest in finding working procedures that would minimize effects of the power stations on salmon and preferably finding a way to eliminate negative effects, see item 3 in minutes of meeting in appendix 1.

Table 1.1 summarises all the research points that are meant to be answered in the report. It will be built up accordingly, addressing first everything related to flow, then alluvial sand and finally substrate material.

Table 1.1 A list of the issues, questions or topics that need to be answered.

Item no.	Issue/question/research topic
Flow related	
F-1	Has daily flow pattern changed?
F-2	Has flooding changed?
F-3	In case the answer to F-1 is yes; Are there some river edge areas that could be prone to isolation?
F-4	In case the answer to F-1 is yes; How do daily flow pattern affect water velocity and water depth in spawning and non-spawning sites?
Sediment transport related	
Alluvial sand	
S-1	Transport and sedimentation of alluvial sand in the system
S-2	Impact of emptying intake ponds versus natural processes
S-3	Possible improvements on flushing procedures
Substrate	
S-4	Short report on removed material that might have contributed to substrate in the river
S-5	Transport and settling of substrate material in the river
S-6	Possible improvements

Before the topics can be addressed a short history of changes made in the river (construction history) is needed.

Table 1.2 lists all construction or other known changes.

Table 1.2 Construction history (Sigmundur Freysteinsson, 2010; Sigurjón Rist, 1979b, p. 68-69).

Year	Construction
In the Laxá canyon	
1939	Laxá I Hydropower plant.
1952	Earth fill construction above the Laxá I Station to protect it from ice surge floods.
1953	Laxá II Hydropower plant.
1973	Laxá III Hydropower plant and changes made to the intake for Laxá I Hydropower plant.
2013	Laxá I Hydropower plant taken out of operation, (penstock removed).
2017	Laxá III, changes made to the dam and intake area to flush sand, rocks and ice past the plant.
In the outlet area of Mývatn	
1945/46	Dragsey Dam, in the south branch from Mývatn with bulkhead gates.
1959/60	Canal in Geirastaðir branch and Geirastaðir Dams with bottom outlet/gates.
1961	Dam and fish ladder in the middle branch from Mývatn.
1970	Dam in the middle branch destroyed by local people.
1995	The fish ladder removed and the site cleaned. A small stone weir built instead.
1998	Small changes made to the branch downstream of Dragsey Dam.

2 Flow characteristics and changes

2.1 The Laxá

The Laxá is mainly a spring fed river, running from the lake Mývatn to the ocean in Skjálfandi bay in the north of Iceland. The river is the second largest spring fed river in Iceland with average discharge of about 40 m^3/s at Helluvað[1] and its length is 59 km. From Mývatn down to Brúar Falls, the river runs through the valley Laxárdalur and is therefore called the Laxá in Laxárdalur. This part is 33 km in length with the Laxá Hydropower Plants located in the canyon Laxárgljúfur just above Brúar Falls. Downstream of Brúar Falls, Laxárdalur opens into a bigger valley called Aðaldalur. There, the river is called the Laxá in Aðaldalur.

The Laxá drops approximately 279 m on its 59 km course, see Figure 2.1, and the whole river basin can be divided into 5 sub-catchment areas as shown on figure 2.2. Geological maps of the area show that large parts of the catchment area are covered with young lava (pink areas in figure 2.3). In those areas the water flows as ground water. This means that the catchment areas are not clear as the water does not follow the topography of the land.

Mývatn has a surface area of 37 km^2, with relatively stable water table of about 279 m a.s.l. The main inflow is through springs opening into the lake. The discharge to the lake through these springs is about 35 m^3/s. The lava formations that cover most of Mývatn's catchment area act as a big groundwater reservoir with damping effects, resulting in very stable inflow to Mývatn. The only surface flow into the lake comes from the brook Grænilækur, draining the lake Grænavatn which is also a spring fed lake like Mývatn.

The upper part of the Laxá has one main tributary, the Kráká, which discharges into the southernmost branch of the Laxá very close to Mývatn, adding about 7 m^3/s to the discharge. The Kráká is also spring fed. It originates in Krákárbotnar, approximately 30 km south of Mývatn.

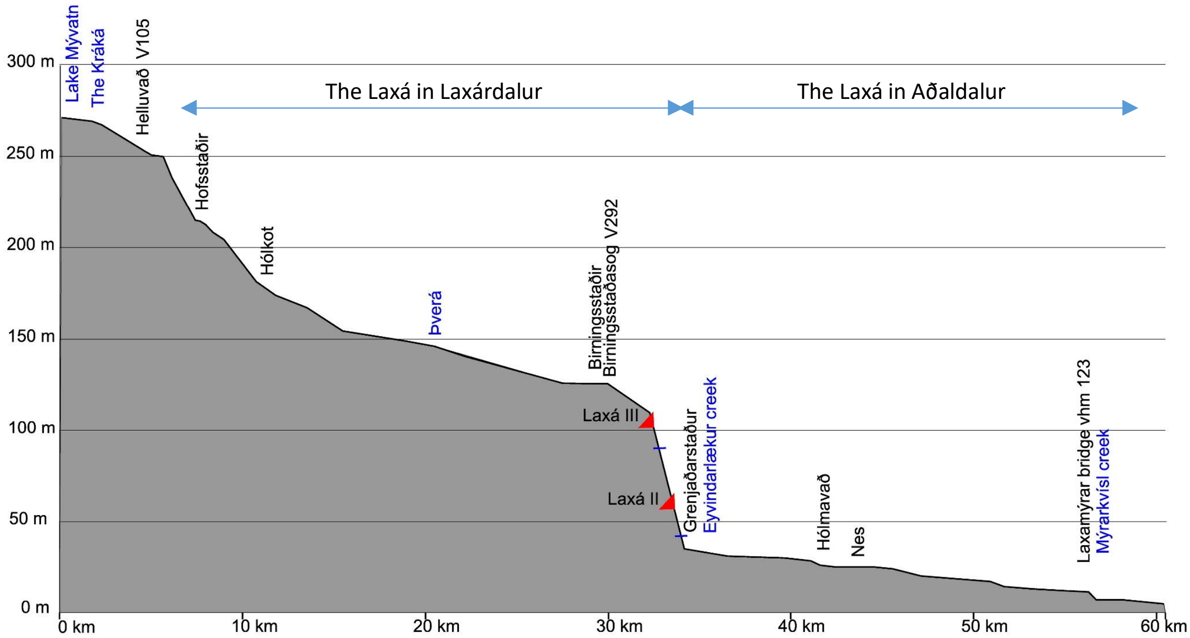

Figure 2.1 Longitudinal profile of the Laxá.

[1] According to Sigurjón Rist the flow from Mývatn is 32 m^3/s, 1m^3/s from Sandvatn and 7 m^3/s from the Kráká resulting in about 40 m^3/s at Helluvað (1979a, p. 271). Data from the measuring station V105 gives 38 m^3/s based on average daily discharge values from the beginning of September 1961 to end of September 2013 (Veðurstofa Íslands, 2014a).

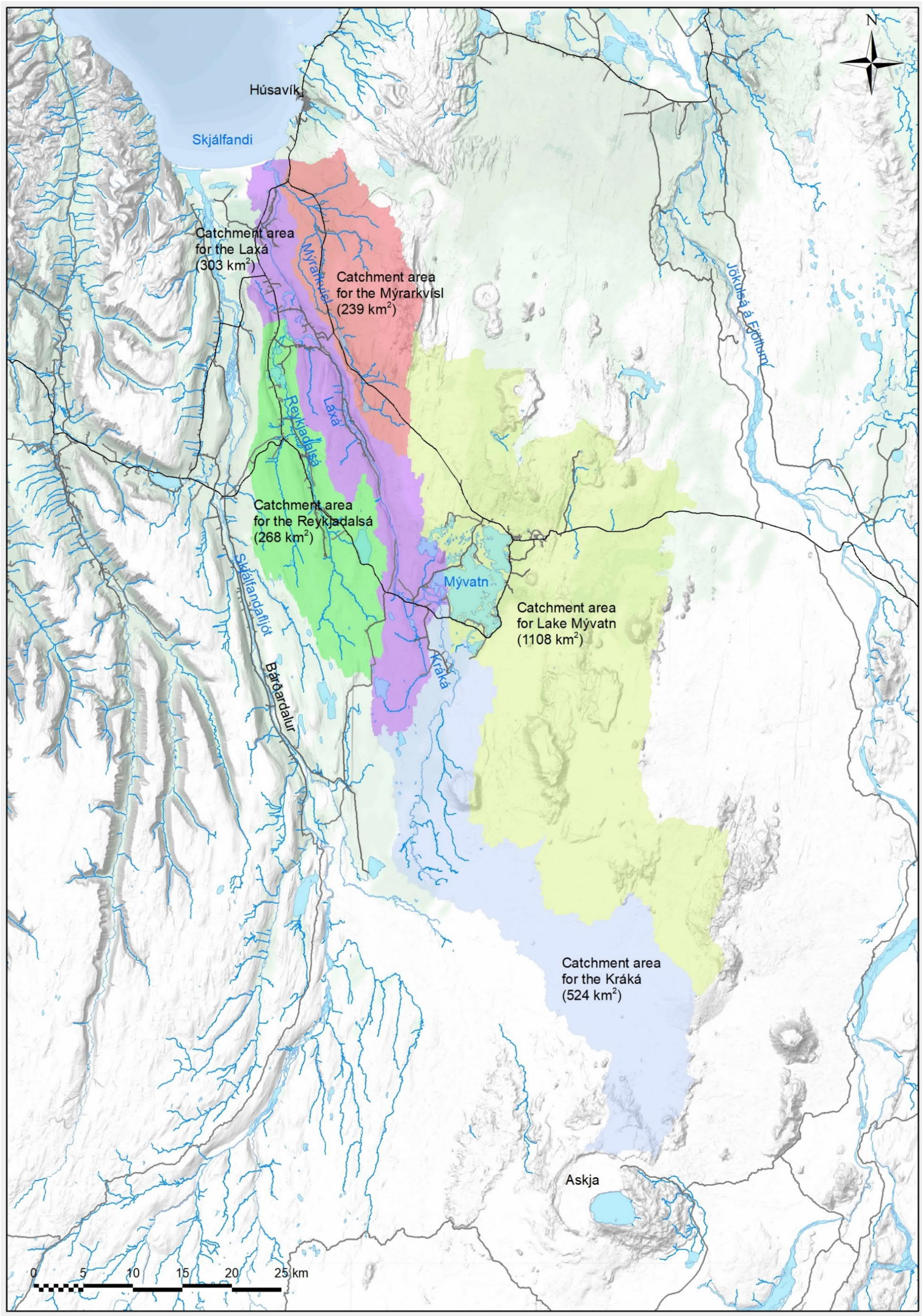

Figure 2.2 The Laxá basin and its sub-catchment areas.[2]

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[2] Based on topography using DEM model where available, TK-50 and in some cases adjusted to a shape file from Landsvirkjun („DEM created from DigitalGlobe, Inc., imagery and funded under National Science foundation awards 1043681, 1559691, and 1542736“, e.d.; Loftmyndir ehf, e.d.)

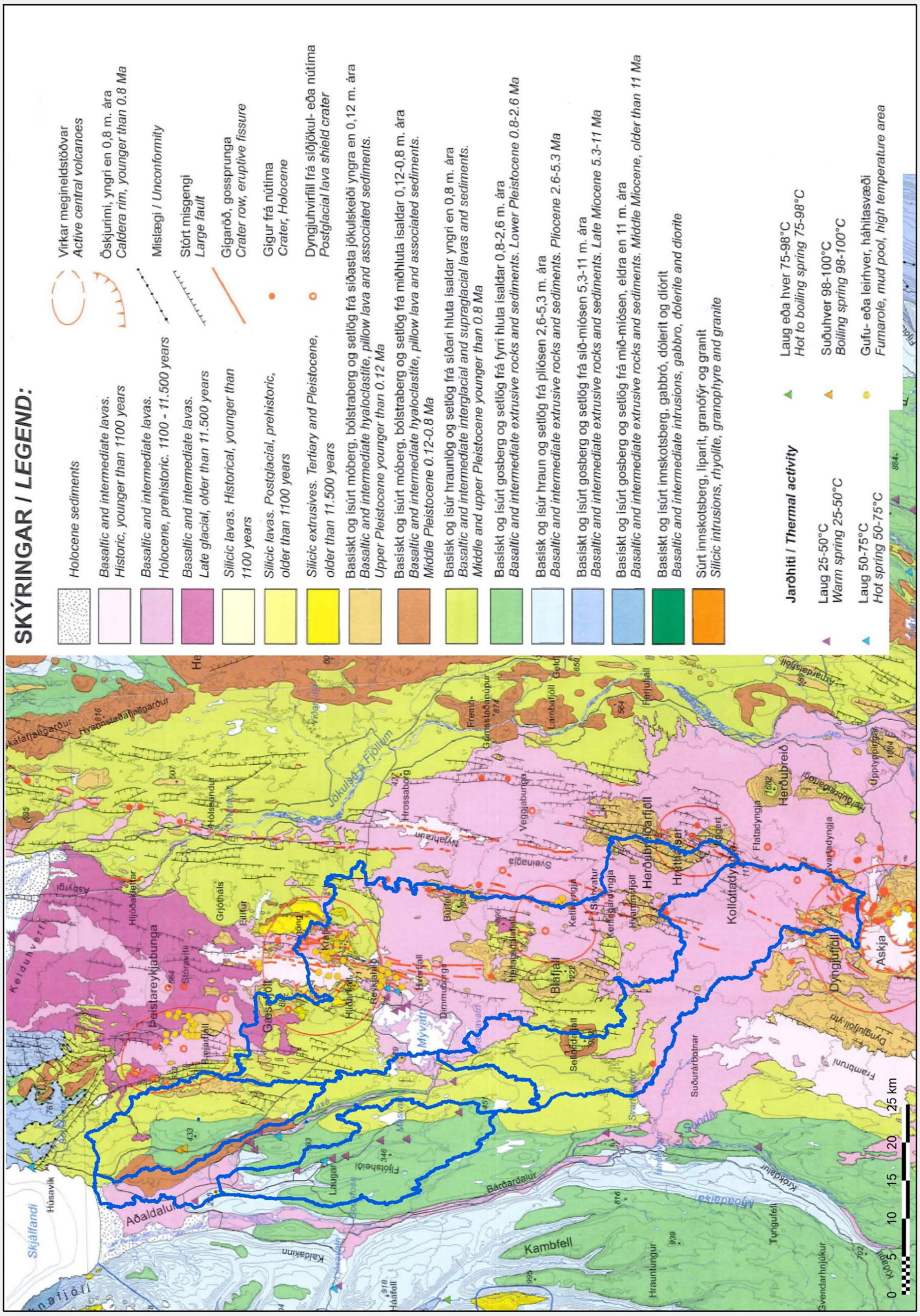

Figure 2.3 Geology of the catchment area for the Laxá („Berggrunnskort af Íslandi: Geological Map of Iceland. Bedrock: 1 : 600 000“, 2014, selected part of the map).

According to Sigurjón Rist, the Laxá is one of the rivers in Iceland with most constant flow (Sigurjón Rist, 1979b, p. 74).

2.2 Daily flow pattern

Spring fed rivers have very stable discharge by nature. They do not have a daily discharge variation like glacier fed rivers that are caused by higher melting rate during the day than during the night, especially during summer time and they do not have the same magnitude of seasonal variations with much higher flow in spring than in winter time. Still, there can be discharge and water level variations in spring fed rivers due to other factors. For the Laxá in Laxárdalur, the natural cause of discharge changes is firstly due to wind and secondly due to the cold winter periods when ice formations come into play. The latter can also cause water level changes that are not related to added discharge.

Additionally, in the Laxá there is the possibility of manmade discharge changes at three locations:

a) control of flow from Mývatn at Geirastaðir,
b) control of flow through the intake pond upstream of Laxá III (and I) and
c) control of flow through the intake pond upstream of Laxá II.

In this chapter the natural fluctuations in discharge and water level (excluding floods, which will be covered in chapter 2.3) will first be looked at in two separate chapters and then the manmade control addressed. The last chapter will summarize the findings.

2.2.1 Flow changes due to wind effects

High water level in the outlet area of Mývatn leads to more water flowing through the outlet branches. Similarly, low water level in the outlet area leads to less water flowing into the river. This is how the wind affects the flow in the Laxá by influencing the water level in the outlet area of the lake. Sigurjón Rist described how this works in an article in Oikos in 1979. There it says:

> Lake Mývatn itself yields 32 $m^3\ s^{-1}$ to river Laxá. The springs yield almost a constant flow into the lake all year round and longtime fluctuation are just perceptible. If instead of the lake there was only a narrow channel from the sources the flow farther downstream would be as stable as the head springs. *In fact it is the Lake Mývatn itself, which causes daily flow variations in the River Laxá*. When the wind is blowing along with the outflow current this will increase, but it decreases when the wind blows against the current. Flow variations are most frequently due to changes in the wind direction, but the greatest variations are caused by ice barriers on the outflow control. (p. 276)

The phenomena Sigurjón is referring to is known as wind set-up. In plain language wind set-up happens when the wind pushes the water in the wind direction. A more scientific description is that wind set-up “results from the shear induced by continuous wind (or regular gusts in one direction)” (Novak, Moffat, Nalluri og Narayanan, 1990, p. 162) causing the water level of a lake to become uneven, raising the water level in the direction the wind is blowing and subsequently lowering the water level on the opposite site. The Zuider Zee equation can be used as a guide to estimate wind set-up:

$$\boldsymbol{s = \frac{U^2 \cdot F \cdot \cos\alpha}{k \cdot d}} \qquad \textbf{Eq. 2.1}$$

where

- U is the wind speed in km/h measured at 10 m height,
- F is the fetch (the free distance which wind can travel over the lake) in km,
- α is the angle of the wind to the fetch,
- k is a constant, about 62 000 and
- d is the depth of the water. (Novak, Moffat, Nalluri og Narayanan, 1990, p. 162-163)

These wind induced water level fluctuations have been measured in Mývatn at two water level stations, one located at the northern most part of the lake, at Grímsstaðir (vhm 15), and the other at the southern part of the lake, at Álftagerði (vhm 40), see locations on the map of Mývatn in figure 2.4. Sigurjón Rist shows the measurements on graphs and talks about them in his article on water level fluctuations in Mývatn. He reports that in the northern most part of the lake, where the lake is shallower (0.6 to 1.4 m), the water level rise can reach almost 70 cm during south and southwest gales. During northern storms the lowering of the water level can be as much as 30 cm. The water level range due to wind in the northern most part of the lake is thus about 1 m. In the southern part, where the lake is deeper (generally 2.5 to 3.9 m), the range is less, or 40 cm rise and 10-15 cm lowering of water level, a total range of over 0.5 m (Sigurjón Rist, 1979b, p. 70-71).

The outlet of Mývatn is to the west so the wind effect there are mostly induced by the eastern and western winds, i.e. wind blowing from east would increase the flow from Mývatn to the Laxá while a wind blowing from west would decrease the flow. The fetch along Mývatn is shorter from east to west than from the north to south. From this it can be deduced that the water level changes at the outflow to the Laxá are less than reported range in the northern most part of the lake.

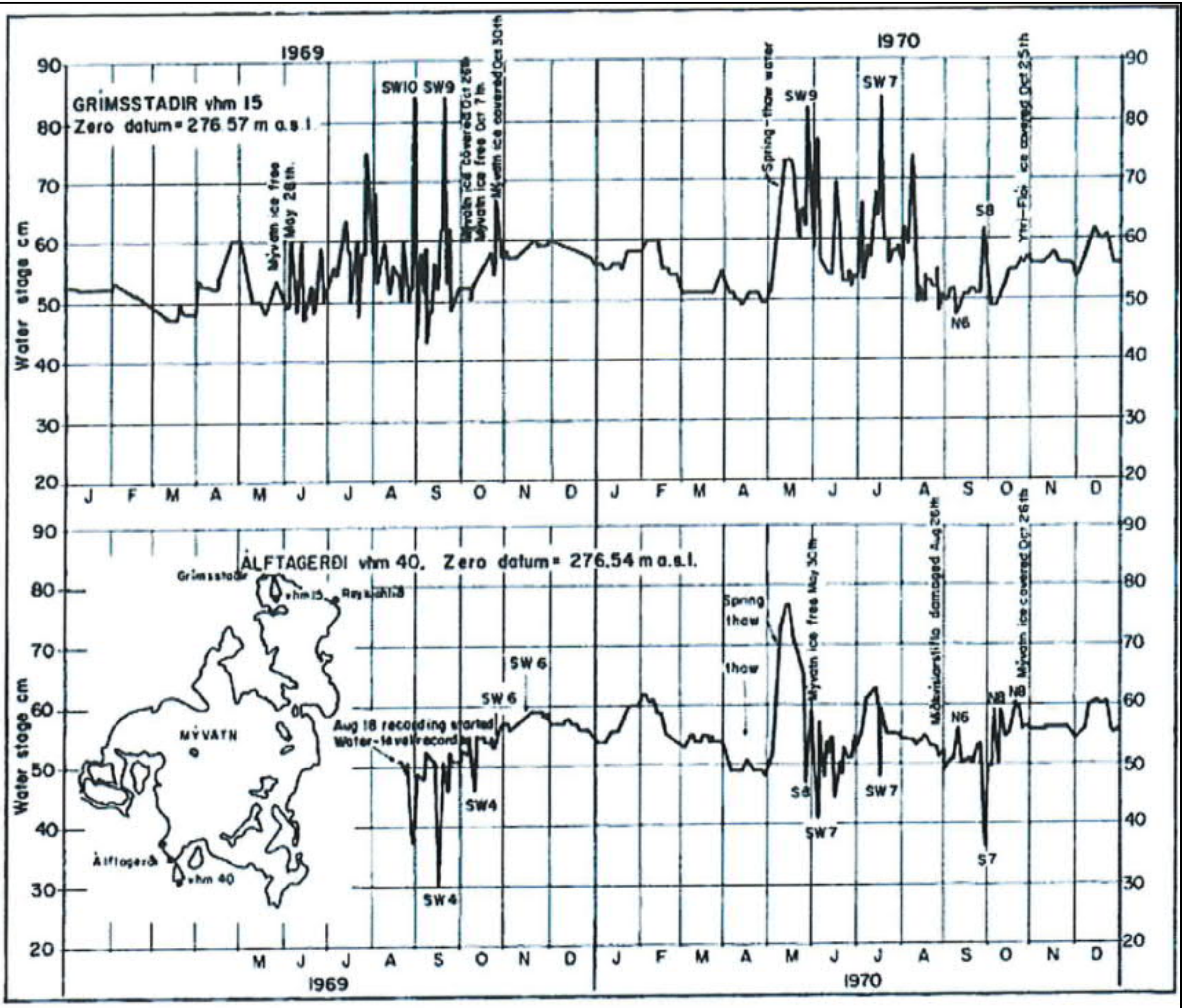

Fig. 1. Water level fluctuations in the north and south basin during 1969 and 1970. Note the stable conditions during ice cover (winter) after building of the Geirastada dam. Note also the gales in August-September 1969 and the spring thaw fluctuation 1970.

Figure 2.4 Measured water level in Mývatn in 1969 and 1970 at vhm 15 and vhm 40 (Sigurjón Rist, 1979b, Figure 1, p. 69).

Another factor that influences how the wind affects the flow in the Laxá is the dampening effects of ice cover on Mývatn. This can clearly be seen on the graphs published in 1979 by Sigurjón Rist, see figure 2.4. All the abrupt changes are due to wind effects and are only present in summer time. When ice cover has formed, only a part of the lake has open water surface and subsequently only that part of the lake can be influenced by the wind so the effect is drastically dampened. Sigurjón Rist reports on this with the following lines; "During winter the windinduced water level fluctuations are small, but perceptible. They amount to 10 cm in the south basin and little more in the north basin." (1979b, p. 71)

2.2.2 Flow and water level changes due to ice formations

Ice formations can both influence flow in the Laxá by affecting the outlet of Mývatn and by forming within the Laxá itself and thus influencing the flow downstream of that location as well as water level at and upstream of the ice formation location.

2.2.2.1 Ice formations at the outlet of Mývatn

Sigurjón Rist studied ice formations on Mývatn and in the Laxá on behalf of the Hydrological Survey department at the National Energy Authority. The main research period was between 1950 and 1953. From his findings he created a table that summarised causes and consequences of ice formation in the outlet of the lake, table 2.1.

Table 2.1 Causes and consequences of ice formation in the outlet of Mývatn (Sigurjón Rist, 1979b, copy of table 1, p. 77).

Causes			Consequences
	Weather	Ice formations	
1.	Strong northerly wind with snow drift, severe frost.	Open water areas. Slush ice, anchor ice, snow and pack-ice.	The most difficult ice-dams, of longest duration.
2.	Westerly wind against the current, clear and dry atmosphere, rapid evaporation from open lake surface, violent cooling, frost -6° or more.	Open water areas. First lowering of water level and reducing the flow, then anchor ice on outlet controls, as bottom ice coat. Closure of channels between ice stacks by small lumps of ice breaking from ice sheet.	Occurred quite frequently, but did not last as long as no. 1 therefore did not cause such serious power production disturbances. On the other hand, it occurred repeatedly and often unexpectedly.
3.	Strong easterly wind with thaw.	Break-up of the ice cover of Mývatn, drifting ice chokes up the outlet channels.	Occurred very seldom.

An earlier account of these ice formations was documented by Steinn Steinsen on the 25th and 26th of July 1936. Steinn Steinsen Moritzsson was at the time the mayor of Akureyri. He was educated as a civil engineer ('Steinn Steinsen - Wikipedia, frjálsa alfræðiritið', n.d.). As a part of preparation in the planning stages of Laxá Hydropower Station I, he interviewed a few farmers that lived and had lived for a relatively long period of time adjacent to the Laxá and knew it well.

Sigurður Jónsson, farmer at Arnarvatn farm and raised at Helluvað farm, reports as follows on how ice formations could restrict flow from Mývatn:

> During frost periods, especially when the westerly wind blows against the flow, ice formations that restrict flow are common, especially after blizzards blowing from north-west. Anchor ice forms and is most noticeable at the islets located a short distance downstream of the outlet. These ice dams lower the flow in the river considerably for one to three days. After very severe north-western blizzards the dams can last longer, up to one week. The worst blizzards occur approximately once every third or fourth year, while the smaller dams occur a few times every winter, mainly during the middle of the winter. The risk of a blizzard is highest if sea ice is present close to the north shore, but not connected to

> the shore. Sigurður does not feel confident in saying with more accuracy how much lower the flow becomes but expects that after the worst blizzards the discharge at Arnarvatn farm becomes less than one third of normal discharge. When the outlet is dammed water level rises in Mývatn, but Sigurður does not know how much the rise is.[3] (Steinn Steinsen, 1936)

Stefán Helgason, farmer at Haganes farm, and Freysteinn Jónsson, farmer at Geirastaðir farm gave the additional information:

> Stefán has heard that opposite Hofsstaðir farm the discharge in the river can become as low as under 1/5 of its usual discharge. He also reports that in 1905 the river became completely blocked at some point during the third week of summer. This ice blockage was caused by snow and ice slush, not anchor ice. … Both Stefán and Freysteinn report that the river has become completely blocked a few times during the last few decades. They think that the water level rise in Mývatn, caused by these events, amounts to about 18 inches[4],…[5] (Steinn Steinsen, 1936)

According to Hjálmar Jónsson, farmer at Ljótsstaðir, the river has never gone completely dry within the boundaries of his land (Steinn Steinsen, 1936). The location of the farms should be kept in mind when reading these last two references. The location of Haganes farm and Geirastaðir farm can be seen on figure 2.1, but they are located close to Mývatn and the outlet area where the Laxá is divided into three main branches. While at Ljótsstaðir farm, some 15 km downstream of Mývatn, the river is in one straight channel giving a good overview over the whole river.

Jónas Snorrason, farmer at Þverá farm also reports on the Laxá:

> The discharge is sometimes much lower due to ice damming at Mývatn. He estimates that when the damming is at its worst the discharge can go down to 1/5th to 1/6th of normal discharge, but this happens rarely with some years in-between events.[6] (Steinn Steinsen, 1936)

Sigurjóns Rist mentions two occurrences where the water level in Mývatn rose about 30 cm (water accumulation in the lake of about 12 million m^3) in November 1947 and more than 30 cm in 1959, (see recorded rise in figure 2.5) (1979b, p. 71). Those are measured maximum water level rises in Mývatn due to ice dams in the outlet area in the period from 1944 to 1967, i.e. over a period of 23 years and 3 months.

Assuming the ice dams lower the discharge in the Laxá to one third of normal discharge at Arnarvatn, taking it from about 40 m^3/s to about 13 m^3/s, it can be calculated that it would take about 5-7 days for the water level in Mývatn to rise 30 cm without any wind effects. The shorter period applies if Kráká is blocked and finds its way to Mývatn through the lake Grænavatn, as it sometimes does in winter time. The water level change in 1947 supports this but the rise in 1959 is much faster, suggesting either additional water level change due to wind effects, precipitation adding to the inflow to Mývatn (snow

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3 In Icelandic: "Í frostum, einkum þegar vindur stendur móti straum, vestlægri átt, ber talsvert á stíflunum í ánni, sérstaklega eftir norðvestan hríðarveður. Áin grunnstinglast þá, ber mest á því við hólma sem eru skammt neðan við árósinn. Þessar stíflanir draga oft úr vatnsmagni árinnar að verulegum mun í einn til þrjá daga, en eftir verstu norðvestan stórhríðar geta stíflanirnar staðið allt að því í viku. Verstu stórhríðarnar koma á að giska þriðja eða fjórða hvert ár, en smærri stíflanirnar koma venjulega fyrir nokkrum sinnum á hverjum vetri, einna helst um miðjan veturinn. Hríðarhættan er mest ef hafís er úti fyrir Norðurlandi, en er ekki landfastur. Sigurður treystir sér eigi til að segja um með meiri nákvæmni, hve mikið áin stíflast, en býst við að eftir verstu hríðar sje vatnsmagn árinnar neðan við Arnarvatn eigi yfir þriðja part af venjulegu rennsli. Við stíflanir í Laxá hækkar vatnsborð í Mývatni, en eigi er Sigurði fullkunnugt um hve miklu sú hækkun vatnsborðsins nemur." (Steinn Steinsen, 1936)

4 The Icelandic inch was about 2.4-2.8 cm ('Metrakerfið', 1995), which means that 18 Icelandic inches are about 43-50 cm.

5 In Icelandic: "Stefáni er kunnugt um að móts við Hofsstaði getur áin orðið svo lítil, að hún flytji þar ekki yfir 1/5 af venjulegu rensli, ennfremur segir hann, að árið 1905 hafi hún gerstíflast um þriðju helgi sumars. Stíflun þessi kom af snjó og ís sem myndaðist af krapi, en áin grunnstinglaðist þá ekki. ... Bæði Freysteinn og Stefán vita til þess að áin hafi gerstíflast nokkrum sinnum á undanförnum áratugum. Þeir telja að hækkun vatnsborðs í Mývatni, vegna stíflunar í Laxá muni hafa numið mest ca. 18 þumlungum, en um það sjéu að líkindum til skýrslur hjá rafmagnseftirliti ríkisins." (Steinn Steinsen, 1936)

6 In Icelandic: "Hann kannast við að áin minki verulega einstöku sinnum vegna stíflananna við Mývatn, býst við að renslið geti minkað, þegar stíflanirnar eru mestar, niður í 1/5 til 1/6 af venjulegu rensli, en svo mikil minkun renslisins komi þó eigi fyrir nema með ára millibili." (Steinn Steinsen, 1936)

and/or snowdrift) or more severe damming at the outlet, i.e. less flow in the Laxá than one third of its normal flow at Arnarvatn. Or maybe a combination of all or some of these.

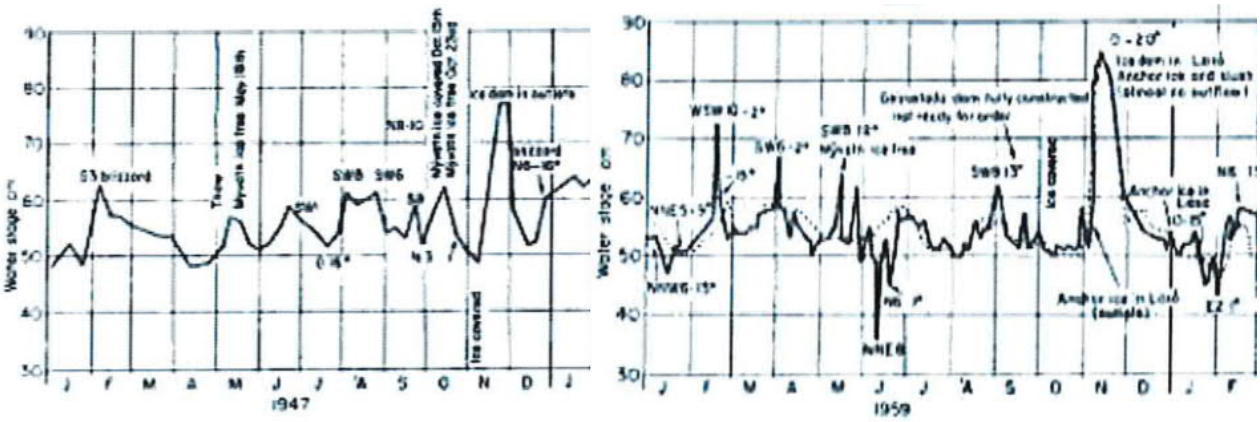

Figure 2.5 Measured water level in Mývatn in 1947 and 1959 at vhm 15 (Sigurjón Rist, 1979b, parts of figures 5 and 7, p. 72-73).

2.2.2.2 Ice formations within the Laxá

__**The Laxá in Laxárdalur**__

Ice formations within the river can also affect flow temporarily. The Laxá in Laxárdalur is relatively steep with water velocity (on average 1.3 m/s) above the critical limit for ice cover formation in rivers (about 0.5 m/s) (Sigurjón Rist, 1979a, p. 272). Still, ice formations can form within the river through other processes than normal ice cover formation.

One is ice dams, due to anchor ice formations at rapids, forming local ice dams built from the river bed and up into the cross section of the river. These cause water level rise upstream and temporary lower discharge downstream while ice and water is building up the dam and gathering upstream. These can form at various locations within the river but have not been researched as such, but some known locations have been reported. One is at the rapids downstream of Birningsstaðaflói. This location is capable of influencing the downstream discharge for the longest time and storing water over the longest distance within the river as Birningsstaðaflói is over one kilometre in length and relatively wide and thus capable of storing much more water than any other location within the Laxá in Laxárdalur.

As mentioned above the river in Laxárdalur is relatively steep, still there are exceptions at few locations where the river widens out and is flatter. These locations are called Flói. The biggest one is Birningsstaðaflói. Two others worth mentioning are Brotaflói, relatively close to Mývatn, and Árgilsstaðaflói, a short distance downstream of Birningsstaðaflói. These are the locations where ice cover can sometimes form, at least in Birningsstaðaflói.

When ice cover forms on Birningsstaðaflói it creates a building point for another ice formation called ice jam. Ice jams can form when ice flows in the river collet at the upstream end of an ice cover, adding to the ice cover in the upstream direction. Some of the ice flow is pulled under the ice and collects there. With added ice and higher water level, the ice which has accumulated, pushes at the ice edge and when the push from ice, water and the shear from the flow underneath the ice cover is higher than the strength of the ice cover/ice jam, the ice cover/ice jam at the upstream end collapses and the ice is pushed together into a thicker and stronger ice formation. The same process happens again and again, each time strengthening and thickening the ice jam which also grows further and further upstream. During this process the water level in the river rises both within the area of the ice jam and a short distance upstream, depending on how far the back-water effect from the ice jam reaches.

This is known to happen at the upstream end of Birningsstaðaflói. The ice jam that forms there is called the Halldórsstaðir ice jam and forms regularly (though not yearly). The water level rise due to the Halldórsstaðir ice jam has been as high as 8 m above Birningsstaðaflói (Sigurjón Rist, 1979a, p. 277). Figure 2.6 shows a part of this ice jam. The ice jam blocks a big part (or sometimes, all) of the river bed forcing the water to find a new path. The new path is usually found along the edges of the ice jam, as can be seen in the figure.

Laxárdalur í febrúar 1965, krap í Laxá. Suðastur, neðan Halldórsstaða.

Figure 2.6 A part of the Halldórsstaðir ice jam. Picture taken in the upstream direction below Halldórsstaðir farm. The river is much narrower at this location than within the Birningsstaðaflói. The ice jam has lifted the water level resulting in overbank flow along the edges of the ice jam ('Laxá Station photo collection', n.d.).

While these ice formations are forming they take a part of the water as building material, additionally water is stored in the form of raised water level. This means that the downstream discharge becomes lower temporarily. If ice dams or jams are forming at various locations along the river at a similar time the discharge is lowered below all these locations and can cause more dramatic lowering of discharge. Sigurjón Rist photographed the Þjórsá at such a time in 1963 where discharge dropped from about 340 m^3/s to about 20 m^3/s in 24 hours, see figure 2.7.

Following are short accounts from farmers along the river:

Hallgrímur Hallgrímsson, farmer at Hólar farm:

> Sometimes ice slush and ice drift dam the river in the land of Hólar farm. When this happens the river flows over its banks and back into the river a short distance downstream. These formations usually last for 3-4 days, but Hallgrímur thinks that their effects are negligible downstream because the water flows over the banks and relatively quickly back into the river. Still, those dams can reduce downstream flow for a few hours, while the water is piling up, before it starts flowing over the banks.[7] (Steinn Steinsen, 1936)

[7] In Icelandic: "Stöku sinnum stíflast áin í Hólalandi af krapi og jakaburði, rennur hún þá upp á bakkana og niður í farveginn aftur neðar. Þessar stíflanir standa venjulega e-a. 3-4 daga, en Hallgrímur álítur að stíflananna gæti lítið eða ekki neðar í ánni, vegna þess að vatnið renni eftir bökkunum og fljótlega aftur í farveginn. Þó munu þessar stíflanir geta dregið úr rensli árinnar í nokkrar klukkustundir, meðan vatnið er að ná sjer upp úr farveginum." (Steinn Steinsen, 1936)

23. mynd. Þurrð í Þjórsá hjá Þjótanda. Myndin er tekin í íhlaupinu* 11. apríl 1963. Eftir mildan vetur var áin alauð upp undir jökla, þegar íhlaupið gerði. Rennslið minnkaði á 24 klst. úr 340 kl/s niður í 20 kl/s.

Thjórsá river near Urriðafoss running dry on April 11 1963. The discharge dropped from 340 kl/s to 20 kl/s in 24 hours. The river was open almost up to the glaciers when a cold, dry storm from NE suddenly sat in, causing an extremely high rate of ice formation over nearly the whole river length.

Photo: S. Rist.

Figure 2.7 The Þjórsá in South of Iceland at a time of a serious discharge drop due to ice formations within the river (Sigurjón Rist, 1962, figure 23).

Jónas Snorrason, farmer at Þverá farm:

> He has heard that in 1869 the river became totally blocked from Þverá farm up to Mývatn in a blizzard in October and that after the blizzard the discharge in the river became so low that people could walk along the river from Brúar in the upstream direction for about 2 km. Jónas heard this from his father that lived for a long time at Þverá farm. He has not heard about similar events, except for this one occurrence.[8]
>
> In wintertime the river sometimes is full of ice during thawing periods causing ice jams in the area that force the water to flow overbank and on to meadows close to the river. Most of this ice rubble ends up in Birningsstaðaflói and cannot flow further north. Jónas does not think that these ice jams influence the discharge much below Birningsstaðir farm. The river is sometimes dammed in this area by anchor ice, but hardly so that it influences the discharge.[9] (Steinn Steinsen, 1936)

These accounts are informative and show that the discharge in the river has been affected by ice formations for a long time.

Reported flow changes at the Laxá Stations

Operation of the power plants add to this information bank. The experience there shows that those events the farmers report on do affect the flow downstream temporarily. Sigurjón Rist reports on observations made in the period from 1948 to 1953. During those five winters flow disturbances due

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[8] In Icelandic: "Hann hefur heyrt að 1869 hafi áin í stórhríð í október stíflast svo á allri leiðinni frá Þverá upp að Mývatni, að eftir hríðina hafi áin verið svo vatnslaus að gengið var um farveginn frá Brúum og upp eftir alt að tvo kílómetra. Jónas hefur þetta eftir föður sínum sem lengi var á Þverá. Hinsvegar hefur hann eigi heyrt þess getið að svona hafi komið fyrir, nema í þetta eina sinn." (Steinn Steinsen, 1936)

[9] In Icelandic: "Á vetrum er stundum mikill jakaburður í ánni þegar hún ryður sig og getur áin þá runnið upp yfir bakkana upp á engjar sem að liggja, ef jakaburðurinn stíflar farveginn. Þó mun mesti jakaruðningurinn stöðvast úti á Birningsstaðaflóa og eigi komast lengra norður. Jónas býst þó tæplega við, að þessar jakastíflanir hafi mikil áhrif á rennsli árinnar fyrir neðan Birningsstaði. Áin stíflast stöku sinnum nokkuð af grunnstinglum á þessu svæði en þó varla svo að það hafi mikil áhrif á renslið." (Steinn Steinsen, 1936)

to ice formations occurred on average 7.5 times per winter (min 5 times and max 10 times). The days affected were on average 20 per winter (min 13 and max 30 days per winter), ranging from 1 to 6 days per event. Of the 34 events reported, 16 were due to a combination of ice disturbances in the outlet area and in the Laxá in Laxárdalur. All the other events were thought to originate at the outlet from Mývatn (Sigurjón Rist, 1952, p. 17-18).

After the Geirastaðir canal was constructed, the flow from Mývatn is much more stable. Ice formations within the river continue to form, but the more stable flow from the lake keeps the ice conveyance of the river also more stable at locations that were previously prone to ice congestion during lower flow periods. In some areas within the river ice formations are rarer than before due to more stable flow from Mývatn.

The Laxá in Aðaldalur

The lower part of the river, the Laxá in Aðaldalur, is much flatter, see figure 2.1. The ice conveyance capacity of the river is thus lower than in the Laxárdalur. Because of this, the river is prone to ice congestion both where the river is very narrow and where it is very wide. Where it is narrow the surface area is too small to convey all the inflowing ice. An ice bridge is easily formed upstream of the narrow parts and from there ice cover and ice jams can form in the upstream direction. Similarly, at location were the river is very wide, the velocity is too low for the water to convey all the ice further downstream. A big part of the inflowing ice kind of "stops" and forms a bridge over these wide and shallow parts of the river. Again, the inflowing ice adds to the formation allowing it to thicken and grow in the upstream direction. If it forms during freeze up periods the building material will be ice slush and the ice jam formed will be a freeze up ice jam. If, on the other hand, it forms during a thaw, the building material will be ice rubble, i.e. ice that was formed somewhere else in the river and is carried down the river when it loses its grip due to the thaw. Then the ice jam is called a break up ice jam.

These ice formations lead to water level rise within and upstream of the formation. The water level has been reported to rise as high as 6 m over normal water level at the outlet from Laxá Station II (Halblaub, 1960, p. 13), see location 4 on figure 2.9. The figure also shows reported locations of flooding due to ice formations, locations 1 to 3, and reported ice congestion locations, marked A and B. Location A is mentioned in the news in February 2006. There it says:

> Laxamýri: The last few days have been relatively warm for this time of the year in Þingeyjarsýsla county, resulting in break-up of river ice. Water has broken through a huge ice jam that had formed in the Laxá, upstream of Æðarfossar Falls, and the water has found a way through the Mýrarvatn.[10]
>
> For some period of time, water level in the river had been unusually high at Heiðarendi and Mýrarsel farms. Water flowed west over the lava field in such a volume that locals think there are many years since similar flooding occurred. [11] ('Laxá í Aðaldal í leysingum', 2006)

Figure 2.8 shows the leftovers from the freeze up ice jam in 2006.

[10] Mýrarvatn is not an actual lake even though the Icelandic name suggests it. Mýrarvatn is the flat and wide part of the Laxá along the farms at Laxamýri, between Æðarfossar falls and the rapids below the bridge.

[11] In Icelandic: „Laxamýri: Undanfarið hefur verið mjög hlýtt miðað við árstíma í Þingeyjarsýslum og hafa vötn víða byrjað að ryðja sig. Mikil klakastífla sem hafði myndast í Laxá ofan við Æðarfossa losnaði og fann áin sér leið í gegnum Mýrarvatnið. Mjög hátt var í ánni á tímabili við Heiðarenda og Mýrarsel og flæddi vatn vestur um allt hraun, svo mikið, að mörg ár eru síðan men hafa séð jafnmikið flóð." ('Laxá í Aðaldal í leysingum', 2006)

Figure 2.8 Leftovers from an ice jam in the Laxá in Aðaldalur. The formations indicate a freeze up ice jam („Laxá í Aðaldal í leysingum", 2006, photo: Atli Vigfússon).

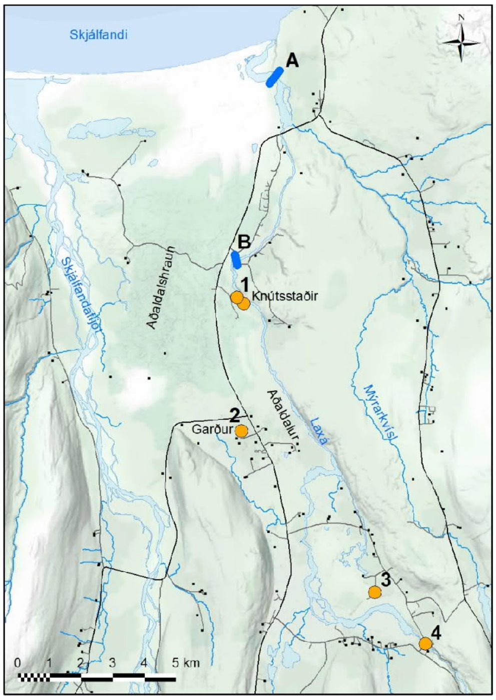

Figure 2.9 A and B: Reported starting points for ice jams. 1 to 4: reported locations of flooded land or elevated water level due to ice formations.

Location B and the point marked with the number 1, are mentioned in the news on the 5th of January in 1996. There it says:

> An ice jam formed from the narrows at Núpafoss Fall and the river flooded its banks, onto the meadows at Knútsstaðir farm and disappeared down into the lava, where it found a path to the Skjálfandi. Jónas Jónasson farmer at Knútsstaðir farm, reported that floods like this occur every now and then, in winter or spring time. [12] (Kristján, 1996)

Knútsstaðir farm, location 1, is again in the news in 2014. Then the ice jam is so severe that water floods up to the farm houses at Knútsstaðir and Lynghóll farms. Jónas Jónsson, farmer at Knútsstaðir farm, reports that this ice jam formed during a blizzard. Snow, snowdrift and ice slush caused the ice jam and he could not remember this severe flooding since 1960 ('Klaki og krapi stífla Laxá í Aðaldal', 2014). In 2011 a journal on horses reported about a rescue mission. Four horses went down through ice after some land around Garður farm, location 2 on the figure, was flooded earlier in the winter due to ice jam formation in the Laxá (Fjölnir Þorgeirsson, 2011).

Location 3 was in the news in 2016. There it is reported that the sheep pen, Hraunsrétt, had been damaged due to repeated flooding from the Laxá (Sveinn Arnarsson, 2016).

Sigurjón Rist describes the ice formations and their effects on water level in the Laxá in Aðaldalur in a report in 1969. The original text is in the footnote. The short version in English is as follows;

In upper Aðaldalur, ice formation in the Laxá starts when ice covers the pool "Álfthylur", south of Árnes. Ice slush is carried to the ice cover and it starts to grow upstream. Normal water level rise due to ice formations in the Laxá at Hólmavað is 1.9 m. Sometimes it gets as high as 2.45 m and it has been reported to rise as high as 3.2 m above normal, sending water to the NV to Brunnar. When that happens

[12] In Icelandic: "Klakastífla myndaðist í þrengslum við Núpafoss og flæddi áin því yfir bakka sína, fór yfir tún við bæinn Knútsstaði og hvarf ofan í hraunið, þar sem hún fann sér leið út í Skjálfanda. Jónas Jónsson á Knútsstöðum sagði að slík stífluflóð kæmu alltaf af og til, ýmist að vetri eða vori." (Kristján, 1996)

a huge ice formation covers the flatland below Ytra- and Syðra-Fjall. At Knútsstaðir the Laxá can become blocked with ice forcing water to flow NV into the lava.[13, 14] (Sigurjón Rist, Haukur Tómasson, & Sigurður Thoroddsen, 1969, appendix 4 and 10).

From all of the references above, it is clear that ice formations in the Laxá in Aðaldalur influences water level in the Laxá tremendously during winter time.

2.2.3 Flow changes due to constructions, question F-1

2.2.3.1 Constructions in the outlet area of Mývatn

Earlier constructions

The construction history listed in table 2.4 does not include older dams made by farmers for irrigation purposes, but according to Sigurður Jónsson, farmer at Arnarvatn farm, the river was dammed in spring time, usually at the end of May or beginning of June in order to use Mývatn to irrigate the meadows. The dams were then removed late in June. This irrigation method was first applied in 1915 and last in 1925 [15] (Steinn Steinsen, 1936). According to Stefán Helgason, farmer at Haganes farm, and Freysteinn Jónsson, farmer at Geirastaðir farm, the water level rise due to these dams was at most about 57-67 cm (24 Icelandic inches)[16] (Steinn Steinsen, 1936).

Sigurjón Rist also mentions this in one of his articles, where he writes:

> In the first quarter of this century the farmers surrounding Lake Mývatn built dams of boulders in some of the outlet channels for the purpose of irrigation. This raised the water level in the early summer a few tens of centimeters. In general, the farmers to the south of the lake maintained that farming gained a profit, but farmers on the north side insisted on the reverse. The resultant wave-action at once began to break down the grassy banks and destroy bird nests. The dams were in operation for only a few years. (Sigurjón Rist, 1979b, p. 68)

Current constructions

Table 1.2 shows the construction history and figure 2.10 gives an overview of the area. The current structures in the outlet area of Mývatn have only one purpose, that is to minimize the ice disturbances on the flow from Mývatn.

The first construction made for the benefit of the power stations, Dragsey Dam, did not deliver according to plan. The construction consisted of a dam with a section made of a simple gate construction with planks that could be removed (opened) when needed. Even though the gate worked fine the ice dams occurred further upstream in the branch and in the Breiðan upstream of the three branches, resulting in restricted flow to the Laxá during ice damming prone weather conditions (Sigmundur Freysteinsson, 2010, Mývatnsósar, p. 1).

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[13] In Icelandic: „Í efri hluta Aðaldals er nú ísalögum þannig háttað, að áin fer fyrst saman á Álfthyl, það er breiðan sunnan við Árnes, þar sem áin beygir austur að Hvammsheiði. Skrið berst að og íshellumyndunin fer upp ána, eins og venja er við allar ár, ísalagnir ganga upp á móti straumi; þversniðið þarf að stækka, svo að straum setji niður a.m.k.niður í 0.5 m/s. Undan bænum Hólmavaði hækkar vatnsstaðan við ísalagnir venjulegast um 1.9 m (sbr. fylgiskjal 10). Stöku sinnum er hækkun vatnsfyllunnar 2.45 m, en þá er vatnsborð Laxár komið upp á þinghúströppur og hefir þá áin frammi verulegan ágang á Hlómavaðstún og á það til að flæða norðvestur í Brunna (sbr. áðurnefnda teikn.). Er þá mikil ísfylla á sléttlendinu undan Fjallabæjunum, Ytra- og Syðra-Fjalli. Þegar áin hækkar allverulega á þessu svæði, kemur vatn víða upp í gjótum og glufum í hrauninu allfjarri ánni. ... Hjá Knútsstöðum á Laxá það til nú að stíflast og hlaupa norðvestur í hraunið. Hefir hún orsakað þar hindranir á þjóðveginum."

[14] In Icelandic: „Hækkun vatnsborðs hjá bænum Hólmavaði, heimildarmaður Kristján Benediktsson. Mælt inn samkvæmt leiðsögn hans 30.5.'66 mælibók IO41. Venjuleg vatnsborðshækkun 1.9m. Fágæt vatnsborðshækkun (þinghúströppur) 2.45m. Samkvæmt heimild Kristjáns 4.6.'69 fór vatnsborð við ísalagnir veturinn 1969/69 að handriði við göngupall undir brúnni, ísinn úti á ánni (undir brúnni) skrúfaðist örlítið hærra upp. Álestur við handriðið er 333 þ.e.a.s. hækkun vatnsborðs 68/69 frá venjulegri stöðu var 1.65 m. Samkv. heimild Kristjáns og Þorgeirs Jakobssonar hefur Laxá náð á þessari öld (milli 1910-20) að flæða NV í Brunna, hækkun frá venjulegri stöðu að efstu stöðu við ísalagnir a.m.k. 3.2m."

[15] In Icelandic: "Laxá hefur um nokkurra ára bil verið stífluð á vorin neðan við Mývatn til þess að veita Mývatni á engjar sem að því liggja. Stíflan var venjulega gerð nálægt mánaðarmótunum maí – júní, og hætt seint í júní. Fyrst var stíflað 1915, og síðast árið 1925." (Steinn Steinsen, 1936)

[16] In Icelandic: "Þegar Laxá var stífluð til þess að hækka vatnsborð í Mývatni til áveitu á landið umhverfis mun vatnsborðið hafa verið hækkað mest um 24 þumlunga." (Steinn Steinsen, 1936)

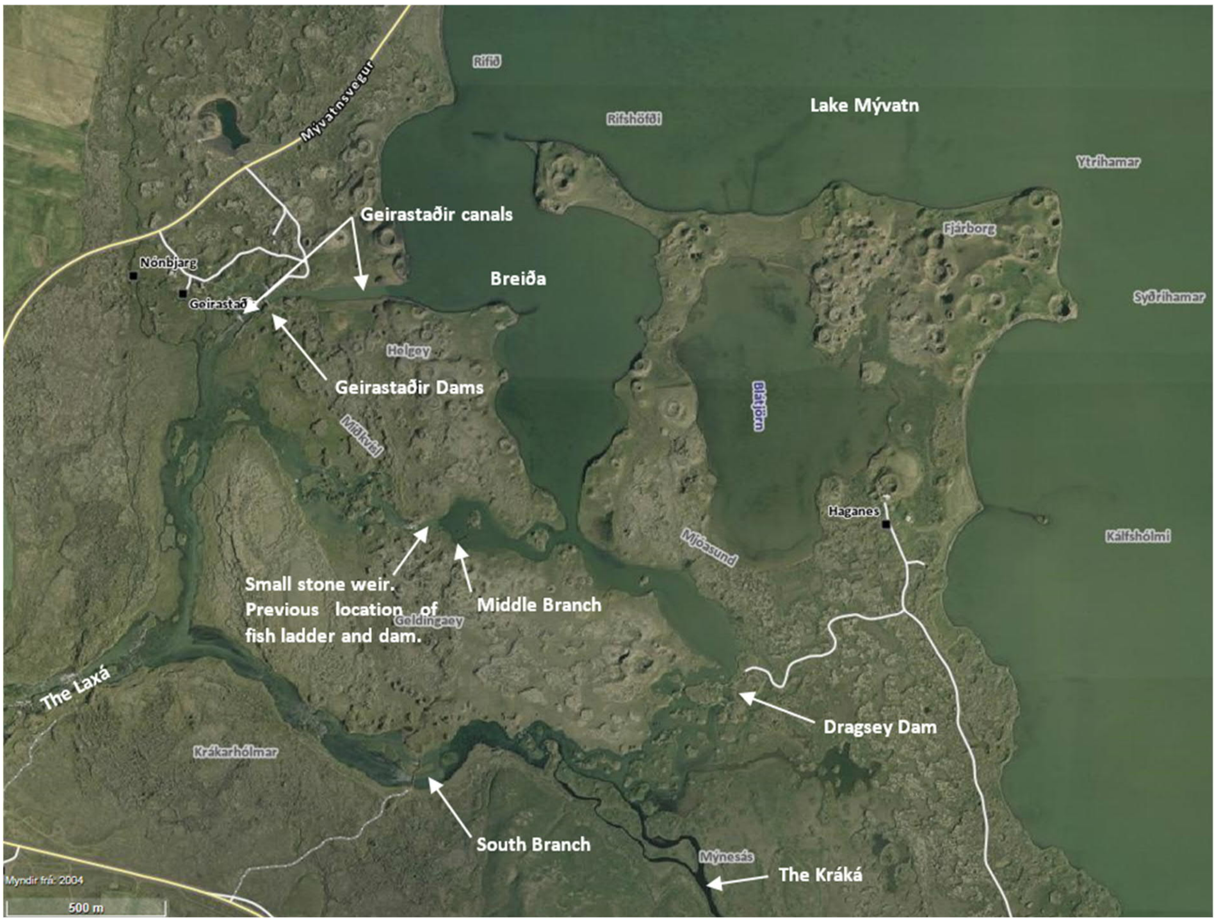

Figure 2.10 The outlet area of Mývatn, including dams and canals (Loftmyndir ehf., 2014).

The second attempt to solve the ice damming problems in the outlet area was successful. This included the Geirastaðir canal with a dam constructed some 400 m downstream of the Breiða in the Geirastaðir branch. In order to keep flow in the original branch downstream of the dam a bottom outlet was included in the dam diverting flow into the branch. The main waterway, that was constructed to convey water during ice prone periods, was the canal, 13 m wide and 3 m in depth. A gated construction was built a short distance downstream of the dam in the canal with 3 gated openings to control flow through the canal. According to drawings a part of the threshold between Mývatn and the Breiða was removed in order to minimize the risk of anchor ice formation there and consequent ice damming (Sigmundur Freysteinsson, 2010, Mývatnsósar, p. 1 and 6).

Other constructions were added and removed as listed in table 2.4. The main construction of interest for the purpose of this report are the ones in the Geirastaðir branch and relevant changes made in connection to them. The key factor regarding this construction was to convey slow moving water with sufficient depth from the lake to the river, i.e. a canal bypassing the shallows in the branches. This meant less open water surface, a key factor in the cooling process of the water, less turbulence and thus less blending of supercooled water within the water column; all leading to lowering the risk of ice formations within this new passage from the lake to the river. The main factor is the depth and the smooth stream lines of the water that reduces the risk of anchor ice formation. As Sigurjón Rist puts it: "The ice slush was the building material for the dam but the anchor ice creates the foundation and sets up the net. The Geirastaðir canal would eliminate one of these factors, i.e. the anchor ice."[17]

[17] In Icelandic: „Krapaförin leggja til magnið í stífluna, en grunnstingullin lagar undirstöðuna og spennir út netið. Með Geirastaðaskurðinum yrði felldur í burtu annar þessi þáttur, þ.e.a.s. grunnstingullinn." (Sigurjón Rist, 1952, p. 6)

Changes in winter conditions after the constructions made in the Geirastaðir branch:

- instances where ice hindered the outflow from Mývatn were much fewer, see comparison between figure 2.11, where water level in Mývatn is very unstable over the winter months due to ice formations restricting flow from the lake, and figure 2.5 where the winter months are much more stable than before and also much more stable than the wind effected summer months.
- ice formations within the Laxá are considered to be less than before due to more steady discharge from Mývatn.

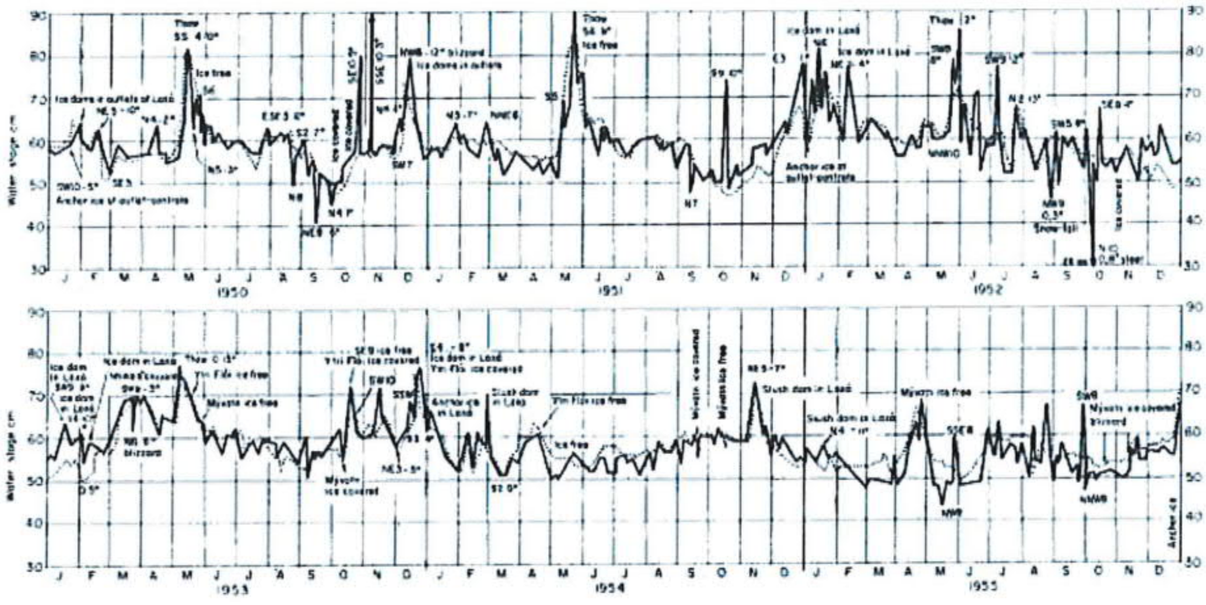

Fig. 6. Water level fluctuations during 1950 to 1955. The summer fluctuations are small, in contrast to the very marked fluctuations at other seasons.

Figure 2.11 Measured water level in Mývatn from 1950 to 1955 at vhm 15 (Sigurjón Rist, 1979b, Figure 6, p. 72).

The result can be summarised as more stable water level in Mývatn and much more stable discharge in the Laxá in winter.

Sigurjón Rist describes this as follows:

> Instead of keeping the outflow at natural level, distributed over a shallow area, and then flowing into three channels, the outflow in winter now runs almost wholly via the Geirastada-channel. As a result of this operation, the water now needs 11 h less than previously to flow off the lake itself and drop 2 m.
>
> The outflow from the Lake Mývatn is now without great ice problems, with the additional asset for the people of the district that the River Laxá no longer forms ice jams between the farms Arnarvatn and Helluvad, which it used to do previously. At least once during each 5 to 10 yr the county road became submerged under ice and water. (Sigurjón Rist, 1979b, p. 78)

<u>Operation of the gates in the Geirastaðir canal</u>

In the early days of operation, before the passing of the law in 1974, the water level in Mývatn was disputed. An article in the newspaper Dagur, published on the 9th of September in 1970, summarizes the dispute as seen by the owners of Laxá power plant. At the time the water level in Mývatn was kept higher in winter time in order to minimize ice problems. For the rest of the year the water level was supposed to be decided by a committee ordered by locals, but according to the article this arrangement did not function (Stjórn Laxárvirkjunar, 1970).

Today, operation of the gates in the Geirastaðir canal is completely governed by Icelandic law. The Laxá and Mývatn are protected by law and changes to water levels are forbidden. According to Landsvirkjun, the water level in Mývatn at Geirastaðir Canal is checked twice per day (once in the morning and again in the evening). If needed, changes are made to the opening of the gates to keep the water level within the target limits listed in the operation handbook for the Laxá Stations:

Maximum water level:	278.80 m a.s.l.
Target water level:	278.77 m a.s.l.
Lowest water level:	278.74 m a.s.l.

Additionally, if the level is out of bounds, the weather is taken into account and water level at two other locations in Mývatn, at Garður, in the south, and at Syðri Neslönd in the north of the lake, is checked in order to estimate if the water level is actually out of bounds or if it might be wind induced water level change.

Table 2.2 shows the percentage of time the water level in Geirastaðir Canal is within the target limits for the years 2014-2017 and how long it was above and below. As the average time within the target zone over these four years was lower than expected, only about 79 %, a graph was created to see together on the same graph the three water level measuring stations for the year 2017, see figure 2.12. The graph shows that in most cases, when Geirastaðir Canal is out of the target zone, one or both of the other stations are within the target limits.

Table 2.3 shows that during the 8.9 % of the time in 2017 the water level at Geirastaðir Canal was below the target limit one or both of the other stations where above. Only 0.1 % of the time all the stations where below target and for 2.3 % of the time two were below and one above the lower limit. Similarly, only 3.6 % of the time all the stations where above target and for 5.9 % of the time two were above and one below the upper limit. This means that in 2017 only 3.7 % of the time all stations where out of bounds in the same direction i.e. all above or all below.

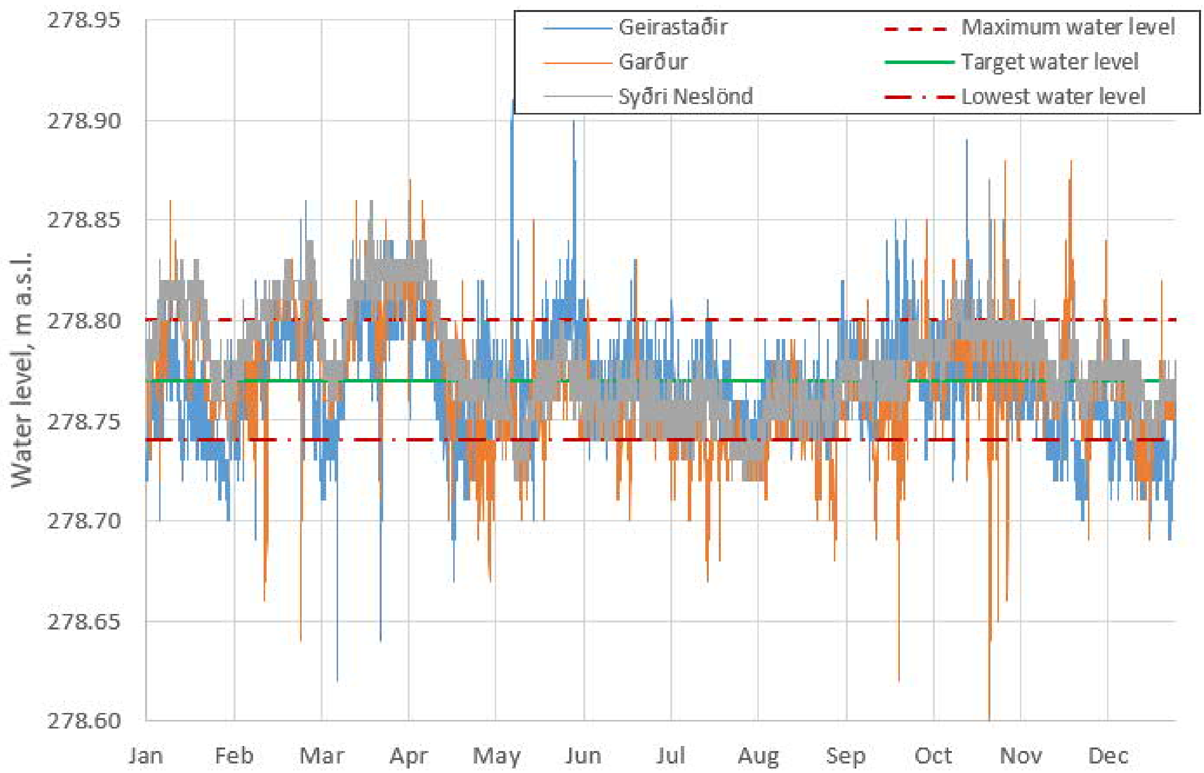

Figure 2.12 Measured water level at all three measuring locations in Mývatn in 2017 (Landsvirkjun, n.d.-c).

Table 2.2 A summary of time within the target limits, above and below, at Geirastaðir Canal.

	2014	2015	2016	2017	Average (2014-2017)
Below 278.74 m a.s.l.	4.1 %	25.9 %	20.1 %	8.9 %	14.8 %
Within target zone	83.5 %	71.2 %	77.5 %	84.7 %	79.2 %
Above 278.80 m a.s.l.	12.4 %	2.9 %	2.4 %	6.4 %	6.0 %

Table 2.3 An overview of the percentage of time in 2017 water level was above or below the target limits at all, none or some of the water level measuring stations.

	No station	One station	Two stations	All stations
below 278.74 m a.s.l.	79.5 %	18.1 %	2.3 %	0.1 %
above 278.80 m a.s.l.	79.2 %	11.3 %	5.9 %	3.6 %

2.2.3.2 Laxá Hydropower Stations

Laxá I and III Hydropower Stations use the same intake pond and thus the same dam. Laxá I is not currently in operation and in this report the dam and the pond will be referred to as the dam and intake pond for Laxá III. The dam was built in 1939 and was modified in 2017. The original concrete dam raised the water level for about 3 m. The crest elevation of the concrete spillway was 107.5 m a.s.l. On top of it a timber beam was used to increase the crest elevation to 107.8 m a.s.l. (Sigmundur Freysteinsson, 2010, p. 1 (Laxá I)). After the changes made to the dam in 2017 the spillway crest was still 107.8 m a.s.l. The purpose of the changes was preventing all particles (ice and sediment) from passing through the power stations machinery, i.e. changing the flow paths of ice and sediment particles while keeping the water level unchanged.

The volume of water stored within the intake pond was only about 0.02 Mm^3 and after the changes in 2017 the volume is slightly more, still less than 0.03 Mm^3. A part of the intake pond was deepened but at the same time the new intake was built into the intake pond reducing its area, see figure 2.13. The area of the intake pond was approximately 0.02 km^2 and after the change in 2017 it is still approximated to 0.02 km^2.

Similarly, Laxá II Hydropower Station, has a small intake pond. The dam is also a concrete dam but higher than the one at Laxá III, with spillway crest at 69.0 m a.s.l. The volume in the intake pond is only about 0.04 Mm^3 and it covers 0.016 km^2. In comparison, Sultartangi reservoir has a storage of 109 Mm^3 and covers an area of 20 km^2.

Figure 2.13 The intake pond for Laxá I and III before and after the changes finished in 2017. To the left a picture taken in 2013, to the right a picture taken in 2017.

The optimum water level for operation of Laxá III is 107.8 m a.s.l., i.e. the same as the spillway crest, and for Laxá II it is 68.9 m a.s.l., 10 cm lower than the spillway crest.

In the operation handbook for the Laxá Stations it is stated that during operation an automation controls the power production with the aim at keeping the water level in the intake ponds as close to the optimum values as possible. In the handbook it is also clearly stated that all changes to flow through the turbines and opening or closing of gates shall be made slow enough in order to keep the discharge below the stations without disturbances. This should guaranty minimal effects from all controllable changes.

Are there some damping effects due to the intake ponds?

The intake ponds are very small and respond quickly to flow changes in the river. The question is how quickly. A data series of available measurements from V105 (the water level measuring station at Helluvað) was obtained. The data starts in September 1961 and the last measurement in the series is from the 14th of May 2018. The time interval is not the same throughout. In the beginning the data given represents daily averaged flow or until end of August 2005 when hourly values are given. A part of the data has 5 minutes values and that part was used to calculate how the intake pond effects the flow.

Figure 2.14 shows the inflow at Helluvað[18] as a blue line over approximately a month in March and April 2016. As there are no measurements available at the intake pond this flow was used as inflow to the intake pond and the outflow calculated based on how much the spillways convey at different water elevations, taking into account the mass storage in the intake pond. As it is difficult to see the difference clearly on the graph a part of it is shown in figure 2.15.

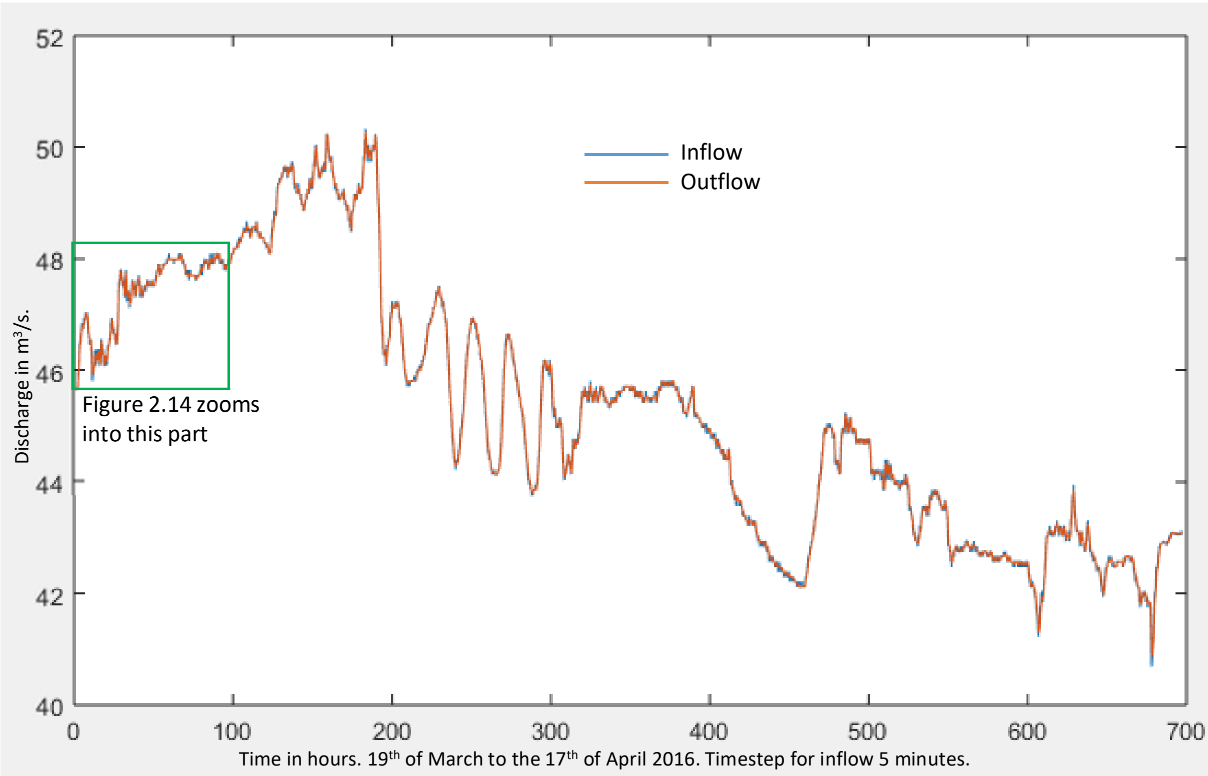

Figure 2.14 Inflow and outflow over spillways to and from the intake pond over approximately a month for Laxá III. 40 m^3/s are assumed to go through the power plant. Inflow in 5 min time steps while calculated outflow has 5 sec time steps. Inflow data rounded partly to 0.1 and partly to 0.01 m^3/s.

There, it is clear, that the lines are not 100 % in sync. The difference is though very small and is probably mostly due to the accuracy of the measurements that are only given with one decimal number within

[18] Based on water level measurements. Discharge calculated using the stage-discharge relationship (rating curve) calculated for the measurement location at Helluvað.

this time range, so the inflow data has 0.1 m^3/s minimum steps. Some part of the time series shown in figure 2.14 has inflow data with two decimal numbers. The max in- and outflow on the figure is 50.33 m^3/s and 50.28 m^3/s and there the inflow has two decimal places. The difference is 0.05 m^3/s which is a very small difference and within error limits.

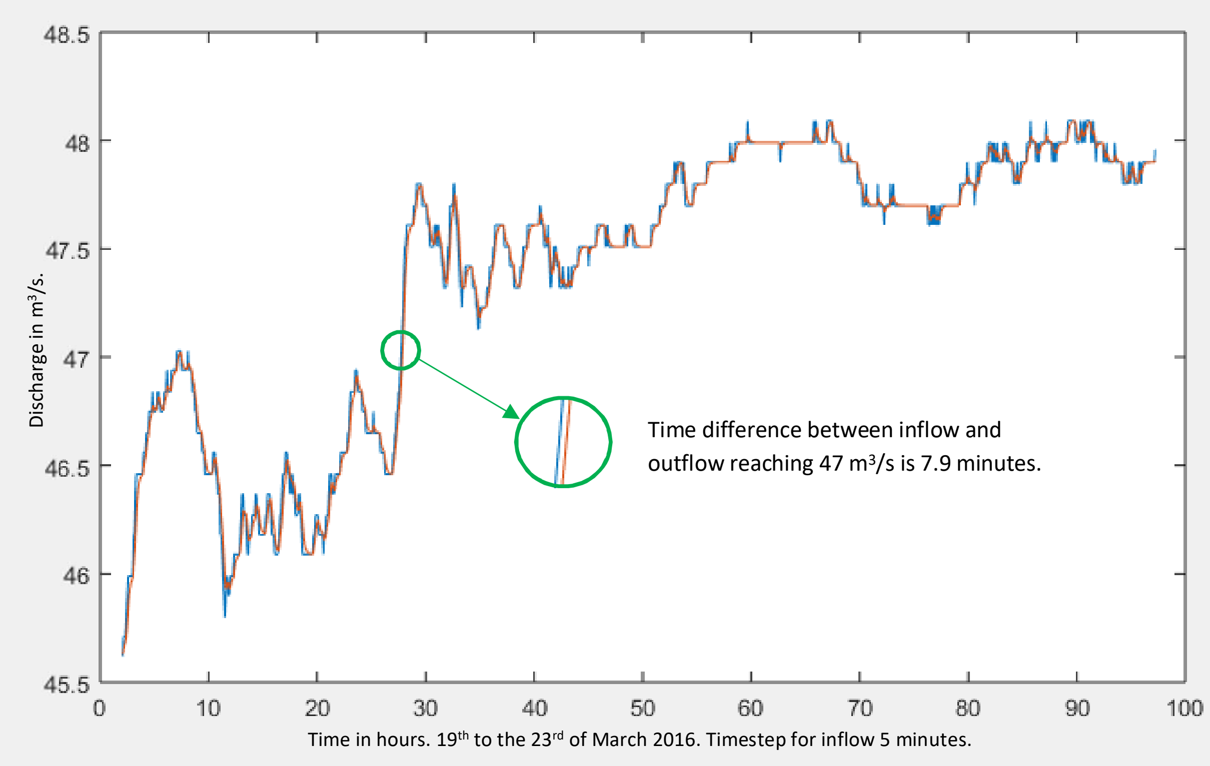

Figure 2.15 Inflow and outflow over spillways to and from the intake pond over 4 days for Laxá III. Inflow in 5 min time steps while calculated outflow has 5 sec time steps. Inflow data rounded to 0.1 m^3/s.

Figure 2.15 also shows a little time lag. A zoom in on the time lag is shown and the calculated time lag is 7.9 minutes. Without the intake pond, assuming average velocity of 1.3 m/s, it would take about 2.5 minutes for the water to pass through the same river reach the intake pond occupies. The difference is thus only 5.4 minutes. The accuracy of the calculations does not justify results with this accuracy, i.e. number with one decimal place. It would be more appropriate to say that the time lag due to the intake pond is between 5 to 10 minutes.

The intake pond for Laxá II has a very similar effect as its size is similar. The difference would be that at the beginning of a period with higher discharge, the additional water would first have to fill up the volume within the reservoir from the optimum water level up to the spillway water level. The difference in elevation is 10 cm, so the volume is about 1600 m^3. If the additional flow is 5 m^3/s it would take about 5 minutes to raise the water level up to the spillway crest. After that the same would apply as for the upper intake pond.

2.3 Floods

There are two different types of floods in the Laxá. One type is rain and snowmelt derived floods and the other is floods produced by ice formations (ice dams) that break suddenly causing a flood wave. The cause, behaviour and consequences are very different and for that reason the discussion about natural floods in the river is split up in two chapters.

2.3.1 Floods due to heavy rain and or snow melt

Rain and/or snow melt induced floods are heavily impacted by the geology of the catchment area. Figure 2.3 shows a part of a geology map of Iceland. The pink coloured areas show areas covered by young lava. The map also shows swarms of faults. The young lava has relatively high leakage compared to other formations and very open surface. The young lava fields and the faults allows rain and snowmelt a quick access into the aquifer that acts as a huge underground reservoir that supplies Mývatn, the Kráká and the Laxá with a steady inflow of groundwater.

Areas covered by these young lava formations usually have no surface flow and, as such, do not contribute water to rain or snow melt floods. For that to happen, special circumstances would have to occur. Sigurjón Rist addresses this issue in one of his articles:

> The river Laxá is mostly a spring-fed river. One of the attributes of spring-fed rivers is that almost no floods occur. Only one exception to this rule exists, due to a special sequence of events. The first event of primary importance is that porous ground must become impervious caused by the freezing of interstitial water. The second necessary condition is that the ground must be a plain, or alternatively, all fissures and depressions must be filled with ice or water. If these conditions are present a flood can start in a spring-fed river's drainage area in thaw and heavy rain just as in the drainage area of a direct-run-off river.
>
> It is obvious that floods cannot exist in the River Laxá or other spring-fed rivers in the summer or in early winter. It is also obvious that at least the second condition does not exist in the uneven volcanic area south and east of Lake Mývatn. The conclusion is that one can expect insignificant floods from the small plains in the neighbourhood of Lake Mývatn late in the winter or in early spring. If we examine Tab. 2 we notice that the percentage of direct-run - off area increases downstream. Consequently the flood trend also increases downstream. (1979a, p. 279)

The table Sigurjón Rist refers to is shown here as table 2.4. In short, he is saying; In the parts of the Laxá where it is dominantly spring fed, floods are almost non-existent. Further downstream, where the geological formations are older and more closed on the surface, the river gains more and more surface runoff area allowing floods to form in the river.

Other references support this. Sigurður Jónsson, farmer at Arnarvatn farm and raised at Helluvað farm, reports as follows on spring floods:

> Discharge in the Laxá is usually very even, when no ice dams are present. It is at its highest during spring thaws, still the water level in the river rises hardly more than 5 to 10 inches[19] from normal water level where it passes Arnarvatn. In the tributaries of the Laxá there is considerable difference between high and low discharge and consequently more difference in discharge in the Laxá further downstream, especially below Grenjaðarstaður farm.[20] (Steinn Steinsen, 1936)

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[19] The Icelandic inch was about 2.4-2.8 cm, ('Metrakerfið', 1995) which means that 5-10 inches should be about 12 to 28 cm.

[20] In Icelandic: "Vatnsmagn í Laxá er yfirleitt mjög jafnt, ef ekki eru stíflanir, verður mest í leysingum á vorin, en vatnsborð í ánni hækkar naumast um meira en 5 til 10 þumlunga frá venjulegu vatnsborði móts við Arnarvatn, en í ám þeim sem í Laxá renna er talsverður munur á mesta og minnsta rennsli og mun því meiri munur á rennslinu neðar í ánni, einkum þegar kemur niður fyrir Grenjaðarstað." (Steinn Steinsen, 1936)

Table 2.4 Overview of the Laxá catchment area (Sigurjón Rist, 1979a, table 2, p. 275).

Tab. 2. Laxá river basin.

	Water Gauge No.	Names of rivers and lakes	Length (km)	Location	Distance from sea (km)	Altitude (m a.s.l.)	Drainage area (km²) Main stream	Tributary streams First order	Second order	Third order	Lakes (km²)	Origin S = spring-fed D = direct-run-off L = lake
1		Laxá	58+35	Ædarfossar	0	0	2,150					S
2	122	Mýrarkvísl	5+26	confluence	4			263				S + D
3		Reykjakvísl	15+11	below Langavatn	24	160			98			S + D
4		Langavatn	.	Langavatn	24	160					0,6	L
5	123	Laxá	.	Laxamýrar-bridge	5		1,885					S
6		–	.	Núpar	7		1,880					S
7		–	.	Núpafoss	8		1,875					S
8		Eyvindarlækur	4+35	confluence	21	24		234				L + D + S
9		–	.	below Vestmannsv.	25	26		223				L + D + S
10		Vestmannsvatn		Vestmannsv.	25	26					2,4	L
11		Reykjadalsá	35	below Vestmannsv.	25	26			223			L + D + S
12		Máslækur	3	below Másv.	47	265				20		L + D
13		Másvatn	.	Másvatn	47	265					3,98	L
14	32	Laxá	.	Birningsst.sog	33		1,550					S + L
15		–	.	north of Helluvad	55		1,470					S + L
16		Helluvadsá	2+15	confluence	55			62				D + L
17		–	.	below Arnarvatn	57			57				D + L
18		Gautlandalækur	12	road to Gautl.	60	270		41				D
19	105	Laxá	.	Arnarvatn-bridge	56	274	1,400					S + L
20		Kráká	35	confluence	58	275		...				S
21	40	Mývatn	.	Álftagerdi	65	277					38	L
22	15	–	.	Grímsstadir	71	277					38	L
23		Sandvatn	.	Sandvatn	65	277					3,66	L

Figures 2.16 and 2.17 also support this with measured data. Figure 2.16 shows how the biggest annual floods are distributed within the year at Helluvað (Arnarvatn bridge, vhm 105) and Birningsstaðasog (vhm 32). Usually the biggest annual floods occur in April or May, but sometimes they occur in the period from November to March, as can be seen on the figure.

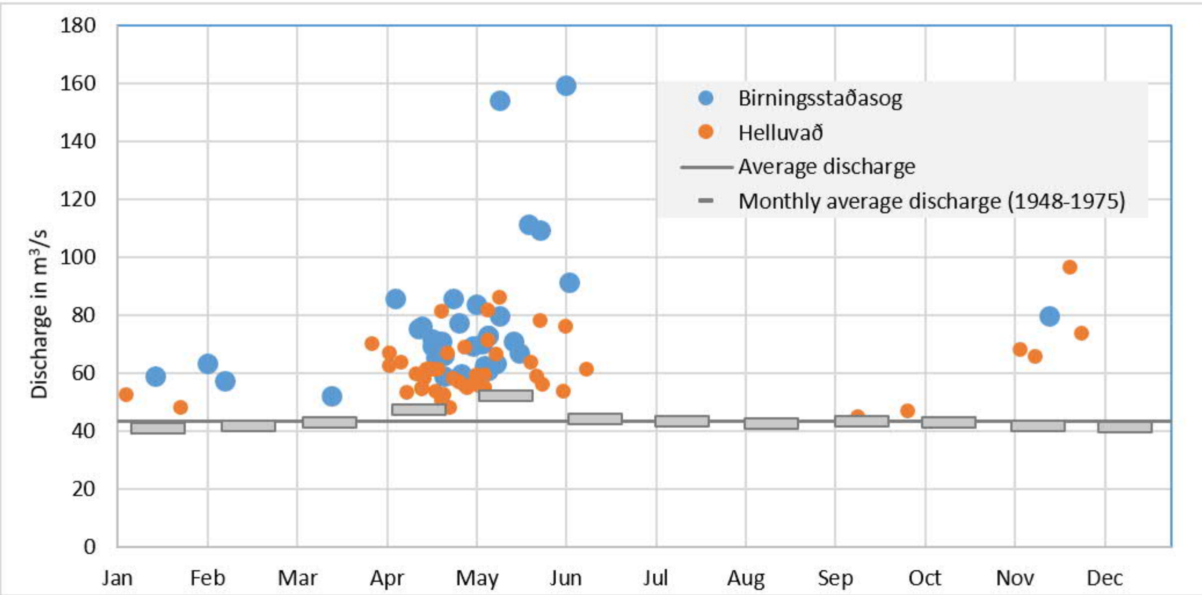


Figure 2.16 Biggest yearly floods at Birningsstaðasog (1964-1999) and Helluvað (1962-2002) (Veðurstofa Íslands, 2014a). Average and monthly average discharge at Birningsstaðasog (Sigurjón Rist, 1979a, p. 278) shown on graph for comparison (data from the years 1948-1975).

Figure 2.17 shows daily averaged discharge at all three measuring stations over 12 years, i.e. the years where measurements are available from all stations simultaneously. The graph shows well how the floods are bigger downstream. That is not surprising, as more area contributes to the flood the further downstream the measuring station is located. But if we look at how much flood water is delivered to the river per km^2 it is clear that areas with older geological formations are contributing much more than areas with young lava formations. Table 2.5 summarises this. The table shows the sub catchment areas for each measuring station, the discharge in the highest yearly flood in figure 2.17 is used, where the baseflow and flood from upstream station has been subtracted. An average, min and max are calculated (1972 is not included as the spring flood is non-existent). Finally, the runoff in litres per second per square kilometre is calculated for comparison. This last column shows that the runoff from the catchment area for the most upstream measuring station (the catchment for Mývatn and the Kráká) is much lower than for the other two. The average runoff value for spring floods for this station is almost ten times lower than for the other two. The maximum runoff during spring floods for this station is also more than ten times lower than for the other two stations. Even the maximum runoff during spring floods for this station (vhm 105) is lower than the minimum for the most downstream station, supporting the description of spring floods given by Sigurður Jónsson.

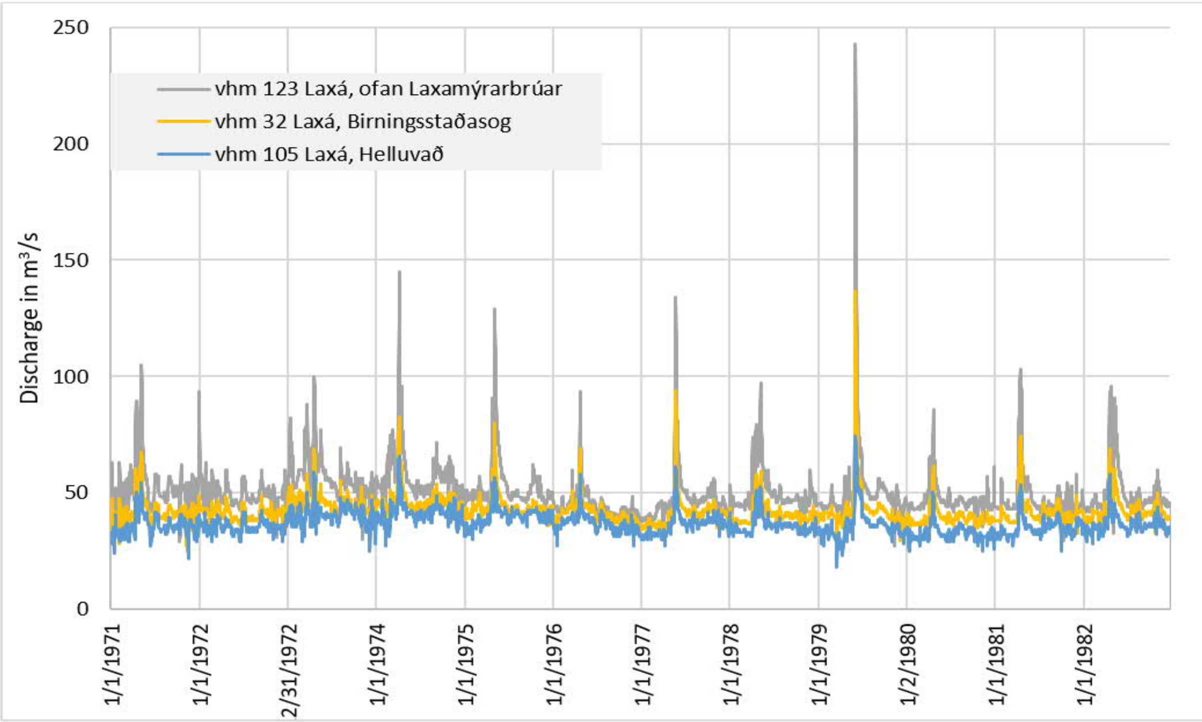


Figure 2.17 Daily average discharge at all three stations in the Laxá over the period when measurements are available from all stations simultaneously, i.e. from 1971 to 1982 (Veðurstofa Íslands, 2015; Veðurstofa Íslands, 2016).

Table 2.5 Discharge and runoff to measuring stations from contributing sub catchment areas minus catchment area for upstream measuring station. Based on floods in figure 2.17.

Measuring station	Sub catchment area* (km^2)	Flood per sub catchment for each measuring station**	
	As shown in Figure 2.2	Discharge (m^3/s) average (min - max)	Runoff $\left(^{l}/_{s\ km^2}\right)$ average (min - max)
Helluvað, vhm 105	1630 (1400)	22 (16-38)	13 (10-23)
Birningsstaðasog, vhm 32	180 (150)	15 (2-57)	82 (11-315)
Laxármýrarbrú, vhm 123	380 (335)	36 (16-100)	96 (43-265)
Total at Laxármýrarbrú	2190 (1885)	73 (40-196)	33 (18-89)

* Just for the relevant station, i.e. the catchment area for the upstream measuring station has been subtracted. Area not 100 % clear as part of the watershed is covered with lava, making the estimation of the watershed divide line uncertain. The number in () is the area as reported by Sigurjón Rist in 1979.

** Discharge in floods: baseflow at station and flood contribution from upstream station subtracted. Example: flood in 1973 at vhm 123 was measured 100 m^3/s, see figure 2.17, from that the baseflow of about 50 m^3/s is subtracted to get the flood at vhm 123. Then the flood for vhm 32 is also subtracted to get the flood contribution from the sub catchment area, i.e. 100 m^3/s -50 m^3/s -22 m^3/s = 28 m^3/s.

2.3.2 River ice related floods

River ice formations in the Laxá causes both the highest water elevation, i.e. flooding, and the highest discharge in the Laxárdalur. This has partly been addressed in chapter 2.2.2 where water level rise due to ice formations within the river has been explained.

In addition to the water level rise at and upstream of the ice formations, temporary ice formations within the Laxárdalur are the cause of the biggest floods in the Laxárdalur in terms of volume per second. These floods are the result of a sudden ice dam break. First, ice dams form at one or a few locations within the river, usually due to anchor ice formations at rapids which then start to collect ice that is flowing downstream, adding to the dam formation. These ice dams grow from the river bed and up into the flow. These dams are not long-lived and when they break the water that was dammed by the ice dam is released all at once. The flood wave that this process creates is usually called an ice surge (in Icelandic þrepahlaup) and is a wave of water and ice rubble that travels faster downstream than ordinary water in rain induced floods. As the flood wave travels downstream, other ice dams in its path break as well adding water and ice to the flood wave. The wave also breaks up border ice and other ice in its path. This means that its origin can be found by examining the river after the flood to see where the river is completely ice free and where some border ice can be found upstream of the starting point.

Reports of these floods indicate that they are short-lived. A relatively large one in 1950 flooded the Laxá I Station building for only 5 minutes (Halblaub, 1950, p. 7). This indicates that the flood peak in these floods/flood waves can be as short as the shortest time step available in the water level measurements time series used in chapters above. These floods can thus easily be missed even though the water level is measured in the vicinity.

Before the construction of the power stations in the Laxá, these floods are difficult to find on record. They affect the operation of the power stations and because of that many records can be found after the construction of the first one. For this reason, it is necessary to base the knowledge of these floods on descriptions made by employees of Laxá Station and description by Sigurjón Rist on the same phenomenon in the Þjórsá in the south of Iceland.

These floods move fast where the thalweg is steep and narrow, as in the Laxárdalur. Where these floods enter areas where the slope is relatively low and the river widens out, like in Aðaldalur or at Birningsstaðaflói, the wave dies out relatively quickly. There, the flood wave loses its conveyance and leaves the ice rubble behind.

2.3.3 Constructions - Influence on floods, question F-2

2.3.3.1 Floods due to heavy rain and/or snow melt

These floods grow slowly in the sense that the responding time of the intake ponds is faster. This means that what has been said in chapter 2.2.3.2 also applies here.

2.3.3.2 River ice related floods

<u>Water level changes due to ice formations:</u>

Water level changes due to ice formations within the river are the same as before except at some locations ice formations are rarer after the Geirastaðir constructions as the discharge is more stable than before. This should mainly apply to locations close to Mývatn and locations where ice formations occurred due to lower discharge than normal when ice blocked the flow from Mývatn. In most places, ice formations continue to form as they are created by snow, snow drift and ice slush that is formed within the river or fall into the river over its whole length. This material collects into ice jams at various locations within the river (Halldórsstaðir ice jam and the ice jams that form in Aðaldalur). The power stations do not change this, even though a big part of the ice slush travels through the power stations and becomes less active at the downstream end. The slush is still a building material for ice jams when it re-enters the river.

Ice surge – þrepahlaup:

The size of the ice surges depends on weather conditions as its strength, amount of building material and degradation is dependent on weather and radiation. Some ice surges are small and others very big, but all are short-lived in time. The intake ponds are small and respond quickly to flow changes, but if the ice surge is small the intake ponds will affect its progress or even dampen the wave completely. In those cases, the ice rubble carried by the ice surge will stop in the intake ponds, see example on figure 2.18.

Figure 2.18 Ice rubble that has ploughed its way into the ice cover on the intake pond for Laxá II. Photo from the 7th of February 2009 ('Laxá Station photo collection', n.d.).

The effect of the dam structures is different between the two powerplants due to their different forms and the planform of the river upstream and within the intake ponds. The planform upstream of the intake pond for Laxá I/III has a turn that directs the main flow to the western branch in the intake pond, see figure 2.19. This means that the power of the flow is directed into the western branch and there, ice rubble is carried straight through, while the eastern branch is on the lee ward side, allowing ice rubble to disperse from the main flow and get stranded in the eastern branch. Additionally, the spillway is located in the western branch and it has nothing on top of it that can hinder the passage of the ice rubble over it. These two facts lead to the common result that after an ice surge the western branch in the upper intake pond is clear of ice and the eastern branch and the intake itself, is propped with ice, see figure 2.20. So, for the upper intake pond the usual effects are:

- Part of the ice rubble is left behind in the eastern branch
- Most of the wave is carried quickly through the intake pond and over the spillway.

Figure 2.19 An overview of the intake ponds and the dams (Samsýn, 2003).

Figure 2.20 Ice rubble on the intake pond for Laxá III. Open surface along the Western bank to the spillway. Photo from the 7th of February 2009 ('Laxá Station photo collection', n.d.)

The intake pond for Laxá II has no island that diverts the flow into two branches. This means that the whole intake pond is active, not just one of two branches as is usually (if the ice surge is not too big) the case in the other intake pond. The dam itself is probably the biggest difference as it has a bridge on top of the spillway. This part of the construction allows this dam to dampen bigger floods than the old dam as the ice carried with the flow can get stuck between the spillway and the bridge, on the pillars and on the bridge.

- Usually, all the ice rubble stops within the intake pond.
- Most of the wave is dampened out in the intake pond as the ice prevents the spillway from functioning properly and increases the response time.

The biggest ice surges might only leave part of the ice rubble behind in the intake ponds if the wave becomes big enough to carry most of the ice with the wave over the dams and bridges down into the Aðaldalur below. But in most cases, the greater part of the ice rubble stops in the intake ponds and surrounding area.

It is possible that the bigger ice surges are fewer or even non-existent after the Geirastaðir construction, but as this phenomenon has not been researched as such, it is impossible to say. Big ice surges would most likely be documented in some way at Laxá Station as they are destructive while the smaller ones cause temporary disturbances and possible blockage of intakes.

For the purpose of this report it is informative to include a description of one of those bigger ice surges. A report on the flood on the 4th of December in 1950 is included as appendix 3. To summarize the main aspects the following points were picked out:

- Laxá I Station flooded for about 5 minutes.
- A car inside the station was moved by the flood.

- A big rock, approximately ½ a ton, was carried by the flood and left behind to the east of the transformers room.
- Ice filled the eastern branch in the intake pond, some ice cubes higher than the dam.
- The western branch was ice free to the spillway allowing all water to flow over the spillway.

Laxárvirkjun, mars 1965. Eftir þrepahlaup, N.B. lón.

Figure 2.21 Ice rubble at the banks of the Laxá upstream of Laxá II Station after an ice surge in March 1965 ('Laxá Station photo collection', n.d.)

2.4 Discussion on questions F-3 and F-4

Questions F-3 and F-4, regarding possible river edge areas that might be prone to isolation (F-3) and possible effects on water velocity and depth due to changes in daily flow pattern (F-4), are only relevant if the findings showed that daily flow pattern had changed. The Laxá has no daily flow pattern. Still, the river has natural flow variations that are governed by the wind and ice formations. The effect of the former is not changed as long as the operation of the Geirastaðir channel takes the wind effect into account.

The ice formations in Mývatn that used to block the outflow and cause the lowest discharge in the Laxá are much rarer and the blockage is not as severe as it used to be. This has led to fewer instances of very low discharge in the Laxá and most likely also, affected some of the other ice formations within the river itself but not all types. The result is:

- More stable discharge in winter time.
- Fewer instances and less area that could be affected by low flow, i.e. fewer river edge areas that could be prone to isolation.

3 Sediment transport

The word sediment, in respect to rivers, refers to all grain sizes transported by the river and range from fine clay particles to large boulders. Two overlapping systems of classifying transport modes in rivers with moderate gradients exist. They are:

a) bed load + suspended load
b) bed-material load + wash load.

In the former, the bed load consists of the coarser particles that travel along the bed by rolling, sliding or saltating, while the suspended load consists of the finer particles that are maintained in suspension by turbulence at the location in question and are advected with the main flow. The latter refers to bed-material load as all sizes normally found in the bed, without distinguishing between transport mechanism, and wash load as all sizes that always travel in suspension and are not found in significant quantities in the bed (MacArthur, Neill, Hall, Galay og Shvidchenko, 2007, p. 8).

The word substrate, in terms of biology, is defined as the surface on which an organism lives and in terms of sediment in rivers, the material that rests at the bottom of a stream (Biocyclopedia.com, e.d.; „Substrate (marine biology) - Wikipedia“, e.d.). Available material for transport and the transport capacity of a river at each location govern the substrate in rivers. Mechanical removal of sediment can thus influence the substrate in a river.

Grain sizes and sediment material density, fluid density and viscosity, and the strength and turbulence of the flow, influence sediment transport and the bed material. Additionally, ice in rivers can affect all these aspects in various ways and can thus change the rhythm of sediment transport when present and affect the bed material. Ice can also transport sediment. The influence of ice on sediment transport is often overlooked. The mechanism of sediment transport in rivers without ice effects has been studied for a long time and various formulas are available to calculate erosion, transport capacity and sedimentation rate. Measuring methods have also been developed and are well established worldwide. The same cannot be said about sediment transport when ice affects the flow and thus the transport.

In this chapter a quick overview is given on sediment transport, just enough to ensure the reader can follow theories that will be presented in the following chapters on likely transport mechanisms in the Laxá.

3.1 Overview on sediment transport

3.1.1 Sediment transport mechanics

For a particle to be transported the first step is initial movement, i.e. from the riverbed or banks into the flow. For this to happen the forces applied by the water on the particle (the hydrodynamic drag and lift) must exceed the resisting forces (the submerged weight of the particle and friction force that becomes present at the time of initial movement). The transport mechanism that transports the particle after it enters the flow depends on its size, shape, weight and the flow at its location.

Smaller particles are more easily transported with the flow and the turbulence in the flow becomes the governing force influencing their path. This means that they are easily transported as suspended load and the turbulence can distribute them evenly across the water column and often also across the whole cross section. This also applies to the so-called wash load.

After the bigger particles have overcome the initial movement threshold they can be transported either as bed load or, if they are small enough and the conveyance capacity of the flow is high enough, as suspended load. If they become suspended the concentration distribution within the water column is usually different from the smaller particles as gravity influences their path in addition to the turbulence in the flow resulting in a downward tendency. This leads to higher concentration of bigger particles closer to the bed than close to the surface.

Randomness is also a factor in sediment transport mechanics. Turbulence is highly random and how particles are distributed and located on the riverbed is also partly random. This means that the initial movement threshold has a randomness to it and the movement of particles as bead load is highly random and thus difficult to measure accurately.

In alluvial rivers the bed material can also form various bed forms like dunes and ripples and those forms migrate downstream and as such are a part of the bed load transport.

Some sediment particles are not initially moved from the river bed itself but are carried into the river by other means. This could be wind-blown particles or particles that fall into the river by other means.

The last mechanism in sediment transport is the settling of the sediment. This happens when the transporting or conveyance capacity of the river becomes low enough for the gravity forces to take over. Bigger particles start to settle before the smaller ones as the gravity force is higher as they are heavier, so the gravity force kicks in at higher velocities than for the smaller and lighter particles.

3.1.2 Sediment load

Sediment transported depends on the sediment transport capacity and the availability of sediment to transport. The sediment transport capacity is the capacity of the flow at a specific cross section, at specific time (discharge) to carry sediment through the cross section, assuming abundance of sediment available upstream. Discharge, slope and cross-sectional shape are among the governing factors affecting the sediment transport capacity. If sediment material is abundant the river should use its total conveyance capacity. If, on the other hand, sediment material is not in abundance the river should be able to transport all the sediment it has available downstream. How much is available can be seasonal or change with time (long time changes).

Because rivers have different slope, cross sections, discharge and bed material along its length the sediment transport capacity varies. In some parts of a river sediment is simply transported through, in other parts the river is adding sediment to the load it is carrying by eroding its bed or banks and in some places it offloads a part or all of its sediment load and deltas or bars form. Where within the river each of these mechanisms are at work also changes with discharge as added discharge increases the sediment transport capacity. Ice formations also affect what happens where within the river system.

3.1.3 Sediment transported with ice

Ice often acts as a vehicle of transport for sediment particles of all sizes. Anchor ice is the main culprit as it forms on the riverbed at locations where the water can become supercooled and the flow is turbulent enough to distribute the tiny ice particles and the supercooled water throughout the water column all the way from the surface to the riverbed. When anchor ice forms on a riverbed made of loose material the anchor ice can grow until the uplift forces, caused by the density difference between the ice/bed material combo and the water, overcome the gravity forces. Then it starts to lift and is carried with the flow downstream. How far downstream the sediment is carried depends on a few factors:

1. Does the ice the sediment material is entrained in:
    a. Stay the same, i.e. just afloat? → Can float anywhere within the water column as the combined density of ice and sediment is just marginally higher than density of water.
    b. Keep growing and thus increase the floating capacity? → Floats to the surface.
    c. Start to melt or break up due to other factors like turbulence in the flow? → The rest of the ice/ sediment combo falls back to the riverbed.
2. Does the ice/sediment combo get trapped somewhere, like in an ice formation? → The sediment material gets stuck there either:
    a. Temporarily, until break-up of the formation when it is transported further down-stream to a new location.
    b. Or gets released and falls to the river bed when the ice formation melts.

For bigger stones, more ice is needed for it to be transported. Anchor ice often follows a diurnal pattern, i.e. forms during the night and loses its bond to the riverbed due to radiation from the sun during the day. If the riverbed is made of sand, anchor ice can start to form but as the sand grains are so small the ice formed on them quickly lifts them up into the flow allowing new trial of anchor ice formation. This way, sand can be entrained into the ice slush formed in the river.

Sediment material can also be entrained in ice that forms at the riverbanks and by other methods like when an ice jam is showed downstream and scrapes the river bed or banks.

The above description is a simplified description of processes involved. A paragraph from a recent book on sedimentation gives an indication of how little we still know about the influence of ice on sediment transport.

> Sediment-laden ice slush and clumps of ice-bonded sediment may appear during the early stages of ice formation in certain rivers and or streams subject to the winter cycle of ice formation. The ice slush and clumps comprise a mix of frazil ice and anchor ice that once was briefly bonded to the beds of such rivers and streams. The amounts of sediment entrained or rafted with the ice slush and clumps can produce a substantial momentary surge in the overall quantity of sediment moved by some rivers and streams, though at present there are no reliable measurements or estimates of ice-rafted sediment-transport rates. Much of the entrained sediment becomes included in an ice cover, where it remains stored until the cover breaks up. Though ice-rafting of sediment is known to occur, the implications of its occurrence largely remain unknown. (Ettema, 2007, p. 625)

The first sentence in the paragraph above does not apply to Iceland, except in the highlands. The climate is more temperate than would be expected this far north due to the North Atlantic current. The winters are relatively mild and there are endless cycles of freeze-up and breakup periods in most rivers, except in the highlands where the temperature usually stays below zero over the winter time.

3.1.4 Increased sediment transport and erosion due to ice formations

Ice in rivers can also increase sediment transport with the water by influencing the flow.

Ice slush increases viscosity of the water. Sometimes the viscosity of the water/ice slush mix becomes so high that the power stations stop producing electricity and start to use it in order to keep the turbines moving.

Various ice formations within the river influence the shape of the cross section and, as a result, change the velocity, both average velocity, the velocity profile and the secondary currents[21]. The effects can be very different between formations. Here are some examples:

A uniformly thick and free-floating ice cover on a river adds a friction surface that affects the flow. The added friction leads to:

- water level change because more cross-sectional area is needed to transport the same amount of flow.
- lower velocity and thus reduced drag on the river bed resulting in reduced rates of bed-sediment transport.
- Changes in velocity change the energy gradient that influences sinuosity of alluvial rivers. This means that alluvial rivers start to shift in order to find a new balance.

A uniformly thick and free-floating ice cover is more common on lakes and very calm rivers than in natural rivers.

[21] Definition: “Secondary currents (or flow): The movement of water particles on a cross section normal to the principal direction of flow.” (MacArthur og Brad R. Hall, 2007, p. 1098) The secondary currents are the result of both change in momentum of the flow and friction.

Sometimes ice cover can become fixed at the banks but then usually just for a short time. That would lead to added pressure and bed erosion. This has not been researched well and will not be addressed further.

Ice jams, as described in chapter 2.2.2.2, and hanging dams can change the cross-sectional area tremendously and cause local scour at a point or along a temporary higher velocity channel formed within the original river channel, see figures 3.1 to 3.3. The first figure explains how an ice jam can cause local scour under its thicker parts where the cross section has been reduced, causing an increase in velocity and drag. These parts can form in more than one location and change location with time as the ice jam is pushed and showed. The other two figures show how frazil slush can accumulate (settle) on the underside of an ice cover and fill all low velocity areas. The frazil slush behaves similarly to alluvial material in alluvial river with the difference of settling on the underside of an ice cover due to buoyancy instead of settling on the river bed due to gravity. The same principles apply with an opposite sign in the vertical direction. The accumulation of frazil usually concentrates the flow into channels increasing local velocity and bed erosion. As can be seen on the figures these channels are not fixed with time and can move, just as channels in alluvial rivers. Both the bed material, i.e. alluvial material, and the frazil ice can be eroded and changed. The frazil ice is different from the alluvial material in the way that it can change with time and bond with other ice crystals.

> Beltaos and Dean (1981) reported measurements on the physical and mechanical properties of a hanging dam that forms each winter in the Smoky River, Alberta. The ice accumulation consisted of frazil slush particles, roughly spherical in shape, 1 to 6 mm in diameter. The permeability of the slush was comparable to that of coarse sand or fine gravel. The dry density of the slush in the dam increased with height above the bottom and so did the shear strength, ranging from 400 to 600 kg/m^3 and from 10 to 50 kPa, respectively. (Beltaos, 1995, p. 81)

If:

a) the discharge is relatively steady,
b) the ice formations form slowly (no showing) and
c) the magnitude of ice transported is lower or equal to the conveyance capacity of the river,

the channels within the ice formations usually stay open. This is because accumulation underneath the ice cover stops when the velocity becomes high enough to transport all the ice through and all locations with lower velocity are already filled with frazil ice.

Showing of an ice jam, too much inflowing ice (more than the transport capacity of the flow) and changes in discharge can break this balance. Then the cross section that had formed within the ice formation can become blocked and force the water to flow above the ice jam or out of the river bed along the flood plains. This also means that sediment can be carried with the flow out of the river onto the flood plains. The ice formation does not have an even surface and is often higher in the middle if it has been showed and pushed. This often forces the water to run along the banks if the banks are still high enough to keep the flow within the river. This often causes added erosion along the river banks and can explain why in some locations within the river the depth is surprisingly deep in small bays with very low velocity, i.e. locations ideal for sedimentation and shallow water.

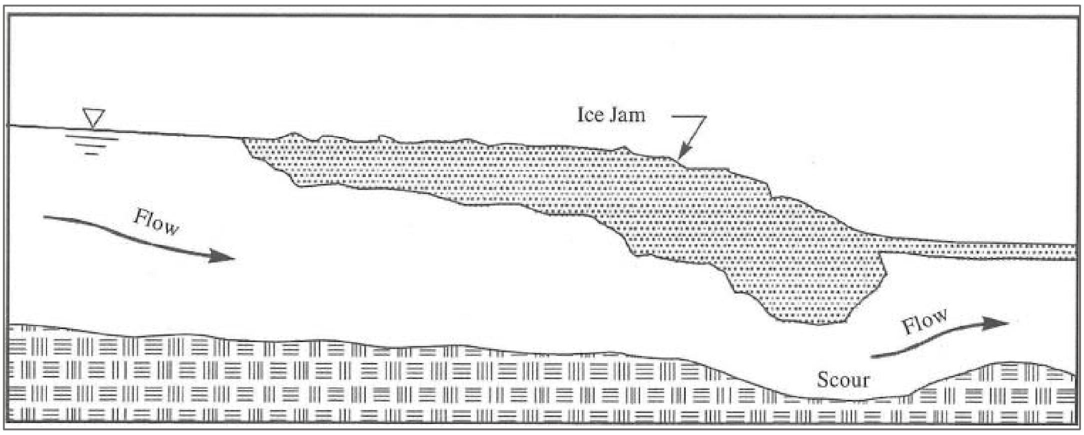


Figure 3.1 Local scour (erosion) of the bed beneath an ice jam (Ettema og Kempema, 2012, p. 532, fig. 37.9).

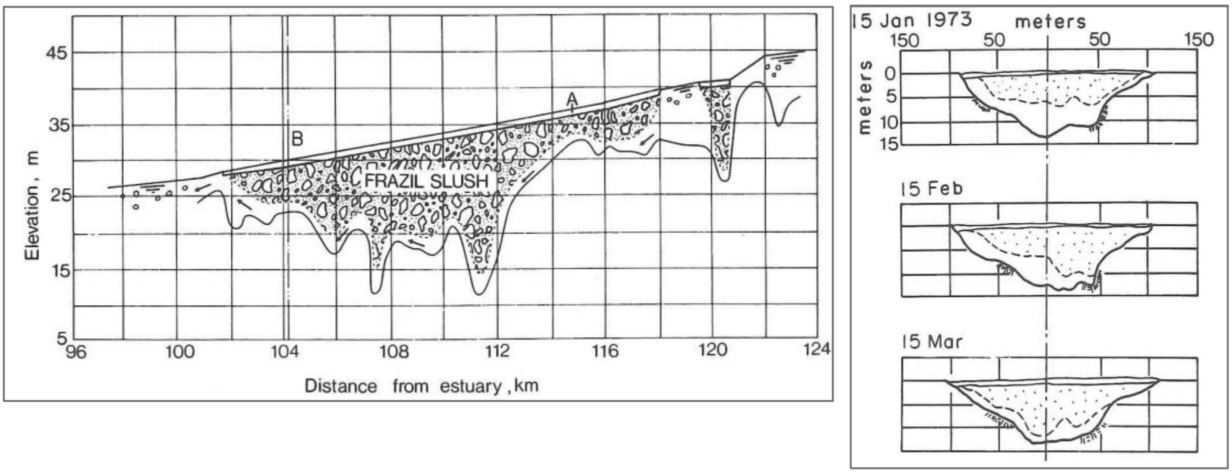


Figure 3.2 Hanging dams in the LaGrande River. Left: Longitudinal profile in February 1973. Right: cross sections at different times in 1973 (Michel o.fl., 1986, p. 280-281, originally from Michel and Drouin 1981).

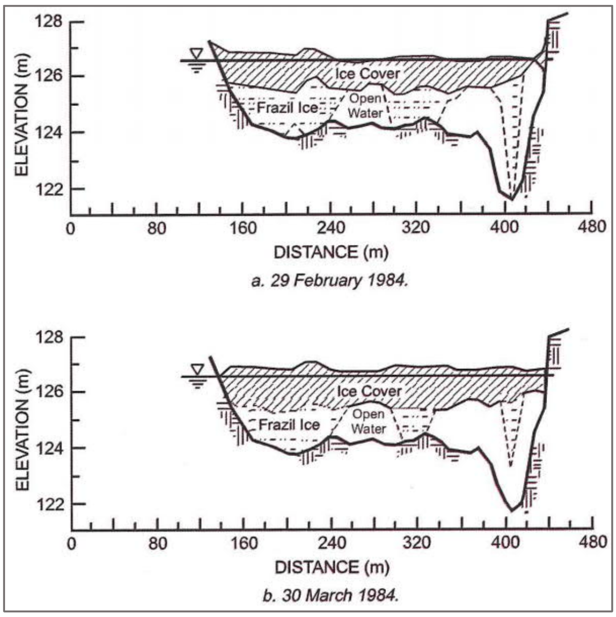


Figure 3.3 Non-uniform ice accumulation across a section of the Tanana River, Alaska (McMahon, 2002, p. 7-5, fig. 7-4).

3.2 Sediment transport in the Laxá

Sediment transport is a complex process and thus difficult to measure accurately. This chapter summarizes available information and research on sediment transport in the Laxá.

3.2.1 Sediment transport measurements within the river system

A well-known method for estimating sediment transport in a river is to measure the suspended sediment and the bedload separately with specialized sampling equipment. The equipment is different for suspended sediment sampling and bedload sampling. Although both must align themselves parallel to the flow, the former samples while in suspension while the latter takes the sample after settling on the riverbed. These methods only measure the smaller size range of sediment transported by the river, not the stones.

For a good and reliable estimate measurements should be carried out:

- over a long period,
- over a wide range of discharge and
- cover all seasons/months.

This is because sediment transport usually changes with discharge, can change over a long period of time and can have some seasonal changes.

3.2.1.1 Available measurements

Available measurements in the Laxá/Kráká river system are as follows:

Measurements of suspended sediment transport (Veðurstofa Íslands, 2014b):

a) 1 in the Kráká at Baldursheimur, 1965, type S1,
b) 1 in the Kráká at Litlaströnd, 1966, type S3,
c) 1 in the Laxá at Birningsstaðasog, 1996, type S1,
d) 177 in the Laxá at the bridge above Helluvað, 1997-2013.

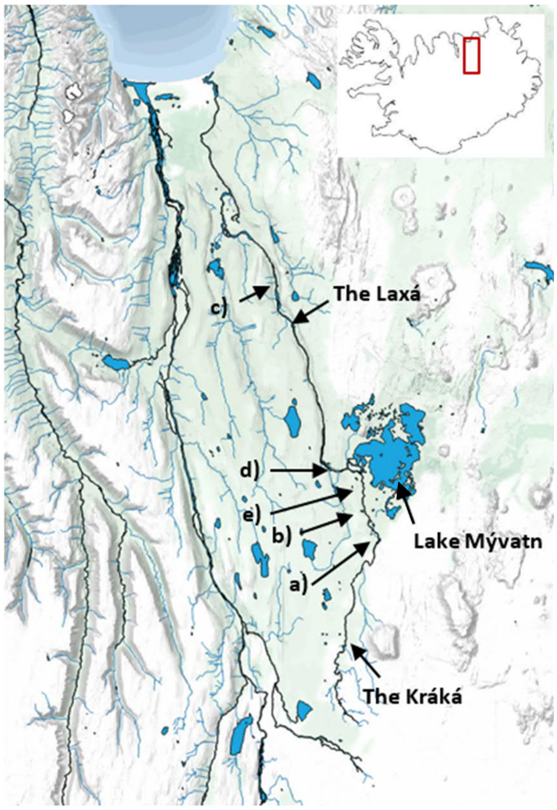


Figure 3.4 Sediment transport measuring locations in the Laxá and the Kráká.

Measurements of bed load transport (Hlín Kristín Þorkelsdóttir, 1999):

e) 2 in the Kráká at the bridge, 1998.

See locations within the watershed in figure 3.4.

None of these measurements include larger particle movement within the river system like stones.

3.2.1.2 Measurement quality

The S1 type measurements represent suspended sediment in the whole cross section as measurements are taken at fixed distances along the cross section and the measurement is made along the water column from top to bottom at each location. These are considered good quality measurements.

The S2 type is taken at one location within the cross section. This location is then considered to represent the whole cross section. These measurements can be good in some locations but are flawed in others. This completely depends on the river, sediment transport and the location. In the Laxá S2 type measurements have been considered relatively good at Helluvað in many reports.

The S3 type measurements are taken in one location close to the bank. This method usually underestimates the sediment transport considerably.

The bed load measurements are difficult to carry out, as the bed load transport is stochastic and can vary immensely within a short time period for the same discharge. Additionally, the riverbed is not level and the bed material can vary, so how and where the measurement equipment lands can influence the measurements. Regarding the measurements in the Kráká, it is more likely that the measurements underestimate the bed load transport. This is not certain and only based on descriptions in the appendix in the 1999 VST report where the equipment often lands on rock or other things in the bed, which can limit the inflow of sediment to the measuring equipment. But then, on the other hand, the equipment sank in sand on two occasions resulting in high peaks in measured transport (Verkfræðistofa Sigurðar Thoroddsen hf., 1999).

Grain size distribution

Figure 3.5 is taken from Reservoir Sedimentation Handbook (Morris & Fan, 1998, p. 5.3). It is a comparison of different national scales for particle sizes with the Icelandic size classing system added on the figure. The Icelandic system is very similar to the French system with the addition of dividing (after 2002) the size class "mór" into "fínmór" and "grófmór". The reason for the splitting of the "mór" class is that settling velocity is calculated differently for smaller particles and larger particles and the split is approximately at 0.06 mm. The finer particles, like clay and silt (< 0.06 mm), as defined by the USA scale, see figure 3.5, are in the laminar range and follow Stokes' equation, while for the coarse grains drag starts to affect the fall velocity so a different formula has to be used in the laminar zone and in the turbulent range the fall velocity has to be determined experimentally (Morris & Fan, 1998, p. 5.16).

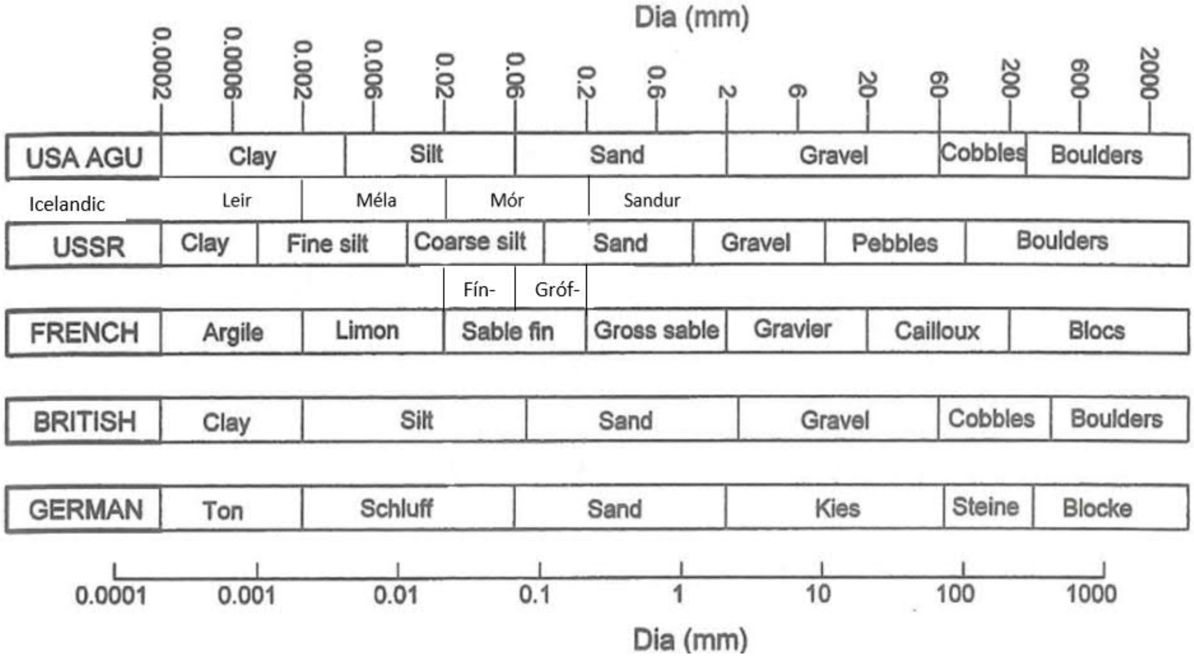


Figure 3.5 Comparison of national scales for particle sizes with the Icelandic size classing system included (Morris & Fan, 1998, p. 5.3, Figure 5.1).

The opening of the nozzle for the suspended sediment samplers are all under 1 cm in diameter. The size of the nozzle is selected based on the velocity. Table 3.1shows the grain size distribution of the available samples of suspended sediment at Helluvað. The median grain size, d_{50}, is just under 0.2 mm, i.e. in the fine sand range. Table 3.2 shows that the largest grain size measured as suspended sediment at Helluvað was 4.5 mm in diameter (gravel sized), while the average largest grain per sample was about 1.6 mm (for both type S1 and S2), i.e. in the sand range.

Table 3.1 Grain size classes and distribution in measured suspended sediment samples at Helluvað.

Size class		Percentage of total suspended sediment transport	
Name	Size in mm	From the VST report in 2002	Based on available data in 2015
Sandur	>0.2	48 %	40 %
Grófmór	0.06-0.2	29 %	18 %
Fínmór	0.02-0.06		10 %
Méla	0.002-0.02	16 %	22 %
Leir	< 0.002	7 %	10 %

Table 3.2 Largest grain (mm) per measurement. Suspended sediment samples at Helluvað (Veðurstofa Íslands, 2014b).

	Type S1	Type S2	Type S3
Smallest of the largest	0.7	0.5	0.3
Average of the largest	1.62	1.56	0.66
Largest of the largest	4.5	3.75	1.7
Number of measurements	*28*	*140*	*9*

The opening of the bed load measurement equipment is 7.6 cm x 7.6 cm. According to Hlín Kristín Þorkelsdóttir (1999, p. 22) the median of measured bed load in Kráká in 1998 was 0.44 mm, d_{35} = 0.36 mm and d_{90} = 0.98 mm, all in the sand range.

3.2.1.3 Magnitude estimates

Older estimates

In 1969 an estimate was made based on the two measurements from the Kráká at the time. The estimate was 0.5 kg/s in the Kráká during normal discharge (or 15 thousand tons per year) (Sigurjón Rist o.fl., 1969, appendix 5, p. 2-3).

Based on the measurements at Helluvað

Using measurements of suspended sediment at Helluvað to estimate total sediment transport (smaller particles from smaller gravel sizes and smaller) is considered to be adequate and represent the Laxá well as the material coming as suspended sediment and bed load from Kráká is most likely in suspension at the measuring location (Hlín Kristín Þorkelsdóttir, 1999, p. 15; Verkfræðistofa Sigurðar Thoroddsen hf., 2002, p. 7). The magnitude has been estimated a few times.

In a report from 2002, the suspended sediment transport in the Laxá was estimated in the range of 40–60 thousand tons per year based on data from Helluvað. The data sample included 24 S1 samples and 20 S2 samples, or 44 samples in total. All the samples were taken when the discharge in the river was less than 45 m^3/s. This restricted the estimation method, as the usual method of creating a sediment-rating curve was not applicable due to the limited discharge range. Instead, the mean value method was used. The grain size distribution calculated at that time is shown in table 3.1 (Verkfræðistofa Sigurðar Thoroddsen hf., 2002).

A re-evaluation made in 2015, as a part of the design process for the changes made to the intake structure and dam for Laxá III in 2016-17, gave about 45 000 tons per year, which amounts to volume of about 30 000 m^3/y, assuming a density of 1500 kg/m^3. The same method as in 2002 was applied, including additional measurements available. The discharge range was between 30 to 58 m^3/s. The grain size distribution is also shown in table 3.1.

3.2.1.4 Changes with time at Helluvað

Seasonal changes

A quick check on seasonal differences in sediment transport at Helluvað, based on the same data, shows no clear trends. The same result was documented in the 2002 report (Verkfræðistofa Sigurðar Thoroddsen hf., 2002, p. 8). This is though not conclusive as the winter measurements are far fewer than the summer measurements and the winter measurements that were made were probably made during good weather conditions and, as such, do not represent the normal winter conditions when ice effects can influence the sediment transport.

Changes with time over the years

A quick check on changes in sediment transport with time shows no clear trends except:

- The yearly averaged value for sediment transport, based on available measurements at Helluvað, in the "méla" and "fínmór" classes (particles size from 0.002 to 0.06 mm, or silt in many national scales) is 3-4 times higher in the years 2005-2006 and again in 2012-2013, see figure 3.6. This might be caused by the eruptions in Grímsvötn (eruption in November 2004 and May 2011). The same trend is not detectable after the eruption in 1998. This has not been looked into in any detail.
- There might be a slight decay in the transport of "grófmór", but more data would be needed to see if this is a continuous trend or just a temporary one, see figure 3.7. If it is a real trend it might be an indicator that the land reclamation program for the Kráká catchment is finally starting to pay off. This might also be a temporary trend that bounces back later.

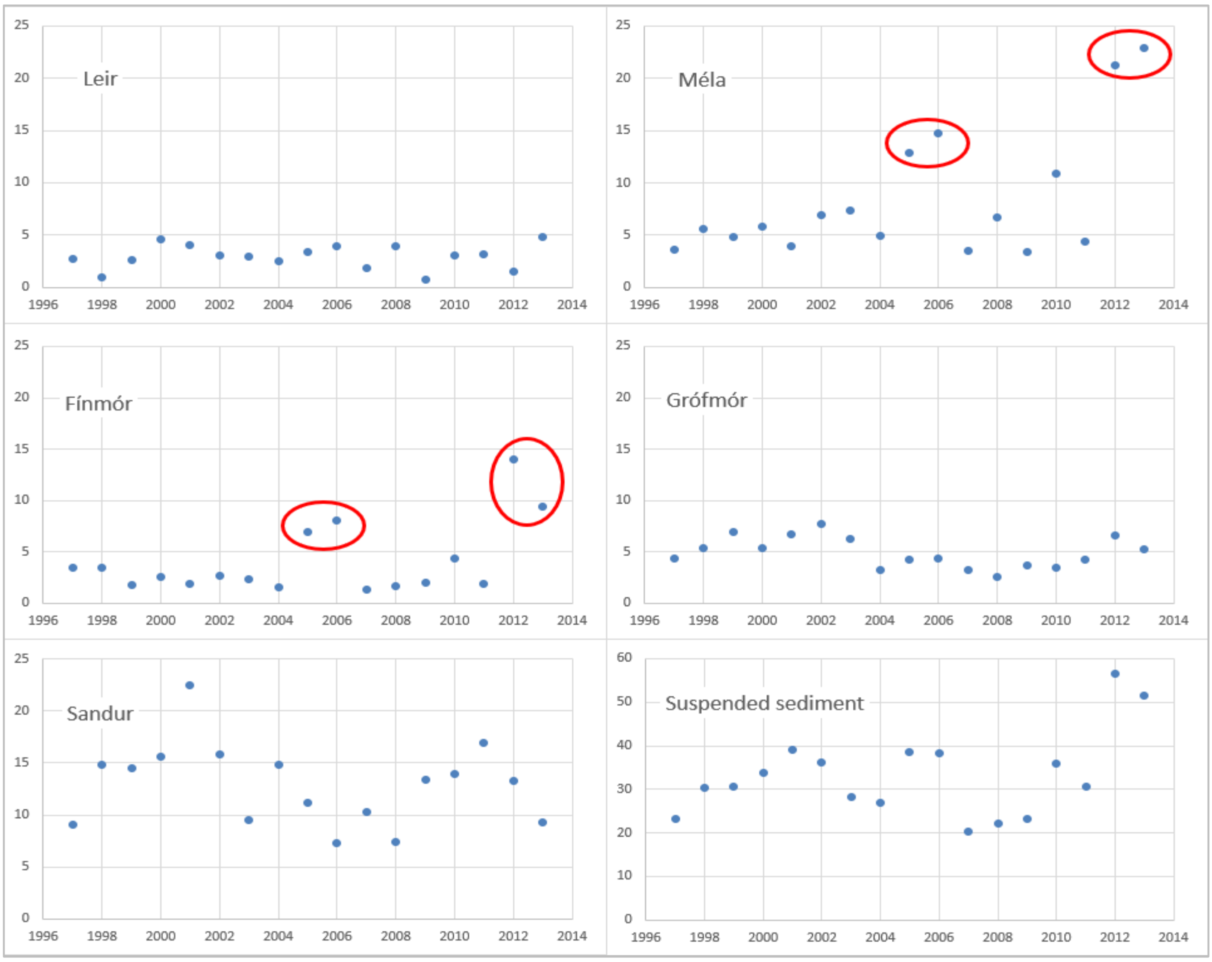


Figure 3.6 Yearly average of suspended sediment in mg/l, based on samples at Helluvað. Max no. of data per year 13 and min 4, on average 9.3 (Veðurstofa Íslands, 2014b).

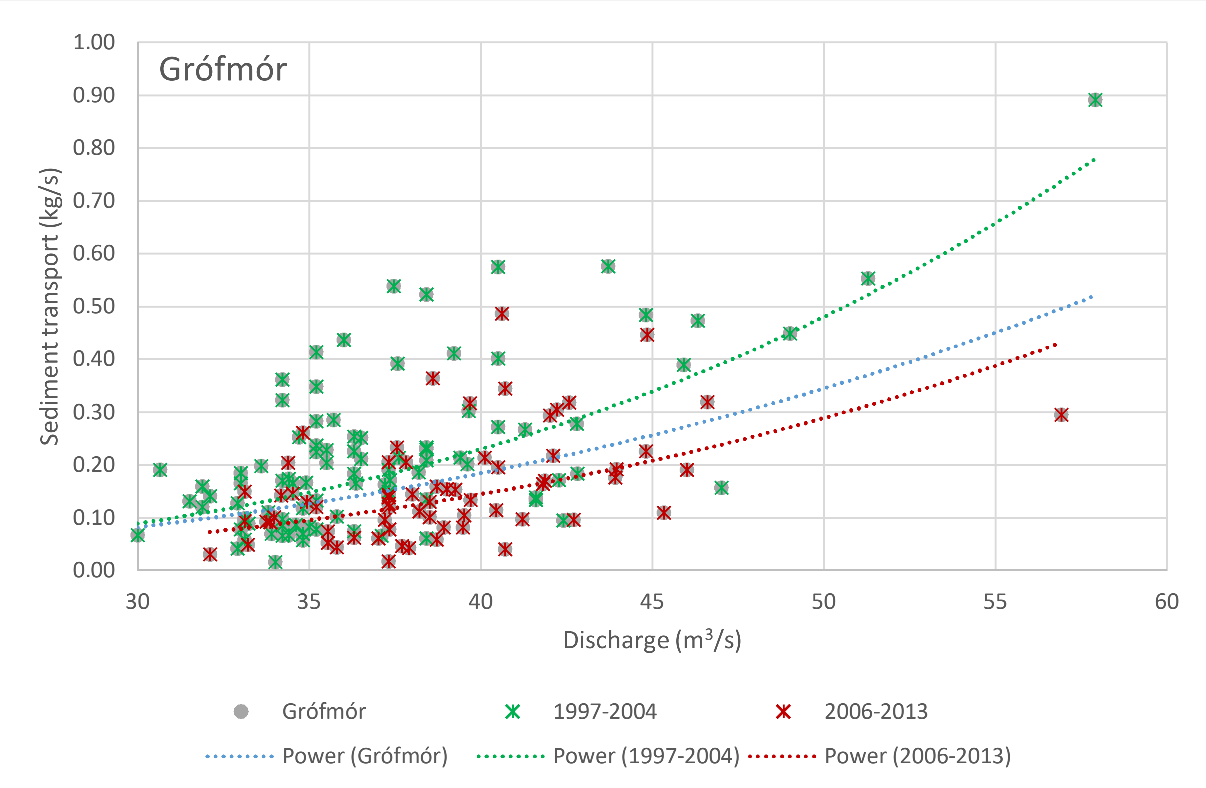


Figure 3.7 **A plot of the grain size class "grófmór", based on suspended sediment measurements at Helluvað. Green marks show measurements made in the period 1997-2005 while the red marks show measurements from 2006-2013. Possible changes with time detected (Veðurstofa Íslands, 2014b).**

3.2.2 Wind erosion and deposition

Quite a few reports have been made on wind erosion and deposition in Iceland. Below are a few points which are of interest to this report.

"Measured erosion fluxes commonly reach 500 to > 2000 kg/m/day during storms. … Deposition rates range from < 25 g/m^2/year far from aeolian sources to > 500 g/m^2/year near or within major sandy areas." (Ólafur Arnalds, 2010, p. 3)

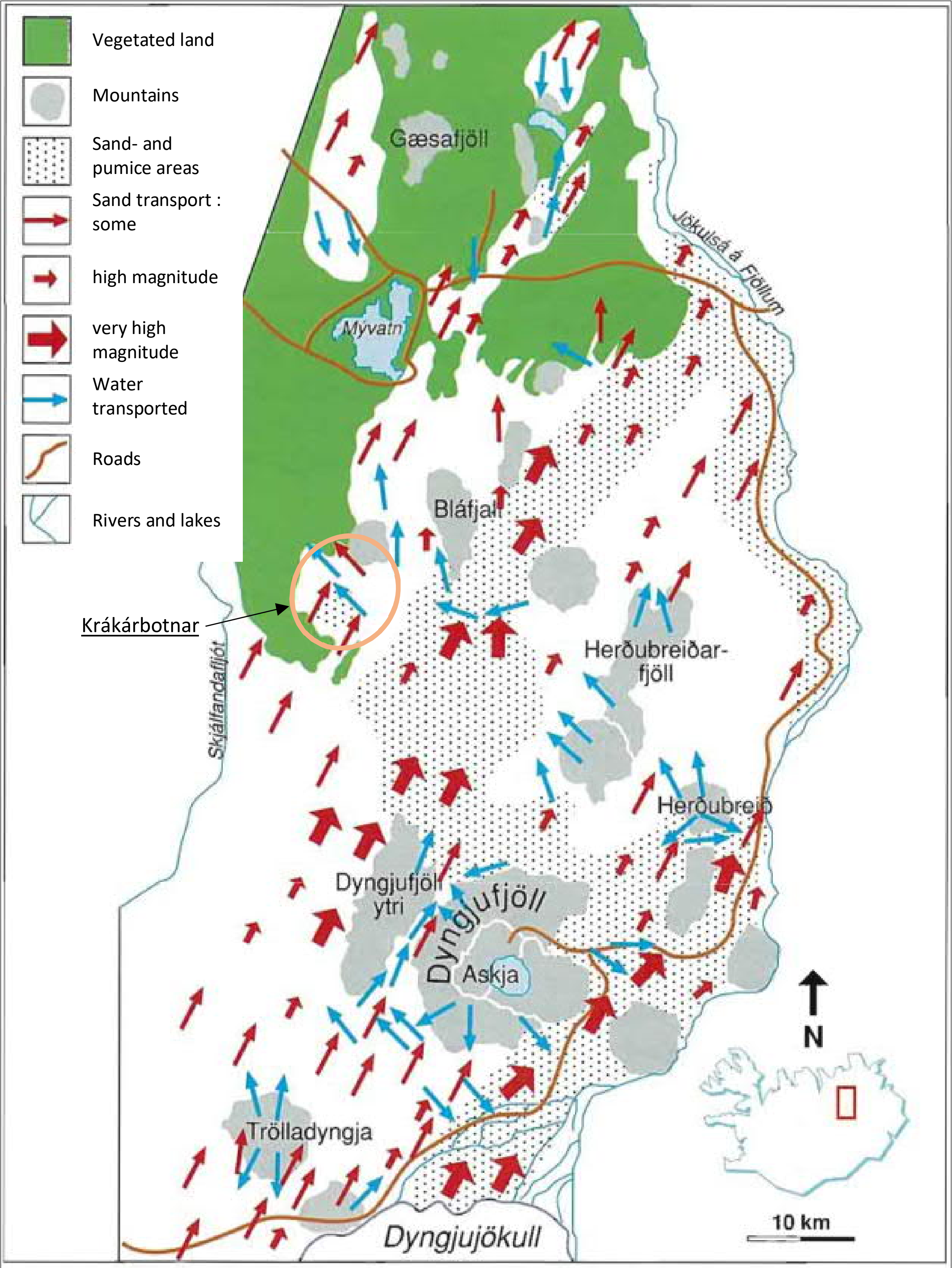
"The medium-sized grains, often ranging between 0.02-0.1 mm saltate along the surface in a bouncing motion, usually below 50 cm (AUI data) and even 20 cm height, colliding with other grains and detaching other grains on impact (e.g. Stout & Zobeck et al. 1996a, van Donk & Skidmore 2001). This is the main force of wind erosion and often moves 70-90 % of the materials during wind erosion." (Ólafur Arnalds, 2010, p. 4-5) A comparison of this grain size with the Icelandic scale used for sediment transport in rivers, puts this material in the "Mór" class, both "fín-" and "grófmór", see chapter 0.

Figure 3.9 shows the main sand transport routes north of Vatnajökull. The location of the headwaters of the Kráká has been added on to the figure. Around the headwater, water and wind help create a perfect sediment source. The rivulets trap some of the wind-transported sand, especially the grains that saltate along the surface or roll along the surface, as these grains loose the surface they travel along when they try to cross the rivers and are trapped there, see figure 3.8 as an example of the same mechanism at work in the Þjórsá in south of Iceland. This newly settled sand is then easily washed downstream with the spring floods. The spring floods also erode the sandy desserts where the headwater of the Kráká is located.

Figure 3.8 An example of wind borne sand that has deposited in the river. Picture taken in the Þjórsá close to Tröllkonuhlaup.

3.2.3 Ground penetrating radar

Ground penetrating radar measurements and other research (like rock analyses using thin sections and stereoscope) in the Laxá-Kráká area were conducted in 1998 and 1999. The purpose of the work was to estimate the amount of sand available in the Kráká and the Laxá area. Sediment samples were also taken at few locations, see example of grain size distribution from samples on figure 3.1. The result was that the sand in the Laxá and the Kráká is mostly eroded from the Kráká headwaters, called Krákárbotnar, and is mainly basaltic glass, i.e. tephra. There, the soil is mostly barren and easily eroded, see also chapter 3.2.2. (Sigfinnur Snorrason, Þorgeir S. Helgason, Friðrika Marteinsdóttir, & Sigrún Marteinsdóttir, 1999).



Helstu sandleiðir norðan Vatnajökuls. Breidd rauðu örvanna veitir samanburð á magni sands sem berst eftir yfirborði landsins, en samfelld sandsvæði eru sýnd með rauðum doppum. Bláu örvarnar sýna hvar vatn ber með sér mikinn sand í vorflóðum. Teikn. Ólafur Arnalds / Jean-Pierre Biard.

Figure 3.9 The main sand transport routes north of Vatnajökull. Continuous sand-areas marked with red dots. The blue arrows show where water transports high magnitude of sand during spring floods (Ólafur Arnalds, 1992, p. 146).

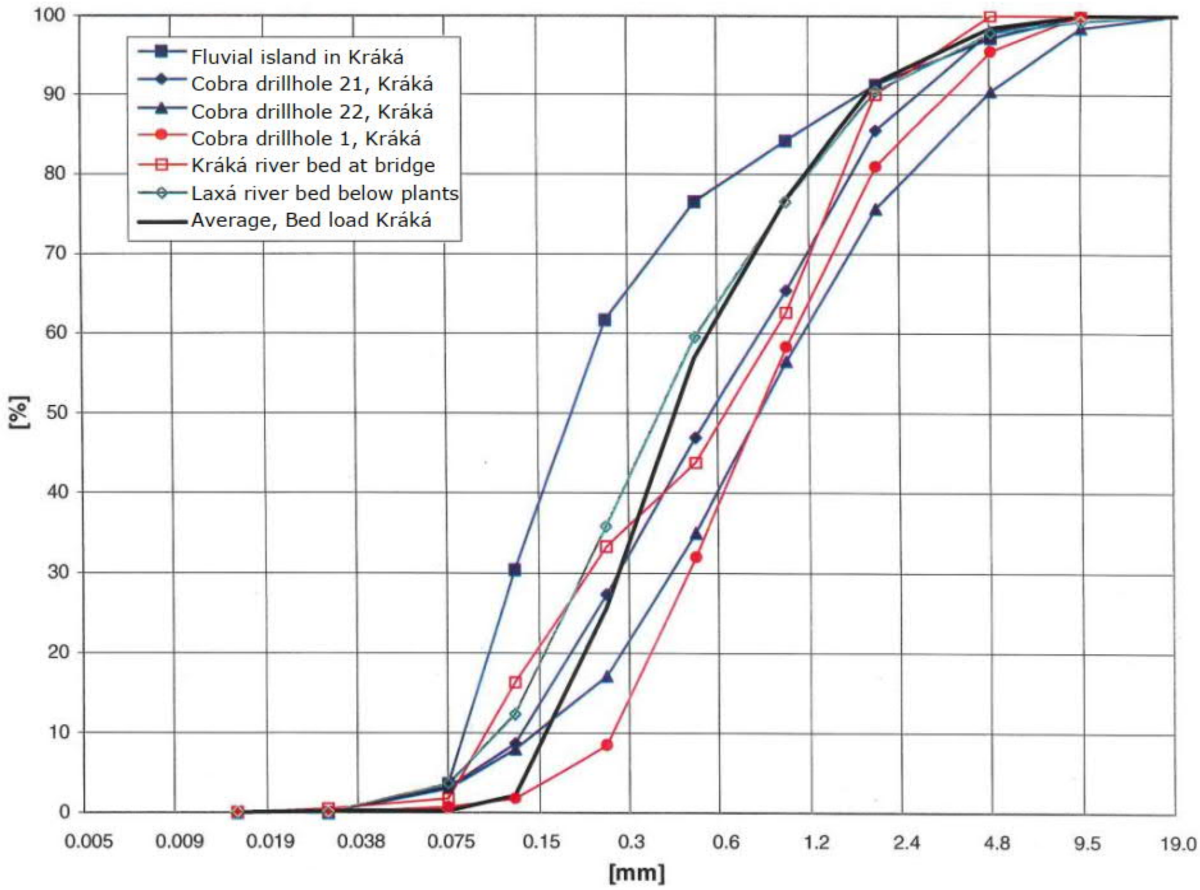


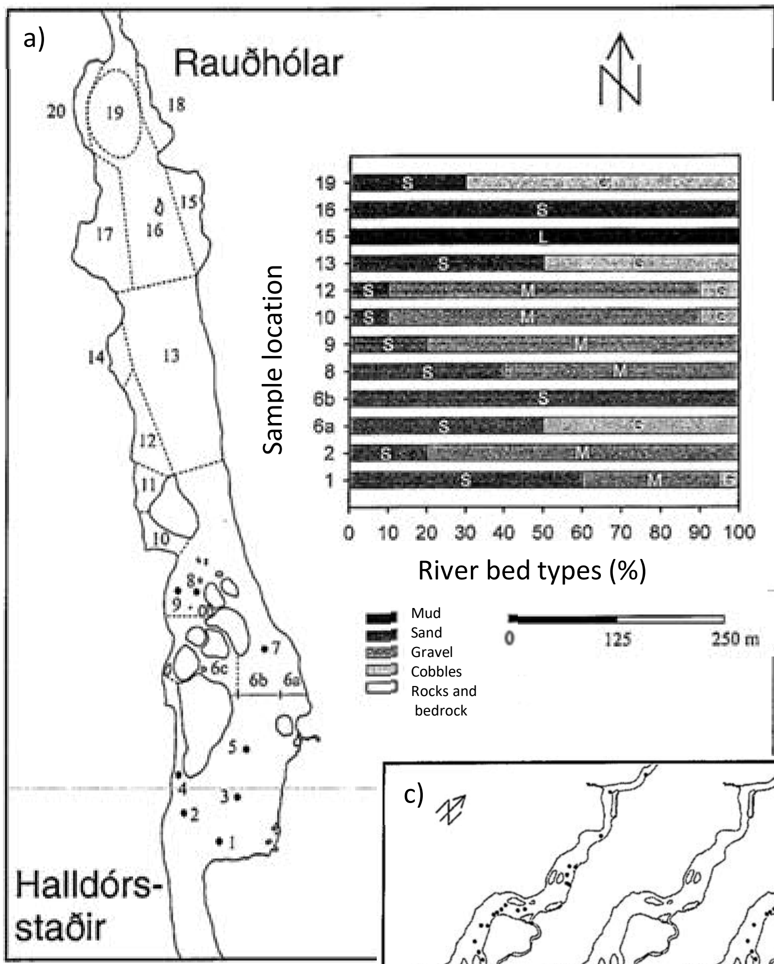
Figure 3.10 Grain size distribution curves from the river bed, areas close to the rivers and from bed load samples (Sigfinnur Snorrason et al., 1999, Figure 7.3).

3.2.4 Mapping of the Laxá riverbed

The riverbed of the Laxá was mapped in 1978 and some parts again in 2003. The fieldwork in 1978 was funded by Þjóðhátíðarsjóður but not the analysing and reporting. That part of the work was not done until decades later through funding from Landsvirkjun. The following description of the riverbed is from the report on the research made in 1978:

> The following types of river beds characterize R. Laxá: between the farms Hólar and Halldórsstaðir in Laxárdalur valley: gravel and stones, from Halldórsstaðir to Rauðhólar: sand, and from Rauðhólar to the Laxárvirkjun Power Stations: boulders and lava floor; below the Laxárvirkjun Power Stations to the bridge at Hólmavað: dominated by sand; from the bridge at Hólmavað to Hrútey: sand with stones and boulders; from Hrútey to Núpafoss: sand and boulders, with riffles made of large boulders and lava, intersected with fast flowing reaches with packed sand, from Núpafoss to the bridge at Laxamýri: diverse river bed, with mud mixed sand near the banks and gravel, stones and lava floor further out in the river, intersected with deeper reaches with packed sand or fine gravel. In Mýrarvatn, where the river widens, the river bed was dominated by sand, main river bed characteristics were that sand dominated areas where the river widened and water velocity was reduced. (Þorkell Lindberg Þórarinsson, Árni Einarsson, Jón S. Ólafsson, & Gísli Már Gíslason, 2004, p. 2)

Figure 3.11 gives an example of figures and tables used to represent the results of the field work in 1978. Another report was written in 2004 where a comparison was made between the results from 1978 and 2003. The field work in 2003 did not cover as large area as in 1978. The main results were that no significant and permanent change was detected. In Aðaldalur the only detectable change worth mentioning was at Hólmavað where sand cover was less than in 1978 and more gravel was present [22] (Árni Einarsson, Gísli Már Gíslason, & Jón S. Ólafsson, 2004, p. 1).



b)

Station Depth (cm)
average range

Stöð	Dýpi (cm) meðaltal	bil	Þráðnykra	Slorpungar	Annað
1	50	40-90		+	
2	40		+		
3	80				
4	30	10-50		+++	
5	60				
6a	40	20-60	+	5	
6b	50	40-60			
6c			+	5	
7	60			+	
8	20	10-40			
9	50			+++	
10		60-100		+++	
11				+++	
12	40	30-60			
13	60	20-90			
14		60-80	10		
15	120		40		Lónasóley 20%
16	70	60-80	+		
17		>120			
18			?		
19	100	80-120	+		
20			20		Lónasóley
Meðaltal	57,1				

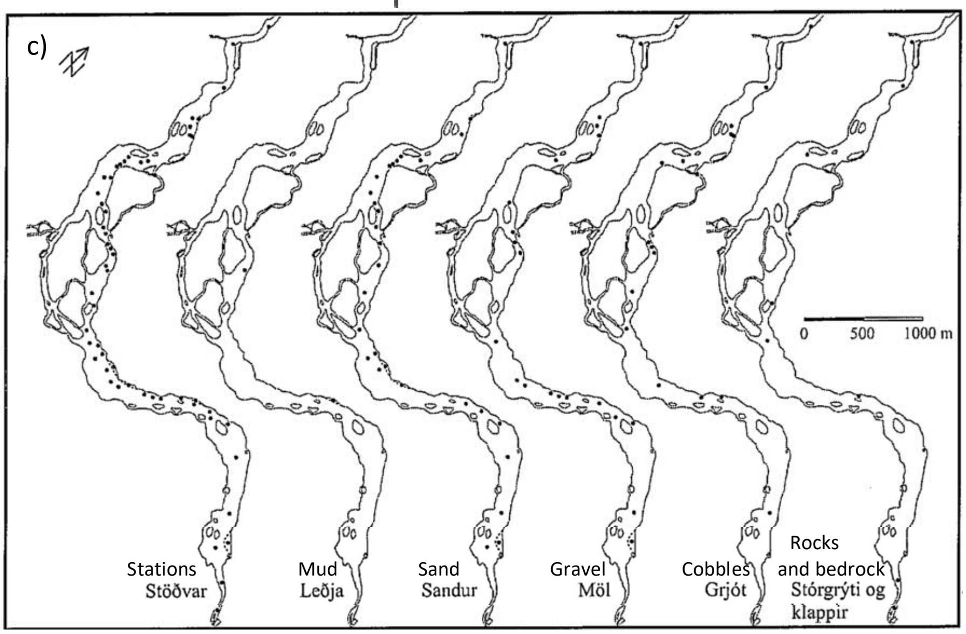


Figure 3.11
Examples of figures and tables from the report on the field work in 1978. a) Riverbed mapping of Birningsstaðaflói,[23] b) data from Birningsstaðaflói and c) Riverbed mapping between the power plants and Hólmavað bridge.

The size classing system used in this report is not the same as used for sedimentation studies. Table 3.3 compares the two systems. The difference is huge and shows how important it is to check what is being meant by the words used.

[22] In Icelandic: Hvergi virðist hafa orðið umtalsverð og varanleg breyting á botngerð í ánni á tímabilinu. í Aðaldal var það eingöngu við Hólmavað sem einhverrar breytingar hefur orðið vart sem orð er á gerandi, en svo virðist sem þekja sands hafi minnkað; þar er nú meiri möl en áður.

[23] Note: the scale on figure a) is not correct. The numbers need to be multiplied by slightly more than 2.

Table 3.3 Grain size classing system used in the mapping of the riverbed.

Name in Icelandic (English)	Size range in mm	Equivalent to size class in table
Stórgrýti og klappir (rocks and rock)	> 250	-
Grjót (cobbles)	20-250	-
Möl (gravel)	2-20	-
Sandur (sand)	0.2-2	Sandur
Leðja (mud)	< 0.2	Leir, méla, fínmór and grófmór

3.2.5 18th century records

In the early 18th century a couple of representatives of the government travelled around Iceland to assess the conditions of Icelandic farms and agriculture. They covered the area around the Laxá in the summer of 1712 (Árni Magnússon & Páll Vídalín, 1943). Some of the descriptions recorded on the farms on the banks of the Laxá, indicated that the river carried rocks and sand onto fields and at some locations the water from the river seeped into the lava under the fields and then striped the turf from the soil. Some complained about water flooding their land or less salmon or trout in the river due to sedimentation. The area around Mývatn and along the Kráká was also covered. There are some descriptions of wind erosion and deposition and the Kráká flooding the land.

Table 5.1 in appendix 4 summarizes the parts in the description where the river is reported to carry sand or rocks onto fields, flood the land regularly and other valuable information in the context of this report. The text is in Icelandic. Two columns show where the Laxá carried rocks or sand onto the fields and those locations are marked in on figures 3.12 and 3.13. Note that the mark is put where the farm is located. The exact location of the field in question is not known. Additionally, the word “rocks” could mean anything from gravel size to bigger rocks, i.e. the definition is vague. The word “sand” is more likely to be what we define as sand today as the material is most likely the same, i.e. sand carried down from the headwaters of the Kráká.

Even though some parts in these descriptions are vague, the records tell a tale about the behaviour of the Laxá. It is interesting to see that the location of the farms that complain about sand and/or rocks being carried on to their fields or their fields or farms being flooded are located where ice formations have big influence on the water level. The ice formations cause a water level rise, the river to flood and where the flow is constrained in the river the flow is forced on to the land around. The combination leads to erosion of sand in the river at some locations, where in summer time sedimentation occurs. The eroded sand is carried with the main flow onto the fields where the velocity falls and the sand settles again. At the same locations and other locations ice carries stones onto the land. This is also most likely the reason for the location of the fields, i.e. the river had been filling the rough, uneven lava surface with sediment and nutrition over the years so these locations where the only suitable locations for fields at the time as the lava itself was to rough and had no soil. Figure 3.14 shows a small part of aerial photograph that shows this, i.e. the rough lava and the smoothed grassland and fields. It is also noticeable on the figure the small dike erected to prevent the water from flowing to the pen. Two additional aerial photographs have been added to the appendix 4 behind the table.

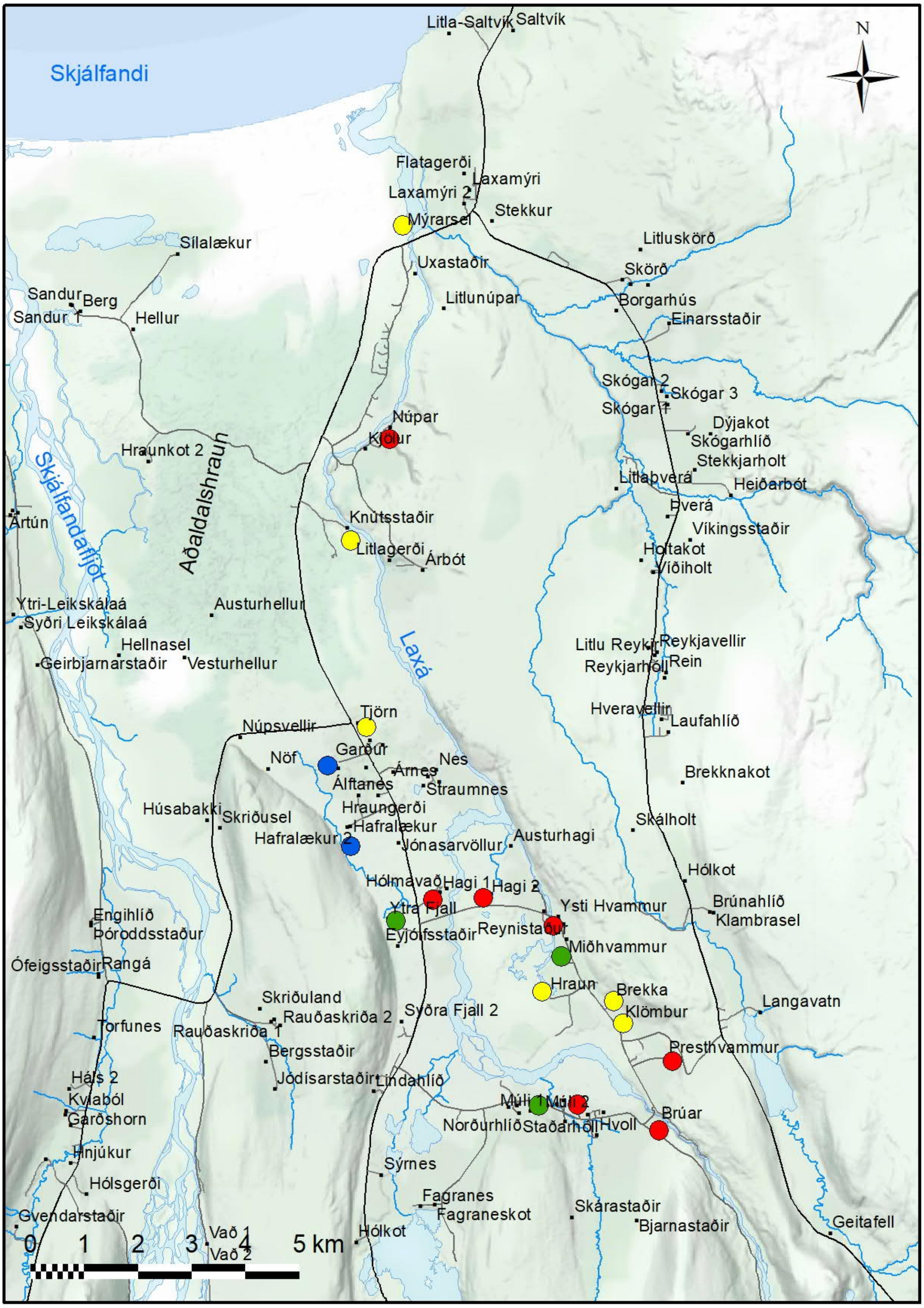


Figure 3.12 Locations with reported field damages due to sand or rocks. Laxá Canyon to the ocean. Yellow dot: sand; green dot: stones; red dot: sand and stones, blue dot: just water.

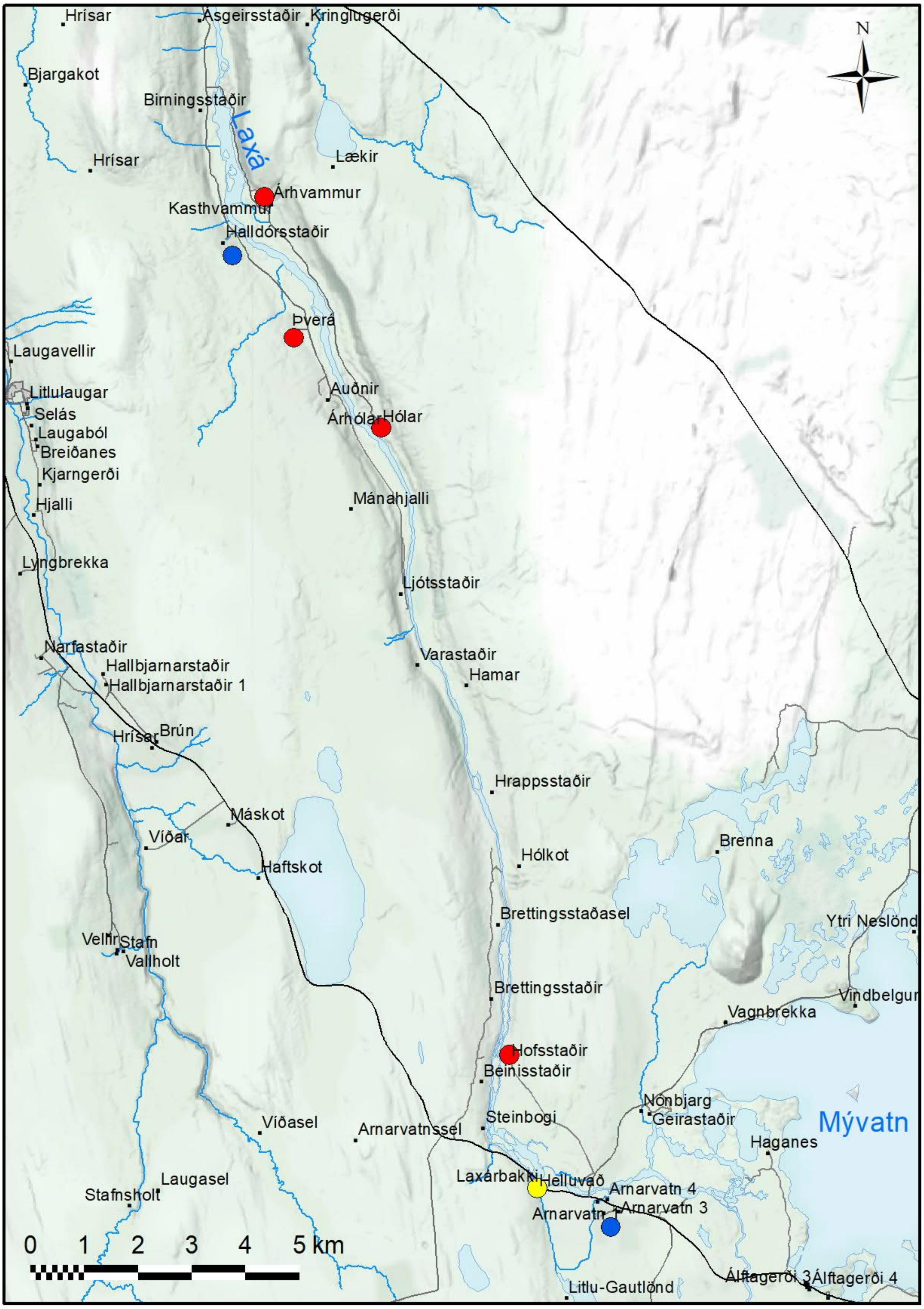


Figure 3.13 **Locations with reported field damages due to sand or rocks. Mývatn to just below Birningsstaðaflói. Yellow dot: sand, green dot: stones, red dot: sand and stones, blue dot: just water.**

Figure 3.14 An example of areas where the Laxá has filled the lower lying parts of the lava field with sediment and nutrition, creating ideal location for fields. The difference between unflooded lava and flooded lava is very distinct. To the left a small dike has been built to stop the river from flooding the pen.

3.2.6 Transport of larger grains

No direct measurements are available of transport of larger material. In magnitude, the sand transport is the main sediment transported by the river. The sand is relatively easily eroded so it seems to be in balance though it might be more or less temporarily dependent on various factors addressed in chapter 3.4.1. The larger material transported by the river is thought to be much less in magnitude but as it is not as easily transported as the finer material it is more likely to be present in the river at various locations for longer time than the sand and as such its importance can be just the same as the transportation of the sand.

Although there are no direct measurements of available of this larger material there are various references that shed light on this part of the sediment transport. In this chapter these will be covered.

3.2.6.1 Various references

The oldest reference, from the 18th century, has already been covered in chapter 3.2.5, see also figures 3.12 and 3.13 for locations where the Laxá has transported stones onto the fields.

References from the Laxá Stations also give a glimpse of the material and the processes. Following are some references.

Ágúst Halblaub wrote the following in 1960. This followed a discussion on denser trash racks at the bottom in the intake structure.

> … Slush in the water was not a problem per se, but if ice got into the machinery, the power production decreased while it broke the ice into pieces and disintegrated the ice.
>
> Slush which breaks free from the river bottom[24], carrying stones and coarse gravel into the machinery, was worse. These rocks are small enough to get carried through the thrash racks

[24] Anchor ice.

> with the slush, but not through the waterwheel, where they get stuck and reduce the power production immediately.
>
> The next summer an attempt was made to double the trash racks at the bottom, as the rocks and gravel were thought to be a part of the bedload. This however, did not improve the situation. Experience showed that the rocks are carried with the ice at all depths, as some of them got stuck in the trash racks just below the water surface.[25] (Halblaub, 1960, p. 8)

This paragraph comes from a collection of descriptions on disturbances at the stations.

> On the 21st of March 1991 turbine 4[26] was non-operational for eleven days, due to slush and rocks that entered it during a three-day storm. It was estimated that six tons of stones and gravel were removed from the turbine.[27] (Landsvirkjun, n.d.-a)

3.2.6.2 Pictures, videos and aerial photos

Pictures, videos, and aerial photographs also give information on this part of the sediment transport.

Figure 3.15 is a shot from a video taken in 2011. The video shows the removal and the removed stones on March 22nd 2011. On the 21st the production was only 9.7 MW even though there was enough water. On the 22nd a leakage was noted from the shaft seal. The same day the production was stopped. The figures show the stones removed. The biggest one is larger than the hammer on the figure, so possibly 400 mm in diameter. After the removal of the stones the production picked up and became 10.7 MW.

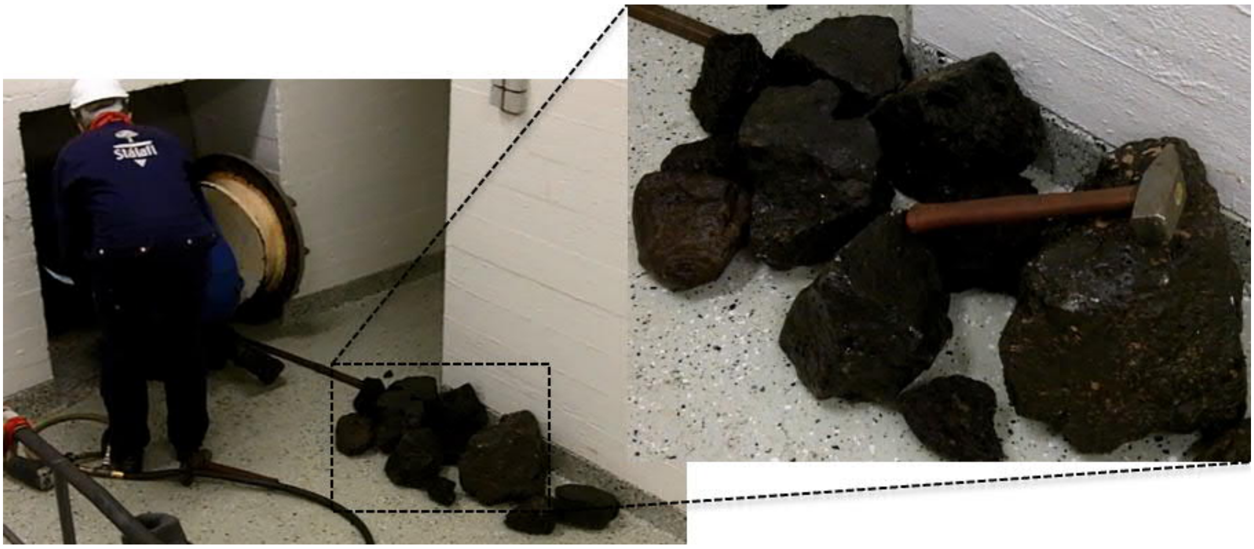


Figure 3.15 Boulders removed on March 22nd in 2011.

Figure 3.16 was taken shortly after emptying of the intake pond for Laxá III in 2016. The picture shows clearly how shallow the pond was and that sand only settled at special locations like in the corner of the intake where the riverbed has been lowered. Mostly the bottom of the intake pond is void of sedimentation as the depth is small and the velocity high enough to transport the smaller particles

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[25] In Icelandic: … Ekki kom það að sök, þó krap bærist með vatninu í vélina, en ef að ísmolar fóru í hana, afkastaði hún minna á meðan ísinn var að molast í gegn um hana og eyðast. Verra var að fast við steina og grófa möl, sem berst mikið með því krapi, sem losnar upp úr árbotninum. Þessir steinar eru það smáir, að þeir fara í gegn um ristarnar með krapinu, en komast ekki í gegn um vatnshjól vélarinnar og festast þar og draga strax úr krafti hennar. Svo var horfið að því ráði að næsta sumri, að gera neðsta hluta ristanna tvöfalt þéttari, því haldið var að steinarnir og mölin skriðu með botninum. Þetta bætti þó lítið úr skák, því að reynslan sýndi, að steinarnir bárust með krapinu á hvaða dýpi sem var, enda festust sumir þeirra í ristunum alveg upp undir vatnsborði.

[26] Turbine 4 is the turbine in Laxá III which is the power station most upstream.

[27] In Icelandic: „21. mars 1991 var vél 4 úr rekstri í ellefu daga vegna kraps og grjóts sem í hana barst í þriggja daga hríðarveðri. Það var mat manna, að um það bil sex tonn af grjóti og möl hefði verið hreinsað út úr vélinni.“

through the intake pond. Along the canyon wall gravel and stones can be seen. Some might have been carried downstream from another location and some have fallen from the canyon walls. A few larger stones can be seen on the lava surface in the intake pond.

Figure 3.16 A picture taken on 12th of May 2016, shortly after emptying of the intake pond for construction work. Taken from the downstream side of the intake up the Laxá Canyon.

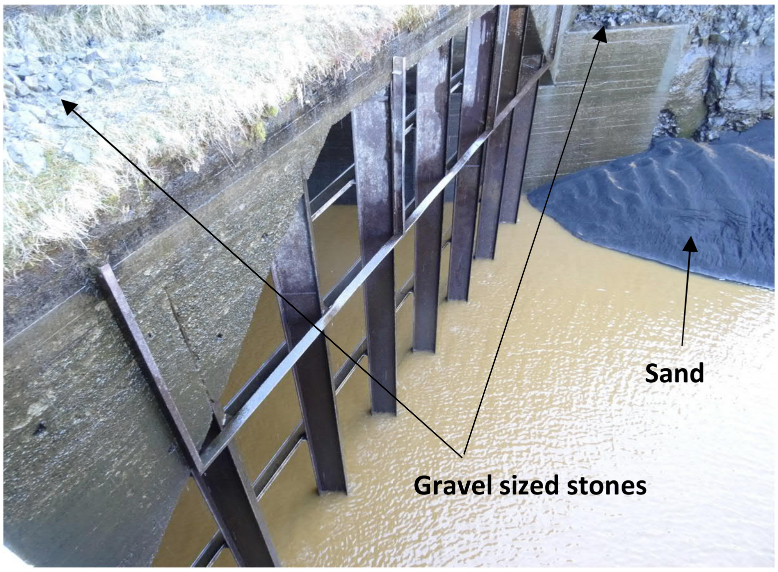

Figure 3.17 A picture taken on 12th of May 2016, shortly after emptying of the intake pond. Taken from the downstream side of the intake down into the intake pit.

Figure 3.17 is taken at the same time into the intake pit. There the two contrasting sediment types in the Laxá can clearly be seen, the sand originating from the Kráká and the material originating from areas very close to the Laxá river, like the Laxá Canyon walls.

Figure 3.18 shows a little bit of the same, except for the additional source of rock material that is the tunnel roof, walls and floor. On this figure the two types are clear, i.e. the sand on the other hand and the gravel and rock sized material on the other.

Figure 3.18 A picture taken on 18th of May 2016, shortly after emptying of the intake. Taken from the outside into the intake cave.

Figure 3.19 is of the eastern canyon wall and shows how the canyon acts as a source for coarse material the river can transport further downstream. This source is though only active where the material has direct access into the river. This direct access has changed with the fish ladders, and roads that stop the material from falling into the river.

Figure 3.19 A picture taken on the 15th of May 2018. The eastern canyon wall a short distance from the dam for Laxá III.

Looking at aerial photographs of the Laxá the Laxá Canyon is likely to be the main source of the largest rocks the Laxá transports. For most of its length the Laxá is vegetated all the way to its riverbanks indicating next to no sediment transport (erosion) from the land around it to the river. There are some exceptions to this as can be seen in figures 3.20 and 3.21 where overbank erosion is noticeable.

Figure 3.20 A picture of the Laxá where it turns a short distance downstream of Helluvað (Photo: Einar Guðmann, 1999). Overbank erosion noticeable. Not caused by the Laxá but can contribute sediment to the Laxá.

Figure 3.21 A picture of the Laxá close to Brettingsstaðir (Photo: Einar Guðmann, 1999). Overbank erosion noticeable. Not caused by the Laxá but can contribute sediment to the Laxá.

Figure 3.22 A picture of the Laxá in Laxárdalur. Overbank erosion noticeable, but access to river very restricted.

Figure 3.22 also shows overbank erosion but between the location of the erosion and the river is flat vegetated area and then a rough lava surface. This prevents the material from entering the river.

In Aðaldalur the river is also vegetated down to its banks. There are some locations where overbank material can be transported down the slopes into the river, but those are also mostly vegetated, indicating unstable inflow of sediment material.

Erosion from the riverbed itself is also ongoing but erosion from the lava bed is very slow in comparison to other sources of material.

3.3 Short report on removed material, question S-4, part 1

This chapter will be focused on estimation of how much sediment has been removed from the river. Sediment has been removed both from the intake tunnel for Laxá III and from the Laxá II intake pond.

3.3.1 Removed material from the tunnel and machinery

Table 3.4 summarises volume from known instances of sediment removal from the intake tunnel for Laxá III. It is most likely that these are all the instances sediment was removed from the tunnel. The reason for this assumption is that the first reference covers the time from the beginning of operation of Laxá III to the date it was written and it was most likely written in 1996 as the text refers to how much power was lost due to disturbances in the years 1994 and 1995 and also refers to the necessity of a stop next year for major repairs, which suggests the year before the known stop in 1997.

The magnitude removed in 2016 is relatively accurate as it is taken from the records from the contractor after removal. The other numbers are more of a guess. The number used for 1997 was given by Landsvirkjun as the estimate made at the time. The number for the first two occasions are based on the description of "half full tunnel", assuming it means a similar amount as in 2016. Then the upper part of the tunnel (about 400 m) was more or less filled with 2 m of sand and the lower part (about 230 m) covered with less sand, possibly in the range 0.5-0.8 m deep on average, see figure 3.23. The balance between sedimentation and velocity should have been similar assuming the sediment material was the same. Still, it is possible that more stones could have been present the first time, but then most likely as the result of stones originating from within the tunnels themselves.

Table 3.4 Known occasions of sediment removal from the intake tunnel for Laxá III.

When	Estimated volume in m^3	References
Two times from 1973 to 1996	3 000 * 2 = 6 000	In records from Laxá Station the following text was found: "…the sand is deposited in the intake tunnel to Laxá 3. The result is that sediment has twice been removed from the half full tunnel since 1973." [28] (Landsvirkjun, n.d.-b)
1997	1 300	In 2015 Landsvirkjun reported of this as the last time sediment was removed from the tunnel. The amount was estimated to be around 1300 m^3.
2016	3 200	According to measurement made by the contractor in 2016-17, about 3 200 m^3 were removed from the tunnel.
Total:	**10 500**	

The estimated volume of about 10 000 m^3 is approximately 50-60% of the sediment transported by the river per year in the size range of particles larger than 0.06 mm ("grófmór" and larger). This size range is chosen based on the settling velocity for various grain sizes (Stokes' equation for grains smaller than 0.06 mm and Rubeys formula for larger grains (Morris & Fan, 1998, p. 5.16 - 5.18)), the time it would take the water to pass through the upper part of the intake tunnel (where most of the sediment was found) and the depth it had to fall. Based on this, smaller sediment grains should mostly pass through the tunnel.

In terms of sediment removed versus sediment transported to the intake tunnel of Laxá III over the years, from the start-up of Laxá III to 2018 (in the size range capable of settling in the tunnel), the percentage is about 1.3 %, i.e. 98.7 % in this size range passed through.

$$\frac{10\ 000 m^3}{30\ 000\ m^3/y \cdot 0.55 \cdot (2018-1973) y} = 0.013 \ \approx 1.3\ \%$$

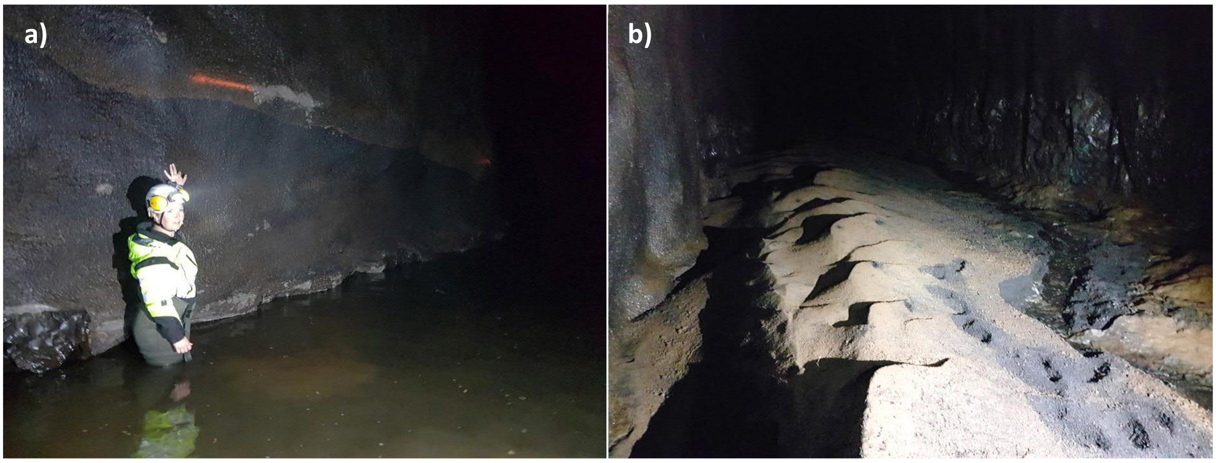

Figure 3.23 Laxá III intake tunnel (photos form Verkís, 4th of August 2016). a) Sediment already removed in upper part of tunnel. The darker part of the tunnel wall is coloured by sand that still stuck to the wall after removal of the sediment. b) Sedimentation in lower part of the tunnel before removal.

In terms of all suspended sediment transported to the tunnel this percentage becomes 0.7 %. It should be noted that the estimated amount of 30 000 m^3, see chapter 3.2.1.3, is only based on suspended sediment and does not include larger material like stones. If a part of the removed material is larger

[28] In Icelandic: … sest sandurinn fyrir í aðrennslisgöngum að Laxá 3 þannig að tvisvar hefur þurft að moka sandi út úr hálfullum göngunum frá því 1973.

than the material measured using suspended sediment measuring equipment, these percentages would become even lower.

3.3.2 Removed material from the intake pond for Laxá II and from the machinery

In the early 90's some material was removed from the intake pond for Laxá II. This is the only known occurrence of mechanical removal of sediment from the pond. How much was removed is not known but based on other information the amount cannot be significant in magnitude in comparison to yearly transport of sediment. The amount could be significant in the context of larger sized particles like stones. This will be discussed further in the chapter about substrate.

Material has also been removed from the turbines.

> On the 21st of March 1991 turbine 4 was non-operational for eleven days, due to slush and rocks that entered it during a three-day snow storm. It was estimated that six tons of stones and gravel were removed from the turbine.[29] (Landsvirkjun, n.d.-a)

These six tons only amount to 2.5-3.5 m^3 which is nothing compared to the estimated annual sediment transport of the river. This comparison is though not valid as the estimated yearly sediment transport is based on suspended sediment transport which is mainly sand and smaller sediment sizes while the material removed from the turbine was described as stones and gravel. It is not known how much the river transports of sediment in these size classes.

3.4 Alluvial sand

3.4.1 Transport and sedimentation of alluvial sand in the system, question S-1

The transport of alluvial sand in the Laxá is slightly complex and it would be good to revisit the longitudinal profile of the Laxá in figure 2.1. As already covered in the chapters above, about 30 000 m^3 of alluvial material, sand mostly, is transported by the river at Helluvað. This alluvial material is originated from Krákárbotnar and the magnitude entering the Laxá at any given time is based on the transport capacity of the Kráká. The Kráká has far less discharge than the Laxá but the Kráká runs into the South Branch, see figure 2.10, before the three branches discharging from Mývatn, come together above Helluvað. This is also likely to influence the magnitude of suspended sediment measured at Helluvað as the sediment could settle temporarily within the South Branch. The Kráká and the South Branch of the Laxá are thus likely to control sediment transport into the Laxá and as the Laxá has much higher transport capacity, both because the discharge is greater and the longitudinal profile is steeper, it can easily transport all the alluvial material entering the main river.

The suspended sediment transported at Helluvað did not show any seasonal changes, see chapter 0.

Here and there are some short parts where the longitudinal slope drops and sediment can settle and create some sandbars. These locations are few in the Laxárdalur and most of them are very small. Birningsstaðaflói is an exception to this as it has a part that is so flat that it is more like a lake than a river. The lake like part is over 1 km in length and relatively wide (166-260 m) compared to the normal width of the river (44-130 m). The depth, according to measurements in 1978, is in the range 0.2 m to over 1.2 m, see figure 3.11, a) and b). Based on the information on the figures the velocity in the lake like part of Birningsstaðaflói can be estimated to be in the range of 0.2-0.4 m/s. In this velocity range the sand grains should settle. In time Birningsstaðaflói should become full of sedimentation leaving only a channel through the sand where the river would run with higher velocity.

Floods do not change this as at the downstream end of Birningsstaðaflói the lake like part ends abruptly where the lava flow only left a narrow opening for the river to flow through. The bridge is located there and the width of the river is only about 28 m. This restricts flow from the Birningsstaðaflói. According

[29] In Icelandic: 21. mars 1991 var vél 4 úr rekstri í ellefu daga vegna kraps og grjóts sem í hana barst í þriggja daga hríðarveðri. Það var mat manna, að um það bil sex tonn af grjóti og möl hefði verið hreinsað út úr vélinni.

to the rating curve for the measuring station that was located a few meters above the bridge, the water level rises 58 cm in the lake like part (at the measuring station) when discharge changes from 43 m^3/s to 90 m^3/s (Jakob Már Ásmundsson & Ragnhildur Freysteinsdóttir, 1999, p. 6). This leads to very little changes in velocity in the lake like part during floods which means the lake like part continues to act like a sediment trap even during floods.

This leads to the question why this part of the river isn't full of sedimentation? The reason is likely to be ice formations that form sometimes and change the balance in the lake like part of Birningsstaðaflói. The processes have been discussed in chapter 3.1.4. If this is the case the changes within the Birningsstaðaflói, when affected by ice formations, explain why this natural sediment trap does not become filled with sediment. The reason would then be that in some winters ice formations create some sort of "clean out periods" where the storage capacity of the Birningsstaðaflói is renewed.

Four aerial photographs taken at different times of Birningsstaðaflói can be found in appendix 5 and figure 3.24 shows the lake like part of Birningsstaðaflói and two different bed formations in the lake like part. One shows bed formations that look like sediment tongues (upper right corner). If they are what they look like they should be forming in periods, like summer time, when the river is free of ice.

The other one could have been formed under the influence of ice cover where different channels might have formed within the ice formation or around and partly under a break up ice jam or leftovers from ice formations that took some time to melt away. This has not been researched. The actual time the photos were taken was not available.

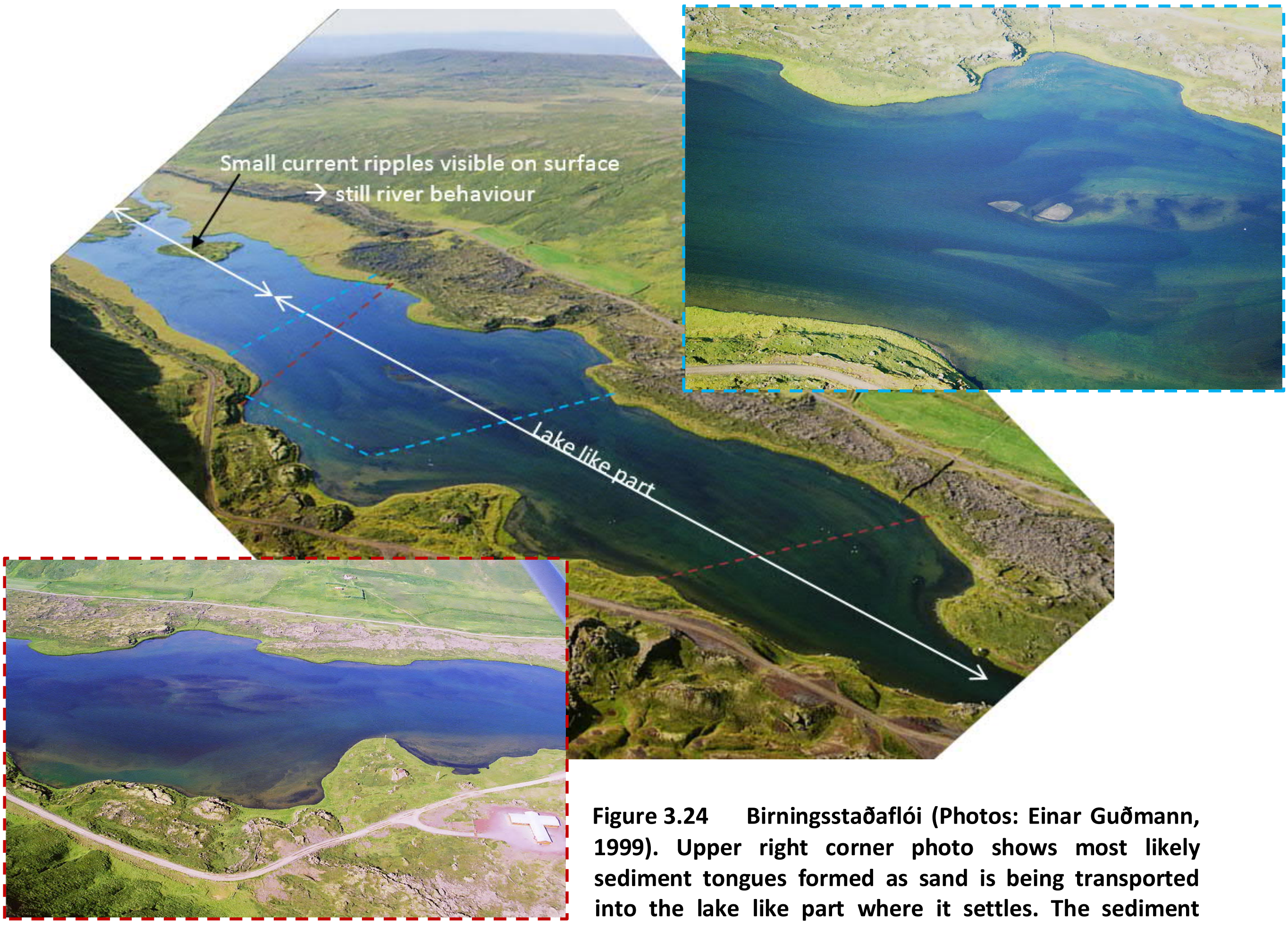

Figure 3.24 Birningsstaðaflói (Photos: Einar Guðmann, 1999). Upper right corner photo shows most likely sediment tongues formed as sand is being transported into the lake like part where it settles. The sediment tongues grow in the downstream direction. The lower left corner shows the same part (slightly larger part) but is taken at another time than the other two as it shows different bedforms.

The aerial photographs and other photos show that the sediment within the Birningsstaðaflói changes with time and even the sediment bars are not exactly at the same locations when they form.

All of this also means that the riverbed is changing within the year and from year to year. Inflowing sediment would settle where the velocity falls low enough, and that location is changing with time. Ice formations can both move sediment within the Birningsstaðaflói via showing and help remove the material from it by changing the velocity at various locations.

The storage capacity of Birningsstaðaflói is much higher than that of the intake ponds. The area of only the lake like part is about 0.2 km^2, i.e. ten times larger than the intake ponds and the volume is in the range of 100-200 thousand m^3, based on the depth data from 1978 (Þorkell Lindberg Þórarinsson et al., 2004). The settling velocity for various grain sizes was calculated using Stokes' equation for grains smaller than 0.06 mm and Rubeys formula for larger grains (Morris & Fan, 1998, p. 5.16 - 5.18). Using the settling velocity and the time it would take the water to pass through Birningsstaðaflói it was estimated that almost all material in the "sandur" and "mór" class would settle in the lake like part of Birningsstaðaflói when the bathymetry was as it was in 1978. According to the data in table 3.1 about 70-80 % of the suspended sediment falls into those two classes. Based on all this, and the estimated sediment transport of 45 thousand tons per year the estimated sediment transport to Birningsstaða-flói, in the two size classes that should settle in the lake like part, is about 20 000 m^3/year. If it was distributed evenly over the lake like part of Birningsstaðaflói the sediment layer would be about 10 cm thick.

The sediment would start to settle in the upstream part where the velocity becomes low enough and with time reach further and further into the lake like part as the settled material leads to higher velocity due to diminished cross sectional area. This is the same process that forms deltas at the upstream end of lakes and can be seen in figure 3.30 at the upstream end of the intake pond for Laxá II.

All the areas in figure 3.11 marked with numbers above 11 are located fully or partly in the lake like part of Birningsstaðaflói. It is interesting that area 16 is reported to be 100 % sand (Þorkell Lindberg Þórarinsson o.fl., 2004, p. 12). This is the area with the possible sediment tongues in figure 3.24. It is also interesting to see that it was noted in the report that rocks and bedrock was not to be found in this part of the river, i.e. in Birningsstaðaflói (Þorkell Lindberg Þórarinsson o.fl., 2004, p. 13). That leads to the next reference, the ground penetrating radar report from 1999 (Sigfinnur Snorrason o.fl., 1999, p. 34-35). According to the report a thick sediment layer was present in Birningsstaðaflói, up to 4 m thick. The measurements took place in winter time with ice formations present. The measurements in Birningsstaðaflói were all located in the most downstream part, or parts numbered from 17 to 20 in figure 3.11. The longitudinal profile could not be measured where the main flow was located as the ice there was not stable. This is not surprising as the velocity in the main channel formed within the ice is much higher than summer velocity and can erode the ice cover and make it thin. Additionally, ice cover rarely forms on this part as reported by Sigurjón Rist:

> The shallow basin Birningsstada-flói is the place of the lowest water velocity, nevertheless along the basin a current-lead remains. The slush ice is carried farther down and coagulates to ice jam in the small intake ponds, causing great ice disturbances.
>
> In exceptional cases northern wind reduces the surface water speed enough for an ice bridge to form across the current-lead of the Birningsstada-flói. The slush ice is then blocked and freezes at the upstream edge of the ice cover. The ice rapidly progresses upstream until it reaches the next rapid. If the flow of slush ice is maintained, it will be carried under the ice cover as long as the velocity is above the critical value 0.5-0.6 m s^{-1} and accumulate beneath it. The buoyancy of the water will lift the cover and cause further rise in the water level behind it, until the upstream velocity is reduced below the critical velocity. When this stage is reached, the slush will no longer flow under the cover, but will freeze at its upstream edge, thereby extending the ice cover further upstream. An ice jam as high as 8 m has been observed in the Laxárdalur-valley above Birningsstada-flói. (1979a, p. 277)

Figure 3.25 shows the early stages of ice formation in Birningsstaðaflói where the current lead is still quite wide or similar to the width of the bridge (about 28 m). In comparison the closed channel, visible on figure 6.4 in the report from 1999, is only about 17 m wide (Sigfinnur Snorrason o.fl., 1999, p. 42). That channel is very likely to represent a channel through an ice formation that has had some time to form and develop.

Figure 3.25 A current-lead in Birningsstaðaflói on the 4th of January 2017. Photo taken from the bridge in the upstream direction (south). Ice slush visible floating along the current.

The ice jam, Sigurjón Rist described, hereafter be referred to as the Halldórsstaðir ice jam, is elsewhere reported to form almost yearly. According to Hólmgeir Hermannsson (Hörn Hrafnsdóttir & Guðmundur Björnsson, 2014) the dam forms almost yearly and he estimated its height to be in the range of 1-3 m. He also informed that when the ice cover on Birningsstaðir Bay is strong enough, the ice jam grows upstream. Sometimes the ice cover is weak and then it can happen that the ice jam pushes downstream and into the Birningsstaðaflói and even further downstream to the intake pond, but that happens rarely.

All this information on Birningsstaðaflói sheds some light on the processes but no actual research has been carried out on the processes involved. The hypotheses put out in this report about the processes in Birningsstaðaflói, are based on:

- physics involved in
    - sediment transport and
    - river ice transport and formations, and
- reports on other matters related to the river.

Below Birningsstaðaflói, the Laxá is again mostly relatively narrow and steep with some minor exceptions like Árgilsstaðaflói. The velocity, in most places, is high enough to carry all inflowing sediment downstream. In this part of the Laxá, i.e. in Laxárdalur below Birningsstaðasog and in the Laxárgljúfur, the sediment inflow is most probably controlled by Birningsstaðaflói. If the hypothesis about the processes in Birningsstaðaflói are correct, then there can be a big difference in sediment transported to this part of the river during ice free periods and periods with developed ice formations in Birningsstaðaflói. The effect, during periods with developed ice formations, could even be similar to flushing of reservoirs.

Before the Laxá Stations all the alluvial sediment transported to this part of the river would have been transported down to the Laxá in Aðaldalur, where the longitudinal profile drops again.

After the construction of the Laxá Stations there could be some lag at the beginning of a period of high sediment transport, during which the intake tunnel for Laxá III and the intake pond for Laxá II are finding their balance for transport of solids (alluvial material like sand and also ice slush). But as the storage capacity is very small, a balance is quickly restored, leading to a throughflow of alluvial material. Table 3.5 gives a comparison on a) volume of the Birningsstaðaflói, and ponds, b) yearly sediment transport and c) possible ice production in the river over a period of 8 hours. The table clearly shows that the intake ponds cannot influence alluvial transport in the river. The volume given is the total water volume. The volume possible for sediment storage is smaller as the water needs space to pass through the pond.

Table 3.5 Comparison of volume. Volume of water, transported sediment and ice slush.

What	Volume in thousand m^3
Approximate volume of	
Birningsstaðaflói	100-200
Intake pond for Laxá III	30
Intake pond for Laxá II	40
Sediment transported per year at Helluvað	
All suspended sediment, estimate	30
Coarse part of suspended sediment (>0.06 mm), estimate	20
Ice slush produced[30] in the Laxá and transported to the Laxá Stations	
Maximum over 8 hours period, after border ice has had time to lower open water surface	20
Common over 8 hours period	2-10
Comparison to reservoirs	
Sultartangi reservoir	109 000
Originally planned reservoir for Laxá III	60 000

It is also most likely that the ponds and the intake tunnel have similar seasonal circles as Birningsstaða-flói but on a much smaller scale. If that is the case the effect of the constructions would be even less as the sediment transport would be more during times with ice formations in Birningsstaðaflói and during such times ice formations would also be forming at other locations with storage capacity leading to the reduction of storage capacity for sediment during the time of higher sediment transport from Birningsstaðaflói. This would lead to the conclusion that the constructions in the Laxá canyon would have almost no effect on the transport on alluvial material in the river.

In Aðaldalur the transport of alluvial material should be independent of the stations except if material is flushed out, see next chapter. Ice formations are also reported to influence the river in Aðaldalur and affects transport of alluvial material. Some is reported to be carried onto the fields. This is probably due to flushing effects in Birningsstaðaflói. This was reported in the 18th century records, see chapter 3.2.5, and is still happening every now and then.

A final note on Birningsstaðaflói is that the more balanced flow from Mývatn, after the changes made in the Geirastaðir branch, might have influenced how often ice formations develop in Birningsstaðaflói.

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[30] Based on weather data, estimated open water surface, density of packed frazil ice slush about 500 kg/m³. Formulae for the heat loss same as used by Sigmundur Freysteinsson (1996).

3.4.2 Impact of emptying intake ponds versus natural processes, question S-2

A process called sediment flushing has been tried in the Laxá. Sediment flushing refers to a technique where the water table in reservoirs is lowered and the flow in the river is used to erode the sediment out of the reservoir. For this to work the river within the reservoir must be steep enough and the reservoir relatively narrow. If this is not the case the river will only be able to erode a small part of the sediment accumulated within the reservoir. Additionally, the waterways used for lowering the water level have to be able to convey enough water to facilitate the lowering of the water level within the reservoir. If the flow is restricted it will be impossible to lower the water level as low as needed. If this is the case, only a small part of the sediment will be removed from the reservoir and some of the sediment will only be moved further into the reservoir or from the erodible part into the ponded area further down in the reservoir.

Sediment flushing is not always an environmentally friendly process as it can lead to unacceptably high concentration of sediment in the river. It depends on the river and how flushing is performed whether this method is sustainable for the river system or not. The concentration during the initial period of flushing (duration between few hours to several days) typically exceeds 100 g/L at the dam site and in some cases even exceeds 1000 g/L (Morris & Fan, 1998, p. 15.3).

In the Laxá the water level in the intake ponds has been lowered in the attempt to flush out as much sediment as possible from the intake ponds and from the upper part of the intake tunnel. According to the station manager, Guðmundur R. Stefánsson, flushing was done once every year until 2012 and the last flushing was made in 2014. The process took on average one day.

The efficiency of this method for removing sediment from the ponds and the intake tunnel has been very limited as the waterways were not designed with sediment flushing in mind so the water level can only be lowered partly. Additionally, the ponds are very small, so they do not store much sediment. Figure 3.26 shows the intake ponds with lowered water levels.

Two separate reports give information on flushing in the Laxá, one is from 2012 and focuses on cross section measurements in the intake ponds, and the other is from 2014 and covers sediment measurements during a flushing event in May.

In 2012 the depth of the intake ponds was measured on the 29th of May and again on the 11th of July. In the time period between the 12th and the 24th of June Laxá II was out of operation due to maintenance of the machinery and during that time the water level in the intake pond was lowered. How much is not known as the water level measurement equipment can only measure down to 66.96 m a.s.l. The water level went below that value.

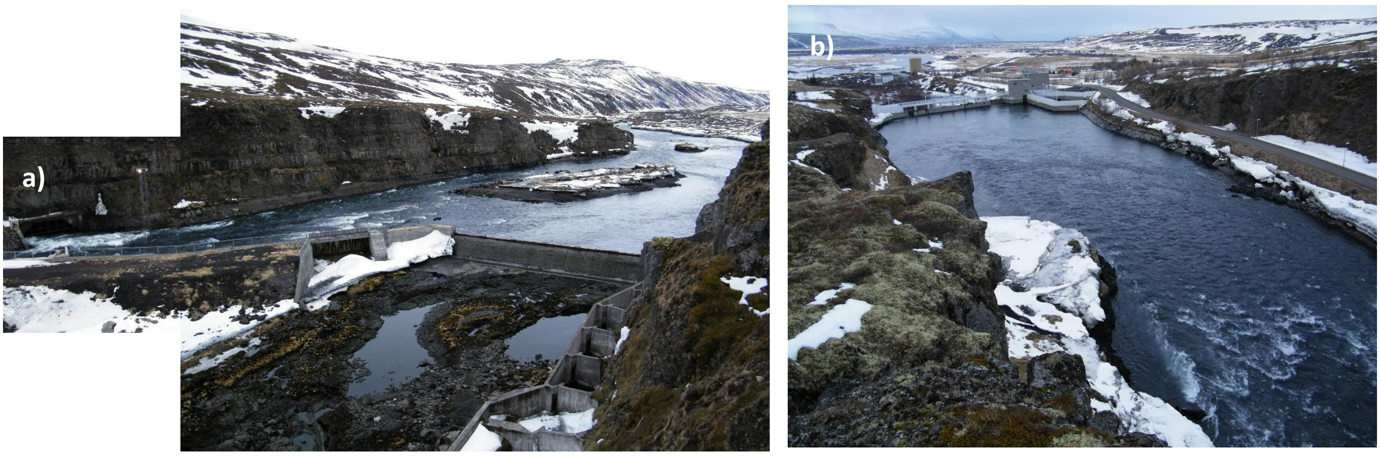

Figure 3.26 The intake ponds with lowered water table on the 5th of April 2011. Discharge about 40 m^3/s. a) Intake pond for Laxá III. Water level 105.37 m a.s.l. b) Intake pond for Laxá II. Water level below 66.96 m a.s.l. but full flushing level not reached. („Laxá Station photo collection“, e.d.; (Landsvirkjun, n.d.-c).

3.4.2.1 Laxá III intake pond

Before the changes in 2016/17 the intake pond had next to no real depth. Sand only settled downstream of the islands and in some corners of the pond with next to no flow, see figure 3.27. The report on the depth measurements in the intake pond in 2012 reports about no sediment in the eastern branch but some sedimentation between the islands and sandbars leading from the western bank (Andri Gunnarsson, Theódór Theódórsson, & Ragnar Þórhallsson, 2012, p. 7).

The pond did not store any real amount of sand as it was too shallow and the transport capacity of the river high enough to carry the sand through the pond. Figure 3.28 shows a pond free of fine grained sediment like sand (in the context of the grainsizes in the Laxá) just after the temporary dams had been constructed for the duration of the construction work in 2016-17. This means flushing had no effect for the intake pond for Laxá III as it did not store any real amount of sand. The report from 2012 reports no measurable change in the storage volume of the intake pond between the measurements made late in May and in July (Andri Gunnarsson, Theódór Theódórsson, & Ragnar Þórhallsson, 2012, p. 7).

After the changes made to the intake in 2016/17 a part of the intake pond was deepened, see figure 3.29. The purpose was twofold:

- Firstly, to create a pit for sediment to settle in, from which it is then sluiced, through special piping network, past the intake tunnel and straight to the river below the dam.
- Secondly, to create access to the pits for equipment during construction time.

The two pits are located in the intake area, the upstream one, with bottom code of 95.0 m a.s.l. and the second one 94.5 m a.s.l. The pits are regularly emptied but upstream of the pits sediment can settle in the deepened part of the intake pond and stay there for years to come. Flushing of this part is not possible as the water level in the intake pond can only be lowered down to about 105.3 m a.s.l. as the tunnel is the controlling factor. Lowering of the water level might move some part of the settled sand within the intake pond, but most of it will not be moved. The small part of what erodes would mostly settle again in the pits.

The sluicing of the sediment from the pits is done every other day, alternating, i.e. each day one of the two is operated.

Figure 3.27 Sediment in the Laxá III intake pond on the 2nd of September in 2014. a) In the corner between the canyon wall and the western most end of the spillway. b) At the downstream (or leeward side) of the island. ('Laxá Station photo collection', n.d.)

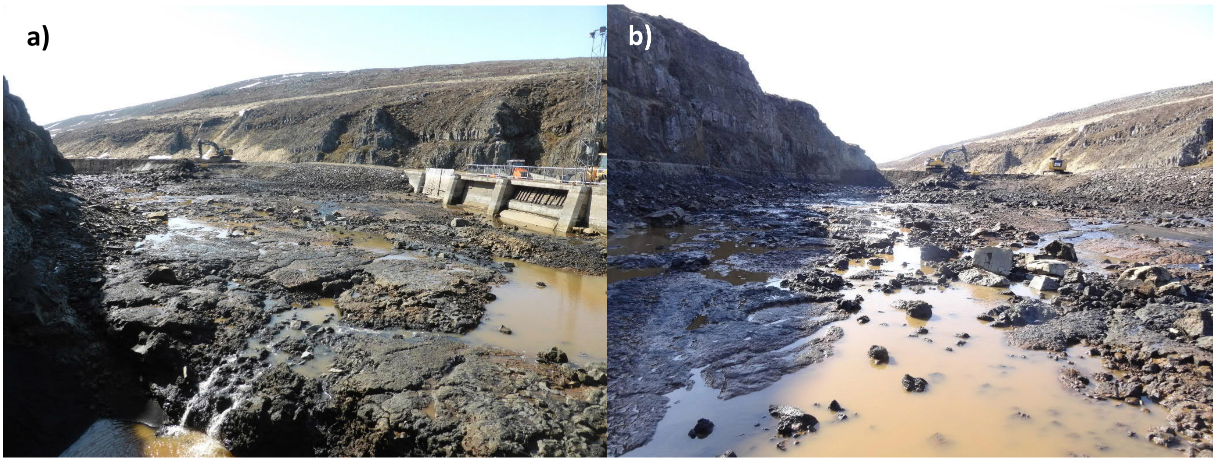

Figure 3.28 Intake pond for Laxá III at the beginning of construction time on the 12th of May 2016. (Photos from construction photo collection).

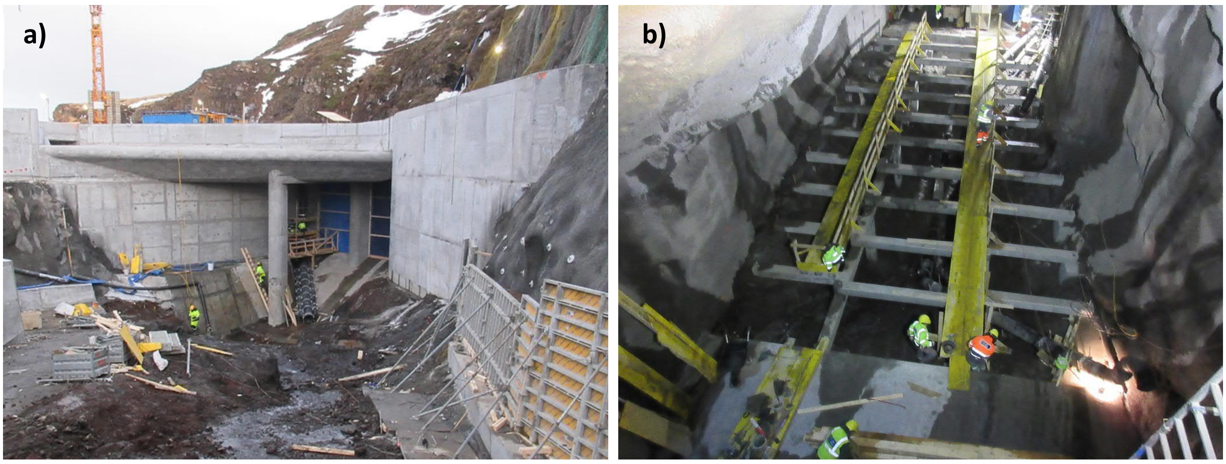

Figure 3.29 a) A view of the upstream pit or the stone collection pit during construction. b) A view over the downstream pit or the sand pit. (Photos from construction photo collection).

3.4.2.2 Laxá III intake tunnel

Before the changes in 2016/17 all the sand transported by the Laxá entered the intake tunnel. For a very short period of time after removal of sediment from the tunnel, sand settled in the tunnel and only part could be transported through. As table 3.4 reveals, the tunnel can only store about 10% of estimated sediment transported by the river per year or about 15 % of the coarse part of the material. An equilibrium between inflow and outflow of sediment should thus be reached relatively quickly. This means that under normal operational conditions sand is transported to and from the tunnel at a very similar rate.

During flushing of the intake ponds a part of the sediment in the tunnel erodes away. It is likely that the sand-delta in figure 3.33 had just formed due to flushing of the tunnel for Laxá III that started on the 5th of April, see figure 3.26.

After the changes made to the intake in 2016/17 the sand is supposed to settle in the settling pits and then it is sluiced out of them through pipes back to the river below the dam for Laxá III. The system seems to be working well. Sand can be seen coming out of the pipes and during inspection of the tunnel in May 2018 no sand was visible, except a small amount in the side tunnel, nothing in comparison with previous condition. Still, one year is not enough time to draw firm conclusions, but the signs are very positive for the operation of the power plants.

3.4.2.3 Laxá II intake pond

The Laxá II intake pond is also very small. Still it can store more sediment than the pond for Laxá III due to different layout. The upper most part is very narrow and shallow, then the pond widens abruptly and the velocity falls sharply. There, a sand delta can form, see figure 3.30, that erodes partly during flushing. Part of the eroded material is transported through the waterways into the river below the dam and a part is simply moved from the delta formation to a new delta formation further downstream in the intake pond.

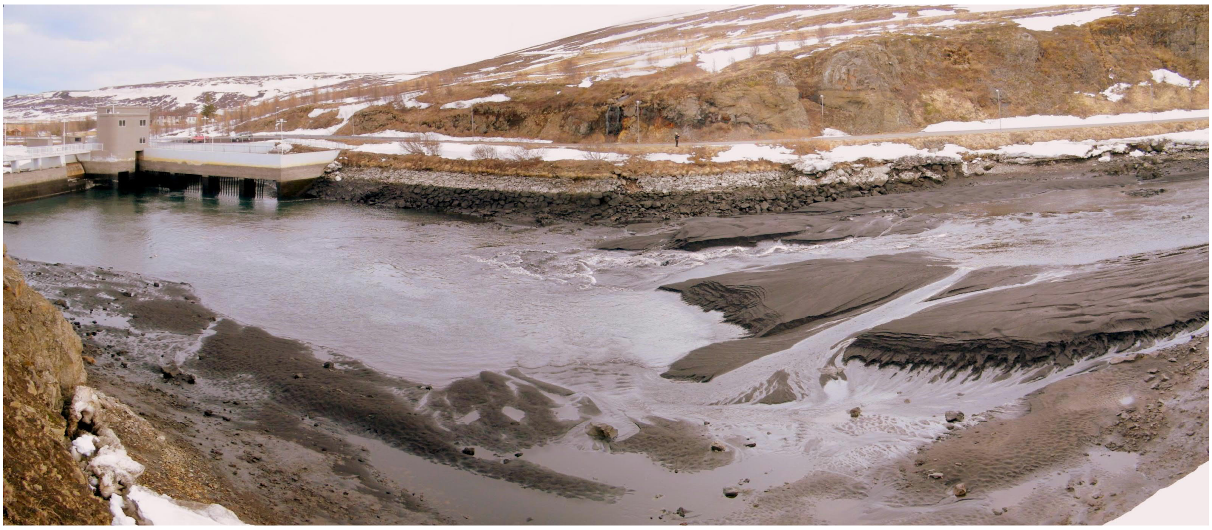

Figure 3.30 Sediment flushing on the 6th of April 2011. Water level in pond in the range 64.4-64.8 m a.s.l.[31] and discharge around 40 m^3/s. ('Laxá Station photo collection', n.d.)

Information about the flushing is limited, still some information is available for three different flushing occasions.

For the flushing event in 2011 only pictures and water level measurements are available. The water level measurement for the intake pond for Laxá II are of no use as the level was out of measuring range but the pictures fill in the gap. In 2011 the water level in the intake pond for Laxá III was lowered many

[31] Below measuring range of equipment. Estimate based on a comparison between the figure and codes on a drawing of the dam.

hours before the water level was lowered further down in the pond for Laxá II for flushing, see difference in water level in the intake pond for Laxá II on figures 3.26 and 3.30. The sand delta on the latter figure is very likely to have formed from the flushed material from the Laxá III intake tunnel. The flushing was done in April and it is plausible that before the flushing of the intake tunnel for Laxá III almost no sediment was present in the intake pond for Laxá II due to "clean out" during the winter period.

Measurements of the riverbed within the intake pond in 2012 indicated that about 3300 m^3 were eroded from the intake pond and about 2000 m^3 settled at a new location within the intake pond between the two dates of measurements, i.e. between 29th of May and 11th of July. The difference, about 1300 m^3, was flushed downstream (Andri Gunnarsson et al., 2012). The flushed sediment in 2012 is thus about 6.5 % of estimated annual coarse sediment transport.

During the flushing in 2014 the discharge was higher than normal, about 50 m^3/s, so the drawdown was probably less than in 2011 and 2012 when the discharge was about 40 m^3/s during the flushing period. As the waterways conveyance capacity is the restricting factor for flushing the added flow increases ponding within the intake pond, so the net result might be less material flushed from the intake pond. The flushing in 2014 only lasted for about 8 hours while in 2012 it went on for over 10 days. Another factor might be the flushed material from the intake tunnel of Laxá III. During the flushing period in 2014 the water level in the Laxá III pond was lowered after the pond for Laxá II and was then changed repeatedly up and down. This affects the eroded material from the intake tunnel and is likely to create some pulses of sediment transported through the pond for Laxá II.

During the flushing in 2014 sediment samples were taken below the Laxá II dam where the flow is very turbulent and the transported sediment most likely all transported as suspended sediment. Fourteen of the measured suspended sediment samples had concentration of 0.3 g/L and three gave values above 0.4 g/L. All samples were under 1 g/L. The measured concentration can be seen in figure 3.31 (Andri Gunnarsson, 2014).

Based on these measurements and the discharge in the river at the time, the total amount flushed was estimated to be about 450 tons or about 300 m^3 (Andri Gunnarsson, 2014). This amounts to about 1.5 % of yearly transport of coarse suspended sediment at Helluvað.

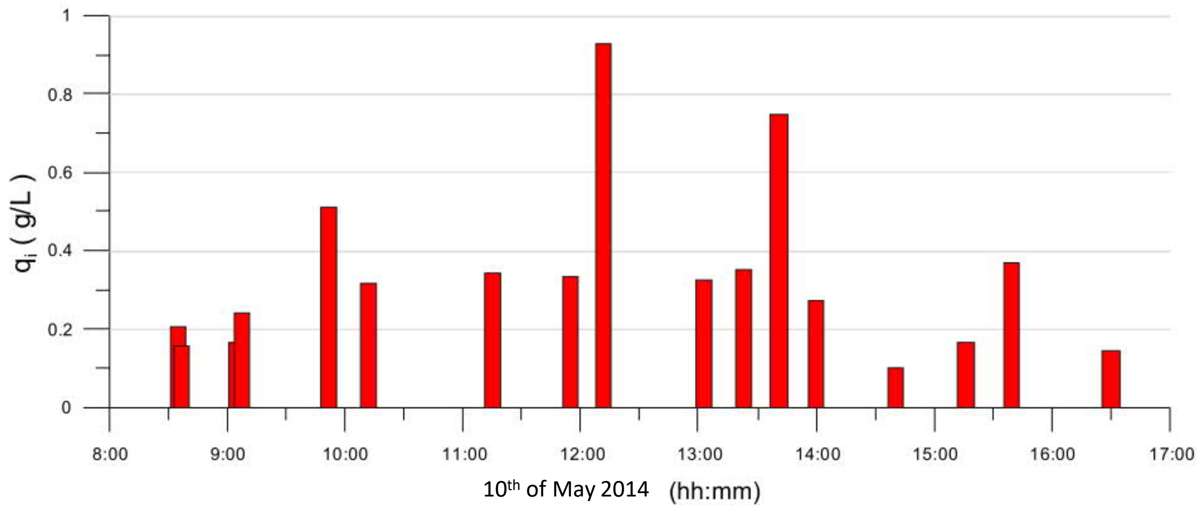

Figure 3.31 Measured sediment concentration during the flushing in 2014 (Andri Gunnarsson, 2014, p. 3).

The measured concentration during flushing in the Laxá below the dam is very low compared to typical concentration during flushing according to Morris and Fan (1998, p. 15.3) where over 100 g/L is the norm.

3.4.2.4 Impact of flushing

The impact of sediment flushing depends on various factors, i.e. sediment concentration deviation from normal, time of year, sediment size distribution, the flora and fauna in the river and so on. In the Laxá the intake ponds store very little sediment. The concentration in the Laxá during flushing is very low compared to typical flushing concentration where flushing is used to empty big reservoirs that store huge amount of sediment. Table 3.6 compares concentration values. The first value is the typical value for sediment flushing, given in the Reservoir Sedimentation Handbook (Morris & Fan, 1998, p. 15.3). The next two lines are measured values in the Laxá and the last two are possible concentration values in winter when ice affects the flow and sediment conveyance capacity.

Table 3.6 Comparison of sediment concentration.

Where	Condition	Suspended sediment concentration
Typical world wide	Concentration during the initial period of flushing	> 100 g/L
The bridge above Helluvað	Average of suspended sediment measurements	0.04 g/L
	Maximum value of concentration for suspended sediment measurements	0.3 g/L
Below the Laxá II dam	Dominant value during flushing in 2014	0.3 g/L
Below the Laxá II dam	Average concentration, assuming ½ the yearly sediment transported to Birningsstaðaflói are eroded further downstream during winter conditions over 5 months period (Nov. to March).	0.08 g/L
Below the Laxá II dam	Average concentration, assuming ½ the yearly sediment transported to Birningsstaðaflói are eroded further downstream during winter conditions over a period of one month.	0.4 g/L

The concentration at Helluvað is considered to be typical for the upper part of the Laxá and relatively stable over the year. A comparison of the dominant value during the flushing in 2014 below Laxá II and the maximum measured value at Helluvað show that the two values are the same. Indicating that the flushing concentration is not unnaturally high per se. Still, the higher concentration during flushing is unnatural to the river at the time of flushing. In case the hypotheses of processes in Birningsstaðaflói are correct, the concentration is not appropriate in this part of the river at this time of the year as the highest concentration should happen during cold spells, when ice formations affect the river and the sediment transport. Even though the concentration is not very high the sediment flushed is likely to settle in the upper part of the river in Aðaldalur and for this time of the year that sedimentation would be unnatural.

The last two lines in table 3.6 are fictional but possible if the sediment transport is dependent on ice formations as stated in this report. These numbers were only put out for comparison. The concentration could also be much higher but then over shorter time periods. This is not known and difficult to speculate. The flushed material from Birningsstaðaflói during ice formation periods is also likely to settle at different locations than material flushed from the intake pond and tunnel as the latter would happen during ice free periods so the material would settle as soon as the velocity drops, most likely just after the canyon opens into Aðaldalur. In winter time ice formations are likely to affect the river further downstream and thus the material would settle elsewhere and some of it might be carried all the way to the sea.

3.4.3 Possible improvements, question S-3

The most natural thing would be to pass the alluvial material downstream as naturally as possible. Based on the volumes involved, it is most likely that the transport of alluvial material down the Laxá canyon has been natural all along, except for the flushing in spring time when the small volume of sediment that could be stored within the intake tunnel for Laxá III and the intake pond for Laxá II was flushed out. The flushing was not in line with the natural behaviour of the river even though the concentration compared to other flushing locations in the world shows that it is relatively low and even though the comparison of the concentration during flushing and maximum measured suspended sediment at Helluvað is similar. If flushing is necessary, it would be more natural to do it during a thawing period in winter time that is likely to be followed by a colder period with ice formations that would redistribute the material more naturally shortly after the flushing.

The changes made to the intake for Laxá III in 2016/17 are likely to be the first step towards a better practice. The new intake has two sediment traps, one located just under the ice skimming spillway and another just a few meters further downstream, see figure 3.32. The first one is equipped with a suction pipe that is designed to remove sediment and stones up to 50 cm in diameter. The second trap is 20 m long, 10 m wide and 5 m deep. It is equipped with sluice pipes that sluice settled sand from the sediment trap. The pipes discharge the sediment back into the river downstream of the dam for Laxá III.

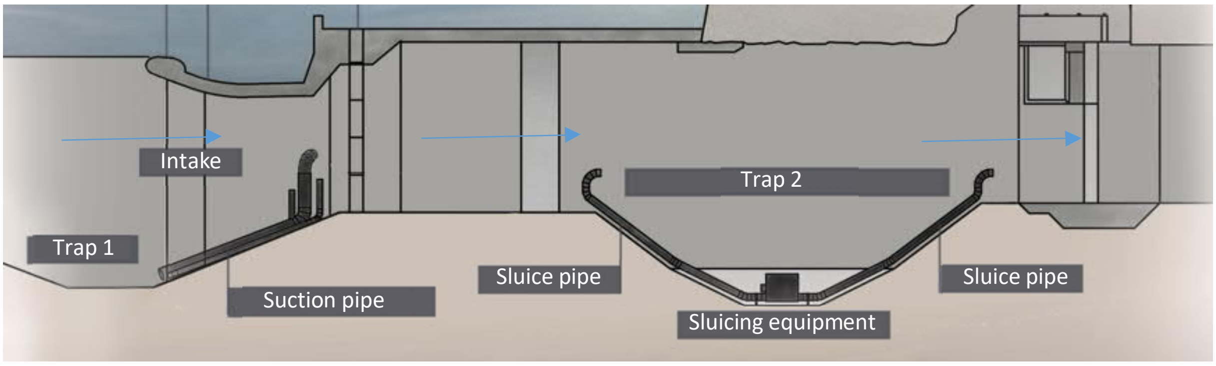

Figure 3.32 A cross section through the new intake, including sediment traps and equipment.

Now the coarse sediment settles within the intake area and is sluiced out every other day. This is more natural than before, but as this is restricted to Laxá III the effect is still local. Based on additional knowledge of the processes in the river it is possible to lengthen the pipes all the way to the downstream of Laxá II and try to flush in harmony with the natural processes in the river in this part of the river.

3.5 Substrate

3.5.1 Transport and settling of substrate material in the river, – question S-5

3.5.1.1 The material and the source

The transported material in the Laxá is not made up of even amounts of all grain sizes. Figure 3.33 shows the upstream part of the intake pond for Laxá II shortly after flushing of the intake tunnel for Laxá III. Sand and cobbles/rocks[32] can be seen with no visual bridging in sediment size between the two. That does not mean that gravel is not present in the river, only that these are the governing sediment sizes in the river at this location at this time. Sand is the dominant sediment transported by the river in terms of volume. The cobbles/rocks are not as easily relocated as the sand and usually need ice to help with the transport downstream.

[32] The grain size classing system used in the report on the mapping of the riverbed is used in this chapter, see table 3.3.

Figure 3.33 Sedimentation in the delta area of the Laxá II intake pond. Photo taken during sediment flushing on the 6th of April 2011. ('Laxá Station photo collection', n.d.)

The rocks seem to be mainly of two origins, a) larger rocks that have fallen from the canyon walls and have distinct form of columnar basalt, see figure 3.34, and b) smaller rocks (and even gravel) that are likely to come from the Laxá Lava, see also figures 3.34 and 3.35. The former is solid rock while the latter is very porous and thus has lower density.

Figure 3.34 Cobbles and rocks in the intake pond for Laxá III, visible after emptying of the pond in 2016. A zoom of a part of figure 3.28 b).

Figure 3.35 Left: Cobbles from the upstream sediment trap, in spring 2018. Right: Gravel and cobbles in Birningsstaðaflói upstream of the lake like part.

3.5.1.2 Means of transport

The material in question is not easily moved under normal conditions and as the floods in the Laxá are not large they do not play as big part as floods in some other rivers. The main transport of this material seems to be related to cold periods where ice comes into play, see chapter 3.1.3. Reports on operational disturbances confirm this. No formulas are available to calculate transport of this kind and information is scarce.

3.5.1.3 Settling

The material in question is dependent on ice and ice formations. It is carried with the ice and stops and settles where the ice stops and later melts or where the ice carrying it loses its grip, so it falls to the river bed. The transportation mechanisms with the ice are different from transport with the water, and that means different spots for settling.

The most likely location for settling of material carried downstream with ice in an ice surge used to be below the canyon mouth where the river widens and the surge wave dies out. After the construction of the dams some of the material can end up in the intake pond for Laxá III while the rest usually stops in the pond for Laxá II.

Settling of material carried with ice formed as anchor ice is dependent on either where the ice stops or where the ice loses its grip of the material. This can both happen within the river itself or on the riverbanks, when the water level is higher due to ice formations within the river and the water has started to flow overbank. This is likely to be the material mentioned in the 18th century records. Figure 3.36 shows an example of this on the banks of the Eystri-Rangá.

Figure 3.36 Gravel and cobbles on the riverbank of the Eystri-Rangá. Example of material transported with ice.

3.5.1.4 Magnitude transported

The report on the removed material from the machinery in Laxá III in 1991, see chapter 3.3.2, gives a glimpse of magnitude per time. The estimation of removed material is 2.5-3.5 m^3, gravel and cobbles/rocks. The material was transported during a three-day blizzard. This only tells us that during a blizzard this amount of material can be transported by the river. It is also known that some gravel and cobbles can pass through the machinery without a stop.

The only conclusion possible from this information is that during blizzards the river can transport larger material downstream than usual. How much depends on the severity of the blizzard, how long it lasts and possibly other unknown factors. How much of the transported material passes through the hydropower stations depends on the largest rocks transported and possibly also the magnitude transported, i.e. if the rocks are small enough to pass through the material will pass, and if the magnitude is not too much it will also all pass through. But if a large rock, too large to pass through, enters the machinery it will either stop or be stopped as soon as someone notices and the material manually removed.

Note that it cannot be said that during winter time approximately 3 m^3 of gravel and cobbles are transported by the river per three days on average. Both because in between, in winter time, there is no transport of this type of material and also because we don't know if more was transported by the river before the stop and whether the river was trying to transport more after the stop.

3.5.2 Influence on substrate, question S-4 part 2

3.5.2.1 Removed material

Chapter 3.3 contains a short report on removed material. Unfortunately, the available information only covers the total magnitude but not the size distribution of the material. We have quite good estimation on the yearly transport of alluvial material, mostly sand, in the river but no measurements on the larger material. Still, the previously mentioned report on the removed material from the machinery in Laxá III in 1991, see chapters 3.3.2 and 3.5.1.4, gives a glimpse of magnitude per time.

From this it can be said that the power plants do have some effect on transport of this type of sediment. It does however not stop all of it, but it stopes some of it, mainly the largest rocks. Also, the power plants do stop most of the ice rubble in an ice surge in the intake pond for Laxá II. These events are likely to carry cobbles and stones. Before the constructions within the canyon these surges transported the material down to the Aðaldalur where the ice rubble would have stranded as the surge wave died out just outside the canyon mouth.

3.5.2.2 Restrictions due to constructions

The <u>source of material</u> to the river has been constricted as the fish ladders and the road in the canyon hinders the material falling from the canyon walls from entering the river.

Additionally, the river has been made narrower resulting in <u>less ice production and anchor ice formation</u> within the river reach from the intake pond for Laxá III down to the outlet of Laxá II Station. The reason is twofold, firstly narrower cross section results in deeper river. That usually leads to less anchor ice production. Additionally, the area for anchor ice production is much smaller, leading again to less anchor ice production. This is likely to result in less amount of substrate material picked up (eroded) from this part of the river.

3.5.2.3 Influence on substrate

Regarding influence on substrate in the Laxá in Aðaldalur it is very difficult to say if or how it has been influenced and can't be quantified with the data and references available. Still, the results from the mapping of the riverbed suggest that the changes are not detectable at the mapped locations within Aðaldalur as the only detected change was less sand at Hólmavað in 2003 than in 1978. But the mechanism of transport and the restriction of the source of material within the canyon suggests that the substrate could have been affected.

3.5.3 Possible improvements, question S-6

The changes made to the intake for Laxá III in 2016/17 should eventually lead to the substrate material from upstream of the intake pond for Laxá III being transported via pipes to the downstream of the stations. This is not realized today. It was the view of Landsvirkjun and the designers of the changes to test the equipment first just at the site of Laxá III. Learn from that experience and if it looks good, then change the design and transport the material further downstream where the river, and its ice formation processes, would take over and transport the material naturally to the rivers chosen locations.

This would though only solve the problem of transporting material originating from upstream of the intake pond for Laxá III. The problems listed in chapter 3.5.2.2 are not solved this way. To compensate for possible lack of substrate material it is possible to transport material and put it in the river at chosen locations. As it is not known how much the river is missing it is advisable not to overdo it and choose the locations with ice formations and transport mechanism in mind. Locations, where it is likely the river will take up the material and relocate it as the river sees fit would be best. One such location is likely to be the most downstream part of the canyon, downstream of the outlet from Laxá II Station. There the river is steep, and it is a known location of ice formation, i.e. ice forming downstream and growing up into the canyon. With time the river and its ice formations should redistribute the material naturally along the river.

3.5.3.1 Further research

It would be helpful to research the river more with both ice formations and processes in mind and transport and influx of substrate material.

4 Summary

The purpose of this report was to shed light on the effects the Laxá Hydropower Stations have on the natural flow patterns of the river and sediment transport and to address the issues listed in table 1.1. This chapter summarises the findings.

4.1 Flow

The Laxá is mainly a spring fed river, running from the lake Mývatn. Large parts of the catchment area are covered with young lava that acts as a big groundwater reservoir with damping effects resulting in very stable inflow to Mývatn that also leads to very stable discharge in the Laxá. According to Sigurjón Rist, the Laxá is one of the rivers in Iceland with most constant flow (Sigurjón Rist, 1979b, p. 74).

4.1.1 Normal flow pattern and changes

Due to its spring fed origin the Laxá does not have a daily pattern. The natural causes for discharge fluctuations in the Laxá are due to:

- the wind, both wind speed and direction, and
- ice formations in the river.

Additionally, in the Laxá there is the possibility of manmade discharge changes at three locations:

- control of flow from Mývatn at Geirastaðir,
- control of flow through the intake pond upstream of Laxá III (and I) and
- control of flow through the intake pond upstream of Laxá II.

<u>Flow changes due to wind effects</u> are the result of so called wind set-up, where the wind pushes the water in its wind direction causing the water level of a lake to become unlevel. In Mývatn the wind set-up can lead to water level changes in the northern most part of up to +70 cm during south and southwest gales and down to -30 cm during northern storms. In the southern part the range is less, or up to 40 cm rise and 15 cm lowering of water level (Sigurjón Rist, 1979b, p. 70-71). The outlet of Mývatn is to the west so the wind effect there are mostly induced by the eastern and western winds, but as the distance the wind has to blow over is shorter in these directions than the southern and northern wind, the water level changes are less. Higher water level at the outlet of Mývatn leads to more water flowing out of the lake down to the Laxá.

<u>Flow changes due to ice formations</u> are slightly more complicated. They can both influence flow in the Laxá by affecting the outlet of Mývatn and by forming within the Laxá itself and thus influencing the flow downstream of that location as well as water level at and upstream of the ice formation location.

Before the constructions in the Geirastaðir branch, ice formations in the outlet area of Mývatn used to reduce the flow to the Laxá every winter. A short description from Sigurður Jónsson, farmer at Arnarvatn farm and raised at Helluvað farm reported on this is as follows:

> These ice dams lower the flow in the river considerably for one to three days. After very sever north-western blizzard the dams can last longer, up to one week. The worst blizzards occur approximately once every third or fourth year, while the smaller dams occur a few times every winter, mainly during the middle of the winter (Steinn Steinsen, 1936).

The discharge in the river is reported to have been severely diminished during these events. Estimates mentioned in interviews range from less than 1/3rd down to 1/6th when the damming was at its worst.

After the constructions in the Geirastaðir branch this problem was drastically diminished.

Ice formations within the river itself also influence both water level and discharge in the river. The ice formations are:

- <u>Ice dams, due to anchor ice formations</u> at rapids, forming local ice dams built from the river bed and up into the cross section of the river. These cause water level rise upstream and temporary lower discharge downstream while ice and water is building up the dam and gathering upstream.

- Ice jams, due to a build-up of ice slush upstream of an ice cover or other hindrance in the water surface. These also cause water level rise upstream and temporary lower discharge downstream while ice and water is building up the dam and gathering upstream.

Flow disturbances in the Laxá in Laxárdalur due to ice formations used to occur (based on five year observation period from 1948 to 1953) on average 7.5 times per winter and affected on average 20 days per winter (Sigurjón Rist, 1952, p. 17-18). After the constructions in the Geirastaðir branch the flow from Mývatn is much more stable. Ice formations within the river continue to form, but the more stable flow from the lake keeps the ice conveyance of the river also more stable at locations that were previously prone to ice congestion during lower flow periods. In some areas within the river ice formations are rarer than before due to more stable flow from Mývatn.

The only noticeable <u>flow changes due to constructions</u> are caused by the constructions in the Geirastaðir branch. The purpose of them was to minimize ice disturbances on the flow from Mývatn. The result is:

- more stable flow from Mývatn and
- less ice formations within the Laxá due to more steady flow from Mývatn.

In the early days of operation water level in Mývatn was regulated differently than today. Today, operation of the gates in the Geirastaðir canal is completely governed by Icelandic law and kept within target values, or as close to 278.77 m a.s.l. as possible, using three water level measuring stations in order to be able to account for possible wind induced effects.

The intake ponds for the hydropower stations are so small that they have next to no effect on flow in the river, i.e. no damping effect on natural discharge changes. Additionally, the operation handbook states clearly that all changes to flow through the turbines and opening or closing of gates shall be made slowly to keep the flow downstream stable.

4.1.2 Floods

There are two different types of floods in the Laxá:

- rain and snowmelt derived floods
- floods produced by ice formations (ice dams) that break suddenly causing a flood wave.

The cause, behaviour and consequences are very different.

<u>Rain and/or snow melt induced floods</u> are impacted by the geology of the catchment area. In the parts of the Laxá where it is dominantly spring fed, floods are almost non-existent. Further downstream, where the geological formations are older and more closed on the surface, the river gains more and more surface runoff area allowing floods to form in the river.

The main flood season is in April and May. The floods are relatively small compared to the size of the watershed. These floods grow slowly in the sense that the responding time of the intake ponds is faster. This means that the intake ponds cannot affect these floods as the intake ponds are too small.

<u>Floods due to river ice formations</u> can result in higher discharge than rain and/or snow melt induced floods. River ice formations in the Laxá also causes the highest water elevation, i.e. flooding. The former is short-lived (minutes) and dies quickly out where the slope is relatively low and the river widens out, while the latter can last over much longer periods.

Water level changes due to ice formations within the river are the same as before any constructions within the river except at some locations ice formations are rarer after the Geirastaðir constructions as the discharge is more stable than before. This should mainly apply to locations close to Mývatn and locations where ice formations occurred due to lower discharge than normal when ice blocked the flow from Mývatn. In most places, ice formations continue to form as they are created by snow, snow drift and ice slush that is formed within the river or fall into the river over its whole length.

Some ice surges are small and others very big, but all are short-lived in time. The intake ponds are small and respond quickly to flow changes, but if the ice surge is small the intake ponds will affect its progress or even dampen the wave completely. In those cases, the ice rubble carried by the ice surge will stop in the intake ponds.

4.1.3 Questions F-3 and F-4

There is not a daily flow pattern in the Laxá. Still there are changes in flow due to wind blowing over Mývatn and ice formations.

The ice formations in Mývatn that used to block the outflow and cause the lowest discharge in the Laxá are much rarer and the blockage is not as severe as it used to be. That has led to fewer instances of very low discharge in the Laxá and also affected some of the other ice formations within the river itself but not all types. The result is:

- More stable discharge in winter time.
- Fewer instances and less area that could be affected by low flow, i.e. fewer river edge areas that could be prone to isolation.

4.2 Sediment transport

Sediment transport in the Laxá is more or less divided into two categories with different origin, size distribution and transport mechanism. These are:

- Alluvial material: originating in Krákárbotnar, mainly sand, transported as both suspended sediment and bedload.
- Cobbles/rocks: originating mainly from the canyon and partly from the riverbed. Mostly thought to be transported with ice.

Sediment transport in the Laxá is more complex than previous reports suggest. The reason is that ice has not been taken into account before in all its complexity and the cobbles and rocks have not been researched as part of the material transported by the river.

4.2.1 Removed material

Material has been removed from the intake tunnel for Laxá III, intake pond of Laxá II and from the machinery. Reports on this are not complete and do not give a precise volume or good indication on the size distribution of the material removed.

Material has four times been removed from the intake tunnel. Estimated volume is about 10 500 m^3, or approximately 1.3 % of transported material in the years 1973-2018 that could settle in the tunnel if the storage capacity within the tunnel was not full. Maximum volume reported was 3200 m^3 in 2016, mostly sand.

Some material was removed from the intake pond for Laxá II. How much is not known.

Material has also been removed from the machinery. On all occasions, ice in the river system was the culprit as it had transported rocks that were too big to pass through the machinery. In March 1991 the estimation of stones and gravel removed from the machinery was 6 tons.

4.2.2 Alluvial material

Measurements indicate that about 45 000 tons, or 30 000 m^3, of alluvial material, sand mostly, is transported by the river at Helluvað yearly. The suspended sediment transported at Helluvað did not show any seasonal changes.

The Laxá is relatively steep from Helluvað down to Birningsstaðaflói where the river suddenly becomes wide and calm with over 1 km of a lake like part. In this part of the river the sand grains should settle and with time find a balance between longitudinal slope, inflow and outflow of sediment transport. This balance has not been reached even though the volumes involved (magnitude of sediment transported yearly, and the water volume stored in this lake like part of the river) suggest it should only take a few years. Ice formations within and around the Birningsstaðaflói are likely to be the reason this has not happened as the ice formations can fill this part of the river and completely change the conveyance capacity of the river.

This has consequences downstream as the transport is constricted through Birningsstaðaflói when no ice is present. On the other hand, the transport of sediment is likely to be very high during the right ice conditions, when large amounts of alluvial material would be eroded and transported from the Birningsstaðaflói over a relatively short period of time.

The intake ponds have much smaller volume than Birningsstaðaflói (30-40 thousand m^3 versus 100-200 thousand m^3). The storage capacity is very limited and the alluvial material is quick to find a balance between inflowing and outflowing sediment transport. Their effect should thus be very temporal and limited.

Sediment transport in the Laxá in Aðaldalur is likely to be affected by both Birningsstaðaflói and ice formations within the Laxá in Aðaldalur. Alluvial material has often been transported from the river and onto the fields around the Laxá. Ice formations within the river change the conveyance and where the water flows allowing the water to transport sediment to overbank areas.

The imbalance caused by sediment flushing from the intake tunnel for Laxá III and intake pond for Laxá II is likely to have had some effects on alluvial sediment transport in Aðaldalur as it is likely to have created periods with higher alluvial material in the system at times it should not be entering this part of the river. The concentration of suspended sediment during these flushing periods is though very low compared to reported flushing elsewhere. The average measured concentration during flushing in 2014 was similar to maximum measured value at Helluvað.

The waterways of the stations are unable to affect the transport of alluvial material for any real period of time as their storage capacity is so limited in comparison to the transported alluvial material per year by the river.

The changes made in 2016/17 were aimed at preventing inflow of alluvial material into the intake tunnel for Laxá III. The intake has now two pits equipped with sediment flushing pipes that are used to flush out small amounts of sediment regularly (currently operated daily or every other day). This only affects the intake tunnel for Laxá III as the alluvial material is diverted past the tunnel and back into the river downstream of the dam where the river transports it into the intake pond for Laxá II.

The long-term goal is to lengthen the pipes to the downstream of Laxá II in order to:

- bypass both power stations and
- make the transport of alluvial sediment as natural as possible.

Before that change can be fully evaluated a better understanding on the natural transportation pattern of the alluvial material is needed in order to be able to mimic the natural fluctuations better.

4.2.3 Substrate material

The material contributing to the substrate seem to be mainly of two origins, a) larger rocks that have fallen from the canyon walls and b) smaller rocks (and even gravel) that are likely to come from the Laxá lava. The cobbles/rocks are not as easily relocated as the sand and usually need ice to help with the transport downstream. This also means that the material is dependent on the movement of the ice it is transported with for settling site.

It is difficult to quantify how much material is transported by the river. We know that during blizzards the river can transport larger material downstream than usual. How much depends on the severity of the blizzard, how long it lasts and possibly other unknown factors. How much of the transported material passes through the hydropower stations depends on the largest rocks transported and possibly also the magnitude transported.

Some material has been removed from the river but it is difficult to quantify it. The main quantity removed is sand. Other factors affecting the transport of substrate material downstream are:

- restricted access to the river due to the constructions in the canyon and
- less ice production and anchor ice formation within the Laxá Canyon due to narrower cross section.

Regarding influence on substrate in the Laxá in Aðaldalur it is very difficult to say if or how it has been influenced and can't be quantified with the data and references available. Still, the results from the mapping of the riverbed suggest that the changes are not detectable at the mapped locations within Aðaldalur as the only detected change was less sand at Hólmavað in 2003 than in 1978. But the mechanism of transport and the restriction of the source of material within the canyon suggests that the substrate could have been affected.

The changes made to the intake for Laxá III in 2016/17 should eventually lead to safe transport of cobbles and rocks from the upstream of Laxá III to the downstream of Laxá II, i.e. bypassing the power stations. This would though only solve the problem of transporting material originating from upstream of the intake pond for Laxá III. Material originating from the canyon, in between these locations, has to be looked at separately.

4.3 Additional notes

This report was written to shed light on the changes and possible changes the hydropower stations have had on hydrology and sediment transport in the Laxá. While researching available reports on the matter the writer came across this interesting paragraph on Lake Mývatn:

> At a glance it seems paradoxical that warm winters result in a cold Lake Mývatn and cold winters result in a warm Lake Mývatn. But systematic temperature measurements of many years by Sigfinnsson show this to be true (see Rist 1969). A very likely explanation is, that in warm winters there are large polls of open water and a lot of melt water of 0°C blends with the lake water. In cold winters on the other hand, Lake Mývatn is protected and isolated from the cooling effect of the atmosphere by a cover of ice and snow. The bottom temperature measured under these conditions is 2.5°C against 1.4°C in warm winters. (Sigurjón Rist, 1979b, p. 76)

As Mývatn is thought to be the food/nutrient source for the Laxá, these effects could lead to a different pattern in the Laxá than in other salmon rivers because when other rivers are affected by cold temperature Mývatn would be relatively warm.

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Appendix 1 Minutes of meeting (in Icelandic)

Minutes of meeting. 13th of November 2015.

Fundur um Laxá í Aðaldal og Láxárvirkjanir

Haldinn Hótel Marina föstudaginn 13. Nóvember 2015 kl. 14:30

Fundarmenn
Orri Vigfússon - NASF/Laxárfélagið nasf@vortex.is
Jón Helgi Björnsson - Veiðifélag Laxár jon.helgi.bjornsson@hsn.is
Árni Pétur Hilmarsson - Nestorfa arnihilmarsson@gmail.com
Hermóður Jón Hilmarsson - Nestorfa hilmodur@gmail.com
Kristján Einarsson - bhmk@simnet.is
Guðmundur Björnsson - Landsvirkjun Gudmundur.Bjornsson@landsvirkjun.is
Jóna Bjarnadóttir - Landsvirkjun jona.bjarnadottir@landsvirkjun.is
Helgi Jóhannesson - Landsvirkjun Helgi.Johannesson@landsvirkjun.is
Sveinn Kári Valdimarsson - Landsvirkjun sveinn.kari.valdimarsson@landsvirkjun.is

1. Orri setti fund og bauð alla velkomna og kynnti þáttakendur
2. Orri fór lauslega yfir sögu NASF og Laxárfélagsins og lýsti samskiptum við Landsvirkjun
    a. Farið var yfir sandburð í ánni og hvað hefur verið unnið þar.
    b. Lýsti áhyggjum yfir að Laxá fylgi ekki almennum sveiflum í laxveiði.
    c. Sagði frá áhyggjum manna um að virkjanir stöðvi grjót á leið niður ánna og komi þannig í veg fyrir endurnýjun búsvæða laxins. Einnig að breytingar á rennsli hefðu tafið fyrir útskolun á hrygningar og uppeldisstöðvum.
3. Sveinn sagði frá aðkomu Landsvirkjunar og lýsti áhuga á að vinna að betra verklagi þannig að áhrif virkjana minnki og hverfi helst alveg.
4. Jón Helgi og Árni Pétur ræddu um aðgerðir sem þegar hefur verið ráðist í varðandi að koma grjóti útí ánna og þann góða árangur sem það hefur skilað. Þar hefur grjóti úr Knútsstaðanámu verið komið fyrir samkvæmt því sem efni og aðstæður hafa leyft. Mikilvægt að skoða þetta í þeirri vinnu sem framundan er, að fá ráðleggingu hvar sé best að losa sig við efnin í ána, þannig að það berist á sem „náttúrulegustu svæðin“.
5. Almennt rætt um verklag Landsvirkjunar varðandi grót sem stöðvast í lónum og vatnsvegum virkjana, en í dag er það keyrt í námur og geymt þar. Aðilar allir sammála um að þetta þurfi að bæta og grjót sem nú er í námum þurfi að komast útí Laxá. Mikilvægt að Landsvirkjun og Veiðifélagið vinni saman að lausnum og hefjist handa strax í vetur.
6. Rætt um rannsóknaráætlun sem lögð var fram í drögum (sjá fylgiskjal). Aðilar sammála um að hægt sé að vinna samkvæmt því.
7. Fundarmenn voru sammála um að veiðifélagið afli nauðsynlegra leyfa varðandi það að koma grófara efni fyrir í ánni neðan virkjana.
8. Gerð var lausleg áætlun um skipulag rannsókna og mun Landsvirkjun strax fara í að vinna liði 2 og 3 í rannsóknaráætluninni. Veiðifélagið mun skoða liði 1, 4 og 5 í samvinnu við Náttúrustofu Norðausturlands og Guðmund Smára Gunnarsson. Aðilar munu svo allir koma að vinnu við liði 6, 7 og 8. Samþykkt var að aðilar gætu ráðfært sig um aðferðir og niðurstöðu rannsókna við þá sérfræðinga sem þeir kjósa.

9. Rætt um mikilvægi þess að hefja vöktun á Mývatni og vinna það vel. Engu að síður bentu fundarmenn á að verkefni er snúa að áhrifum virkjana á framburð sé aðskilið verkefni og ekki rétt að blanda þessu tvennu saman að svo stöddu.
10. Fleira ekki rætt
11. Fundi slitið um 16:30.

Sveinn Kári Valdimarsson

Appendix 2 Research plan submitted by Orri Vigfússon

Research plan submitted by Orri Vigfússon at a meeting on the 13th of November 2015 on behalf of NASF/Laxárfélagið.

Draft Laxá River Research Plan

A long-term downward trend in salmon stocks, both adult runs and juvenile densities, in the mainstem Laxá River as well as in the two main tributaries, has been observed in recent years. The Laxá River, located in northeastern Iceland, drains from Lake Mývatn and extends 58 km northward to the Bay of SkjalfandiI. Lake Mývatn is a shallow spring -fed lake that together with some tributary input provides an average daily discharge of approximately 40 m3 sec-1, with peak flows normally occurring in April and May. The Laxá River was developed for hydropower with the first power plant (Laxá I) completed in 1939, the second (Laxá II) in 1953, and the third power plant (Laxá III) completed in 1973.

Research Objective

The goal of the project is to identify factors contributing to the decline in salmonid survival that are attributable to the construction and operation of power plants in the Laxá River.

Background

Power plants can affect salmonid survival through several ways, including: alterations in flow patterns, interruption of normal streambed substrate processes, interruption of cleansing flow mechanisms, increased sedimentation, as well as decreasing recruitment of suitable spawning substrate.

Changes in salmonid survival can occur as a result of seasonal and daily flow changes, reduction in suitable juvenile rearing habitat through sedimentation, or altering the available adult suitable spawning habitat. Emphasis of the study should be placed on reviewing existing information and identifying critical uncertainties, characterizing suitable juvenile and adult habitat, estimating current juvenile and adult habitat availability, identifying the mechanisms involved in affecting that habitat, and develop mitigation measures that can be implemented to increase the suitable habitat availability.

Project Outline

1. Compile and Summarize Existing Information.

    a. Compile present information regarding salmonid abundance, presence and habitat usage, and identify critical uncertainties.

        i. Review existing data (e.g. field abundance estimates, trapping data, and radio tag data) and describe preferred juvenile and adult spawning habitat.
        ii. Review impacts of sedimentation to available juvenile rearing habitat.

iii. Review impacts of substrate removal to spawning habitat.
iv. Identify critical uncertainties that must be addressed.

2. Compile and summarize existing data on flow in Laxá River, pre and post power plant operation to answer the following questions.

    a. Determine if flooding (peak flows) in the Laxá river changed since the construction of the power stations.
        i. Review existing historic flow data, pre and post construction.

    b. Determine if there daily changes in flow (daily power peaking) at the power plants that affect water levels downstream.

        i. Review flow data on as fine a scale as possible (hourly).

    c. If flow changes over a short time scale (hourly, daily) as a result of power plant operations, determine if the river geography is such that there are river edge areas shallow enough to form pools of water that can become isolated from the main river as water recedes.

    d. If flow changes over a short time scale (hourly, daily) as a result of power plant operations, determine how this affects water velocity and water depth in spawning and non-spawning sites.

3. Provide a description of the interaction between the power stations and the substrate below the power plant in terms of alluvial sands and substrate removal.

    a. Alluvial sand
        i. Describe the historic relation between the transport and sedimentation of alluvial sands in this system.
        ii. Describe the effect that the power stations have on the normal river alluvial processes.
        iii. Determine the impact of emptying lagoons on the distribution of alluvium compared to the natural alluvial processes.
        iv. Review the present procedures for flushing sand and determine how these procedures can be improved.

    b. Substrate Removal from Laxá river

        i. Describe and determine the magnitude of substrate material that has been removed from Laxá River.
        ii. Determine the normal processes of rock deposition in the river that would occur if the power plants were not present and compare to the present removal of rock and subsequent settling downstream due to the presence of the power plants.

iii. Review the present procedure of removing rocks from lagoons/traps. If it is necessary to remove material from lagoons/rock traps, determine the best procedure of returning it to the rivers (locations, timing etc.) using the habitat information obtained in tasks 4 and 5 described below.

4. Juvenile rearing habitat

    a. Describe the bathymetry of the Laxá River associated with known juvenile rearing habitat slope and substrate. Based on survey data estimate present habitat suitable for juvenile rearing and occupation and identify potential habitat for future mitigation.

    b. Investigate the relation between the alluvial deposits and decreased peak flows for cleansing and present practices for releasing large quantities of alluvial sediments.

    c. Explore the relation between the alluvial deposits and the potential impact on the chironomid population.

5. Adult spawning habitat

    a. Estimate current available spawning habitat
        i. Identify present spawning habitat based on existing radio tag fish information to identify red locations or, if necessary, conduct new spawning ground surveys to identify redd locations.

    b. Characterize spawning habitat based on redd locations collecting the following information:
        i. Geographic location;
        ii. Water Temperature;
        iii. Lateral Slope;
        iv. Water Depth;
        v. Water Velocity;
        vi. Substrate size.

6. Implement habitat improvement measures

    a. Using the information collected for juvenile and adult habitat preferences identify potential juvenile and adult habitat available for improvement.

    b. Develop mitigation measures to be implemented.

7. Develop draft report for review and comment addressing items one through six.

8. Incorporate comments and provide a final report.

Appendix 3 About the flood in the Laxá 4th of December 1950

(Halblaub, 1950)

Um flóðið í Laxá. S.-Þing. 4.des. 1950

Afrit.

Um kl. 23 mánudagskvöldið 4.des. hringdi vaktmaðurinn í rafstöðinni í mig og segir að stöðin sé að fyllast af krapi og vatni, og spyr hvað hann egi að gera. Eg sagði honum að slá vélunum út, til að reyna að forðast skemmdir á þeim ef unnt væri. Þetta gerði hann, að svo miklu leiti, sem hann gat, vél I, stöðvarspennir og sp.I og II sló hann út aftan á rofunum, en vél II leysti sjálf út (mismunastraumsliði), þar sem að vatn var komið í gryfjuna undir generator II. Síðan féllu segulmögnunarrofar vélanna út, á vél I vegna yfirspennu þar sem að aðalrofa hennar hafði verið slegið út þegar hún var fullestuð, en á vél II féll segulmögnunarrofinn út um leið og aðalrofinn. Vaktmaður var Gísli Dan. þetta kvöld.

Þar með voru vélarnar orðnar spennulausar og frekari hætta á skammhlaupi liðin hjá.

Nú var komið vatn í allar gryfjur og rennur í stöðinni, ásamt krapi og jaka hröngli, og jusu kasthjól vélanna og rotorar vatninu upp um allan vélasalinn þar til að vélarnar stöðvuðust. Báðar dyr stöðvarinnar höfðu verið opnar þegar flóðið byrjaði, stóru hurðirnar lokuðust sjálfar svo að segja strax þegarkrapið skall á þeim, en litlu dyrunum lokaði vaktmaðurinn þegar hann komst að þeim vegna strumþungans og jakaruðningsins.

Það sem hér á undan er skrifað skeði á styttri tíma en þarf til að skrifa það.

Strax og vaktmaðurinn hafði hringt í mig, klæddi eg mig og fór, ásamt öðrum starfsmönnum rafveitunnar hér, suður í stöð til þess að hreinsa til og fyrirbyggja frekari skemmdir, ef hægt væri. Þegar við komum niður að ánni hér neðan við húsin, sáum við að áin hafði flætt yfir stífluna, sem gerð var í kvíslina norðvestur af "Tivoli". Þegar lengra kom suður veginn, sáum við að flætt hafði yfir tréstífluna, sem er þar sem hin væntanlega stífla nýju virkjunarinnar á að koma. Þó hafði aðeins flætt yfir tréstífluna þar sem hún liggur sem þverast við straum árinnar, en ekki neðar.

Þegar þangað kom, voru ekki liðnar meira en c.a.lo mínútur frá því að vaktmaðurinn hafði hringt, en samt var flóðið hjaðnað svo mikið þá, að hætt var að flæða yfir tréstífluna. Enn var þó vatnsflaumur upp á veginn í króknum þar sunnan við en við komumst þó tiltölulega auðveldlega þar yfir, þrátt fyrir mikið jakahröngl og krap á veginum og þreifandi myrkur.

Þegar suður að stöðinni kom, sáum við að áin hafði flætt niður sundið austan stöðvarinnar, og voru háar krap- og jakahrannir beggja megin við farveg þann, sem myndast hafði meðfram stöðinni og út í aðalfarveginn hjá brúnni, norðan stöðvarinnar. Vatnsrennslið í þessum nýja farvegi var að mestu hætt, þegar við komum að honum.

Þegar inn í stöðina kom, gaf á að líta: Krap og jakaruðningur um allt gólfið í allt að meters hæð næst dyrunum og á verkstæðinu, og var þá vatnið samt mikið til sigið undan ruðningnum. Allt lauslegt, sem verið hafði í stöðinni hafði færst úr stað, þar á meðal bíll, sem staðið hafði innan við stóru dyrnar. Hann hafði færst til hliðar, þar til hann stöðvaðist á steinsúlu við stóru dyrnar, síðan hafði hann breytt stefnu á krapflaumnum þannig að meira rann inn með töflunum og þar norður með vesturveggnum, en minna í stefnu á generator I, en annars hefði gert.

Samt var gólfið allt umhverfis vélarnar þakið jökum og krapi, og eins og áður segir, allar gryfjur í gólfinu. Nokkuð hafði komið inn um glugga, á austurhlið stöðvarinnar, sem hafði staðið opinn, og má af því marka hæðina á flóðinu útifyrir. Bíll þeirra Alfreðs og Gísla stóð og stendur enn, við austurhlið stöðvarinnar útifyrir þessum glugga og hlóðst ruðningurinn upp í kringum hann, jafn hátt þaki hans, braut luktir og framrúðu, beiglaði skerma og skemmdi hann ef til vill meira, en það er enn ekki komið í ljós, þar sem að hann er enn í kafi að miklu leiti.

Flætt hafði inn í geymsluskúrinn austan við stöðina og var hæðin á ruðningnum þar inni upp að vinnuborði. Allt lauslegt í sundinu meðfram stöðinni hafði hreyfst úr stað. Stór steinn c.a.1/2 smálest hafði komið með flóðinu einhversstaðar að ofan og stöðvast austan við spennarúmið.

Það fyrsta sem við gerðum var að reyna að koma í veg fyrir, að vatnið ígeneratorgryfjunum næði upp í statorvindinga vélanna. Ekkert afrennsli er úr gryfjunni undir vél I, né úr kasthjólsgryfju hennar og var það ráð tekið, að láta vatnið renna um tvær 1" slöngur undan generatornum og niður um gat, sem er niður úr botni gryfjunnar, sem er kring um spjaldloku vélarinnar. Fór þá vatnið brátt að lækka í gryfjunni og var svo ísnum og krapinu mokað burtu, þegar að vatnið var búið. Niðurfall er úr gryfjum vélar II og rann vatnið þaðan sjálfkrafa, eftir að mesta flóðinu linti, en ís og krapi varð að moka þaðan upp eins og við vél I.

Jafnframt þessu var sent eftir mönnum til þess að moka ruðningnum út úr stöðinni og var það 4-6 tíma vinna fyrir 8 menn, en þá var eftir að þrífa gólfið, sem var allt útatað í sandi og aur úr krapinu.

Aðrir unnu við að þrífa upp vélarnar, gera mælingar á þeim og háspennustrengjum í strengjarennum, því að þær voru fullar af vatni og ekki hægt að fá straum frá Akureyri fyr en fullvíst var, að strengirnir væru óskemmdir. Ljós var á varalýsingarkerfinu frá rafgeymi, en ekki var hægt að nota kranann við sundurtekningu vélanna fyr en straumur fékkst á hann frá Akureyri. Einangrunarmælingar sýndu að háspennustrengir væru þéttir einnig háspennuvafningar vélar I, eftir að búið var að þrífa upp einangrara og önnur virki í generatorgryfjunni. Farið var að nota straum frá Akureyri c.a. kl. 3, þann 5/12 .

Þrátt fyrir það, að mælingar sýndu einangrun vélar I góða, þorði eg ekki að taka upp spennu á henni fyr en að búið var að láta hana ganga skammhleypta í 2 tíma með yfir 2oo amper straum, þar sem að hún virtist vera meira og minna rök eftir allan vatnsausturinn. Var þá farið að athuga hvernig umhorfs væri fyrir ofan stífluna og hvort að nokkuð vatn gæti runnið að inntakinu, svo hægt væri að láta vélarnar snúast og þurka sig.

þegar þeir, sem upp að stíflunni fóru, komu upp að þeim stað, sem að flætt hafði yfir veginn s.l. vor, kom í ljós að flóðið hafði komið á sama stað nú og þá, en aðeins miklu meira nú, sem flætt hafði í gamla farveginn í austurhluta gljúfranna.

Á stíflunni var ljótt um að litast: Flætt hafði yfir hana alla , íshrannir hærri en stíflan, sumar hverjar, fylltu lónið og kvíslina austan við hólmann sem er ofan við stífluna, en vesturkvíslin var alauð og rann því nær allt vatnið í ánni fram af yfirfallinu. Lítið eitt rann þó meðfram stíflunni og út um austustu flóðgáttina, sem opin var. Mikið af lausum trjám, sem verið höfðu á stíflunni, var horfið, eða þá að það sást á nokkur þeirra upp úr ruðningnum neðan við stífluna. Háar jakafyllur risu upp við stífluna og var sú hæsta þeirra fram undan inntakinu og var hún eins há og skúrinn á stíflunni. Handrið úr 2" rörum var meira og minna beygt. Inntaksþróin full af jökum og krapi. Flætt hafði umhverfis og yfir pípuna fyrir neðan stífluna.

Að þessu athuguðu, var ljóst, að þó að vélarnar reyndust óskemmdar í stöðinni, mundi verða vonlaust um nokkuð rafmagn frá stöðinni, fyr en að búið væri að ryðja einhverju af ísnum og krapinu úr lóninu.

Þó að vitað væri að pípan væri meira og minna full af krapi, var samt reynt að setja vél I af stað, til að þurka hana, og einnig til þess að ekki frysi í pípunni. Það sýndi sig, að nóg vatn sé undir ísinn og krapið í lóninu, til þess að vélin gæti snúist undir sjálfri sérð en meira ekki. Var þá farið að þurka hana, með því að láta hana ganga skammhleypta, eins og fyr segir.

Á meðan var svo vél II hreinsuð upp og mæld á sama hátt og vél I.

Það kom í ljós, að skammhlaup hafði orðið við úttök statorvindinga hennar og einnig hafði slegið yfir einangrara á enda háspennustrengs niðri í gryfjunni Þetta var allt hreinsað upp og þurkað, eins og tök voru á og var vélin síðan mæld og reyndist hún þétt eins og hin vélin, en rök af vatnsaustrinum. Ekki var nóg vatnsrennsli að inntakinu, til þess að hægt væri að þurka II vélina líka, og var það þá látið bíða þar til seinna um daginn.

Klukkan um 8 var svo spenna tekin upp á vél I og hún látin ganga fyrir álagið á stöðvarspenni og Staðaveitu.

Strax og bjart var orðið og síminn opnaður á Húsavík, var hringt þangað eftir mönnum til þess að hreinsa úr lóninu. Einnig var safnað mönnum í sveitinni, eftir því sem til náðist. Milli 2o og 3o menn komu frá Húsavík um hádegið þann 5. og var þá farið að ryðja göng meðfram stíflunni vestan frá yfirfallinu, svo að hægt væri að fá meira vatn í pípuna.

Tiltölulega fljótt gekk að ryðja milli yfirfallsins og flóðgáttarinnar, sem opin var, þar sem að hægt var að láta ruðninginn berast út um hana með vatninu. Erfiðara var að ryðja milli flóðgáttarinnar og þróarinnar, þar sem að moka varð ruðningnum yfir stífluna að nokkru leiti og að nokkru var hægt að fleyta ruðningnum inn í inntaksþróna og þar út um skarð og í skurðinn, sem liggur niður úr vesturþrónni. Ekki var vogandi að nota sprengiefni svo nærri stíflunni, svo að allan ís varð að höggva sundur með járnum en það var ekkert áhlaupaverk, þar sem að hann var yfir 2 fet á þykkt þar sem hann var þykkastur og mörg lög, hvert ofan á öðru og jakarnir upp á rönd og í öllum mögulegum stellingum. Þrátt fyrir það, að verkamönnum væri skipt í vaktir og unnið væri sleytulaust að þessu, var ekki komið nóg vatnsrennsli að inntakinu handa vél I fyr en kl. um 5 þann 6/12. Þá var Húsavík tengd við, og farið að þurka vél II á sama hátt og vél I áður. Klukkan tæplega 8 var svo farið að tengja hluta af Akureyri við, og það smá aukið eftir því sem skurðurinn meðfram stíflunni var breikkaður og dypkaður meira. Klukkan rúmlega 13 var svo vél II fösuð við, en vél I tekin út og ekki fösuð við aftur fyr en um kl. 17, en þá var vatnið orðið lítið eitt meira en handa vél II einni. Kl. um 19 var svo álagið orðið um 39oo kw. og gat nú vatnið runnið hindrunarlítið vegna krapsins, meðfram stíflunni. Ekki var hægt að fá meira vatn þessa leið meðfram stíflunni, þar sem að svo grunnt er vestur undir yfirfallinu, enda barst nú mikill ísruðningur inn í inntakið og erfitt reyndist að fleyta honum út úr þrónni, þar sem að svo mikið af þessu vatni var notað á vélarnar. Var þá farið að gera tilraun til að ryðja kvíslina austan við hólmann, sem er fyrir ofan stífluna.

Fyrst var gerður smá skurður alla leið frá flóðgáttinni, upp kvíslina og upp í ána, þar sem hún var auð, ofan við hólmann. Öllum greftri varð að moka upp úr þessum skurði, þar sem að ekki var hægt að fá rennsli í hann fyr en að hann var kominn alla leið. Skurður þessi var grunnur fyrst í stað, eða niður að vatnsborði þar sem að hann var grynnstur. Að vísu voru bakkar hans sumstaðar nokkuð háir, eða allt að 2 m. þar sem að krap- og íshrönglið var hæst í lóninu og kvíslinni. Þegar skurðurinn var kominn alla leið var orðið svo dimmt um kvoldið þann 6. að ekki voru tiltök að vinna við hann um nóttina, þar sem að þetta var orðið svo fjærri stífluljósunum, en hættulegt gat verið að klöngrast um í myrkrinu innan um sprungur og jakahröngl. Menn voru líka orðnir allþreyttir og í þörf fyrir hvíld, og þar sem að vélarnar gátu nú unnið með yfir 3ooo kw krafti var það ráð tekið að hvílast þar til í birtingu næsta dag. Klukkan 8 var svo hafist handa á ný, skurðurinn breikkaður og dypkaður, og gekk nú allt miklu betur, þar sem að vatnið sem komið var í skurðinn bar allan ruðninginn burtu. Svo þegar á daginn leið, var svo farið að nota sprengiefni við að stækka skurðinn, og var hann gerður 5-8 m. breiður og dýpkaður til botns, en kvíslin var full til botns af jökum og krapi. Í myrkri um kvöldið var eftir c.a. 2om. kafli af kvíslinni óhreinsaður, en vatnsstraumurinn var þá orðinn það mikill í skurðinum að hægt var að lesta vélarnar um c.a. 4ooo kw. en það var nóg til að halda spennu þar sem að Hjalteyrarverksmiðjan sendi straum til Ak. og næturhitinn hjá notendum á Ak. var ekki hafður í sambandi.

Alltaf þurfti að hafa menn til að hreinsa jaka úr inntakinu, bæði nótt og dag þar til að austurkvíslin var orðin hrein og auð.

Að kvöldi þess 7. voru svo húsvíkingarnir sendir heim til sín, en daginn eftir var svo lokið við að hreinsa kvíslina, og var það gert af vélstjórum og mönnum héðan úr sveitinni. Þessu var lokið í myrkri um kvöldið.

Auk þess sem áður er sagt, flæddi áin um kvöldið 4. des yfir hólmann vestan stöðvarinnar kring um vatnsmælingarþróna, yfir hana og fyllti hana af krapi og jökum, svo að ekki var hægt í bráðina að lesa af vatnshæðina í henni. Þetta flóð rann allaleið að vesturvegg stöðvarinnar, hlóð þar upp stórum bing af ruðningi og rann svo út í sográsina, norðan við stöðina. Hægt var að sjá á kletti, rétt hjá mælingaþrónni, hvað flóðið hafði farið hátt þar, en það var í koda 76,74 en yfir svo mikla hæð eru engar töflur til hjá okkur.

Innig flæddi áin upp í áveituskurð staðamanna og heim undir húsið á Kambi, en olli þar engum skemmdum.

Hólminn hjá hinu fyrirhugaða stöðvarhúsi er allur undir ruðningi; flætt hafði yfir grjótstífluna fyrir ofan hann og einnig yfir tréstífluna.

Nokkuð af krapi hefir hlaðist upp við dæluskúrinn, en ekki hreyft hann, en sográsin er að öðru leiti mikið til hrein og auð, þar sem að stefna flóðsins hefir verið aðallega yfir hólmann, vestan við sográsina.

Dægrin á undan flóðinu hafði vatnið í ánni verið lítið eitt minna en venjmalt, þó ekki minna en það, sem oft gerist, vegna vestan áttar við Mývatn.

Eftir upplýsingum, sem ég hefi fengið úr Laxárdal, hefir flóðið átt upptök sín við Sogið, sennileg á Árgilsstaðaflóa. Þar er tiltölulega lítið jafnlendi fyrir vatn að safnast saman, enda auðséð á flóðinu, að það hefir ekki verið samsafnað á stóru svæði, þar sem að það stóð svo stutta stund, aðeins nokkrar mínútur, innan við 5 mínútur, sem flæddi inn í stöðina. Miklar skarir voru að ánni allri í Laxárdal, áður en flóðið kom, og rekið hafði í ána mikið krap á Birningsstaðaflóa, svo að hún hafði flætt upp á engjar þar efra. Allar skarirnar meðan við Sog höfðu sópast með flóðinu, og magn þess af krapi og ís, þannig aukist á leiðinni niður að stöðinni. Ekki hafði neitt hreyfst í þetta skipti, það sem rekið hafði í Birningsstaðaflóann, enda varla mögulegt, þar sem að þrengslin eru svo mikil, að vatnið hlýtur að lyfta krapinu, sem þar safnast saman og renna undir það, án þess að krapið hlaupi fram með vatninu.

Eftir er að rannsaka nánar þar efra, upptök flóðsins, og verður það gert, þegar tími er til og veður skánar, því að eflaust verður hægt að sjá á bökkum árinnar íshröngl[ið], alla leiðina upp að upptökum flóðsins.

Ég vil geta þess hér, að eftir að áin hafði flætt s.l. vor yfir veginn fyrir neðan fossinn uppi í gljúfrunum, var til athugunar hvað hægt væri að gera til þess að fyrirbyggja slík flóð í framtíðinni. Kom þá til greina, annaðhvort að gera varnargarð úr steinsteypu meðfram veginum, eða að stífla austurkvíslina rétt neðan við fossinn með stórgrýti, eða á annan hátt.

Mér og rafveitustjóra kom saman um að seinni leiðin væri heppilegri, enda erfitt um sement í steyptan garð, vegna gjaldeyrisörðugleika, og auk þess virtist upplagt, að fá stórgrýti í stíflu, þegar farið væri að sprengja vegna nýju virkjunarinnar. Svo þegar "Stoð" fór að vinna hér, samdi ég við fram-framkvæmdarstjórann hér á staðnum, um að hann legði til grjót í þessa stíflu, en Laxárvirkjunin sæi um bíla til að aka grjótinu á staðinn og sæi að öðru leiti um að gera stífluna. Þetta virtist vera til hagræðis fyrir báða aðila "Stoð" þurfti ekki að kaupa bíla til að aka burtu grjótinu, sem búið var að losa og Laxárvirkjunin þurfti ekki að kosta til að láta sprengja grjót og láta það upp á bíla, þar sem að það mundi verða gert með krana, skammt frá staðnum. Þetta var allt gert með samþykki eftirlitsmansins hér, Rögnvaldar Þorlákssonar. Svo þegar fór að líða á haustið, og ekki komu nein fyrirmæli um að senda bíla til að sækja stórgrýtið, en talað hafði verið um, að ég yrði látinn vita, þegar þar að kæmi, áréttaði ég þetta aftur við framkvæmdastjóran sagðist hann þá mundu gera þetta fljótlega og láta mig vita þegar þar að kæmi

Sagði ég þá, að ekki mundi koma að sök, þó að þetta drægist eitthvað, aðeins ef tryggt væri að þessu væri lokið fyrir vorflóðin, og sagði hann þá að ég mætti treysta því. Svo fór, að Stoð hætti vinnu hér á þessu ári, án þess byrjað væri á þessu verki,og spursmál,hvort hægt er að ljúka því, fyrir flóðin næsta vor. Á því sem hér hefir verið ritað sést að ekki var búist við flóði að vetrinum,enda hefir ekkert slíkt flóð komið hér,síðan stöðin var reyst.

Þetta hefi ég viljað taka fram,til þess að svara þeim,sem vildu spyrja hvers vegna ekki væri búið að fyrirbyggja það,að vatn gæti komist inn í stöðina. Eg vil líka benda á,að jafnvel þótt þessi stífla hefði verið komin,hefði þetta flóð samt sem áður fyllt lónið og rekstrarstöðvun hefði orðið jafn löng af þeim sökum,því að þótt vélarnar skemmdust ekki,sem telja má eins og hvert annað lán,þá tafði hreinsun og þurkun þeirra lítið sem ekkert fyrir því,að vinnsla hæfist á ný.

Svo er annað mál,hvernig hægt er að koma í veg fyrir slík flóð í framtíðinni,því að vitanlegt er að þetta getur komið fyrir aftur og valdið rekstrarstöðvun bæði gömlu og nýju virkjunarinnar.

Ég tel,að um tvennt sé að ræða,annaðhvort að sprengja allar stíflur,sem myndast í ánni,áður en vatn hleðst upp fyrir ofan þær,eða að gera stíflur virkjananna þannig úr garði, að slík flóð komi ekki að sök,eða hvorttveggja. Þetta verður að athuga,áður en nýja stíflan er byggð, og eins áður en aðgerð fer fram á gömlu stíflunni,em það þarf að gera strax og nýja stöðin er tekin til starfa.

Laxárvirkjun, 9.-12.-195o
Ágúst Halblaub

Appendix 4 Information from Jarðabók

Table 5.1 Information from Jarðabók about sediment transport from the Laxá onto the land around it, flooding and some additional information.

Staður/Location	Grjót/ Rocks	Sandur/ Sand	Lýsing í Jarðabók/ Description	Bls./ page
Laxamyre			Silúngsveiði í vatninu, Laxárósi og sjónum með dráttar og lagnetjum að nokkru gagni, hefur áður ágæta góð verið, einkanlega í sjónum, sem Laxá hefur spilt og borið þar í sand og grynníngar. Túninu grandar vatnsuppgángur og sandfok, þó er það ekki ennþá til stórrar eyðileggíngar.	251
Myrar sel		X	Túnið er bæði lítið og sendið og valla teljandi. Enginu spillir Laxá með sandsáburði.	252
Nupar	X	X	Engjarnar fordjarfar Laxá stórlega með grjóts og sands áburði, en hefur þó miklu af því með stórerfiði verið af komið, er þó síðan mjög ilt að vinna og liggur undir sama skaða.	219
Knutstader/ Hnutstader		X	Enginu spillir Laxá öðru hvörju með leirs, sands og mosa áburði, en sprettur upp aftur þess í milli.	166
Tiorn		X	Enginu spillir Laxá einstöku sinnum með sandsáburði, sem þó hefur orðið afræktað, og sprengir upp grasrótina með stórum stykkjum eður fléttum.	169
Gardur			Túninu spillir grjótfok úr uppblásnum melhólum innan garða, sem þó verður með erfiði afræktað. Engið spillist af vatnsgreftri og ágángi Laxár öðru h<v>örju, þó ekki til stóreyðileggingar.	170
Hafralækur			Enginu spillir Laxá með vatnságangi, sem sprengir upp jörðina með stórspildum eður flettum og fleytir sumum í burt, en sumar síga niður aftur.	171
Hage	X	X	Enginu spillir laxá með grjóts og sands áburði, en hefur þó orðið hingað til með stórerfiði í hauga saman komið.	218
Holmavad	X	X	Enginu spillir Laxá með grjóts og sands áburði, sem þó verður nokkurneginn afræktað híngað til.	172
Ytrafiall	X		Útigangur svipull fyrir fannlögum og ágángi úr Laxá, sem hleypur stundum vor og haust oftast nær alt í kringum völlinn oft og tíðum, so að hjeðan verður hvorki komist á skipi nje hestum, ... Hraun er undir öllu enginu, og grandar því grjótsuppgángur til stórs skaða, því Laxá hleypur í þessa urð og á engið, og þvær sá vatnsagi moldina undan grasrótinni úr hrauninu, hvar af hún visnar.	172
Ytste Hvammur	X	X	Enginu spillir Laxá með grjóts og sands áburði til stórskaða, ...	217
Midhvammur	X		Enginu spillir Laxá með grjótsáburði, en þó ekki til merkilegs skaða híngað til.	216
Hraun		X	Enginu grandar Laxá, sem áður segir um Klömbur.	216

Brecka		X	Enginu spillir Laxá til stórs skaða ut supra[33,34].	215
Klaumbur		X	Enginu spillir Laxá með sandsáburði og hleypir upp grasrótinni með flettum oftlega til skaða merkilegs, sem að á eykst meir og meir.	214
Mule	X		Enginu spillir grjótsuppgángur og sumstaðar vatn, sem jetur úr rótina, einkanlega því sem er í Laxá eður þeim eyjum sem þar liggja, og er þaðan ilt að flytja heyið yfir ána. Uthagarnir eru nægir á sumrin, en liggja mestir undir ísum á veturna á undirlendinu.	196
Greniadarstadur	X	X	Túninu spillir bæjarlækurinn með vatnságángi, sem gjörir mýri og jetur úr rótina, og so ber hann á það leir í vatnavöxtum, þó er þetta ennþá ekki mikil spjöll en sjer út til meiri skaða með framtíðinni. Enginu spillir Laxá oftlega með grjóts, sands og mosa áburði, sem híngað til hefur þó orðið með stórerfiði af komið. Þar með hleypur hún í hraunið, sem er undir öllu þessu engi, og sprengir upp stórar flettur, fleytir sumum burt, en hinar síga niður aftur, þar með er engið grýtt og seinunnið, annars gott og grasgefið að öllu.	199
Presthvammur	X	X	Enginu spillir grjótsuppgángur og leirs og sands áburður úr Laxá.	214
Bruar	X	X	Laxveiði í Laxá hefur áður verið að nokkru gagni með lagneti undir einum fossi fyrir neðan gljúfurin, sú veiði er ekki til hlunninda teljandi undir xx ár, og verður nú ekki brúkuð, því áin bar sand og grynníngar í fossinn á næstliðnum vetri. Engið sem undir jörðina hefur legið er stórlega fordjarfað af grjóts og sands áburði úr Laxá, og verður ekki slegið nema með blettum, ...	201
Kasthvammur	X	X	Túninu spilla tveir lækir öðru hvörju með grjótsáburði, sem þó hefur orðið híngað til mestan part af hreinsað. Engið er snögglent og spillist þar með af grjóts og sands áburði fyrir Laxá, sem áður segir um Hóla.	210
Halldorstader			Enginu spilli Laxá öðru hvörju, sem hleypur undir grasrótina og hleypir upp stórum hnausum og flettum, og grær so upp aftur þess á milli.	204
Þveraa	X	X	Enginu spillir Laxá með grjóts og sands áburði, og einna mest á næstliðna vetri, og verður sumt afræktað með stóru erfiði og mann fjölda, en sumt liggur undir sama áfalli.	205
Holar	X	X	Hætt er við að skriða hlaupi á túnið, sem híngað til hefur orðið með garði við varðað, og so af vatni, sem jetur úr rótina. Enginu spillir Laxá með grjóts og sands áburði.	209
Hofstader	X	X	Engið er í áðursögðum hólmum í Laxá og spillist af grjóts og sands áburði ...	243

[33] Ut supra: Latin phrase. Definition: as (shown or described) above - used in texts to refer to a preceding discussion or illustration. ('Ut Supra \| Definition of Ut Supra by Merriam-Webster', n.d.)

[34] Hér vitnað í texta um Klaumbur.

Helluvad		X	Túninu spillir leirvatn í leysíngum á vorin, sem jetur úr rótina. Engjar öngvar, nema nokkuð litlar í sömu hólmum í Laxá, sem hún spillir með landbroti og sandsáburði.	223
Arnarvatn		X	Enginu spillir Kráká með sandsáburði, og er hún stífluð af því með stórerfiði.	227
Skutustader			Útigangur mjög svipull fyrir fannlögum og þó einkanlega fyrir ágángi úr Kráká, sem oft og tíðum hleypir því í svell, sem liggur á til vordaga, ...	229
Sveinstrønd			Engið er mjög votunnið og blautt, so ekki verður hestum að komið, og verða menn að bera heyið til þeirra lángan veg. Það er enginu að meini að Kráká hleypur yfir það jafnlega og liggur so lengi á því sem hún er ekki af stífluð, hvað eð kostar stórerfiði og verður naumlega til leiðar komið, og er einn stíflugarðurinn 40 faðma lángur.	226
Græna vatn			Útigángur hefur verið góður, en spillist mjög af sandfoki, ... Túninu spillir Grænavatn með landbroti sem á eykst meir og meir. Kráká hleypur á engið, og verður að stífla hana af á vorin, sem nokkuð þykir erfitt.	231
Gardur			Túninu spillir sandfok öðru hvörju, er þar með lítið og sprettur lítt fyrir grjóti í jörðunni. Kráká gengu ryfir engið, sem áður segir um Grænavatn, það spillist og af leir og rotum.	233
Balldurs Heimur			Túninu spillir sandfok til stórskaða og hefur eyðilagst af því undir tveggja daga slátt, og horfir til meiri skaða. Kráká gengur á engið, og verður hana að stífla á vorin, sem kostar ómak og erfiði, annars verður ekki engið slegið.	225

Lava: Hætt er kvikfje fyrir hraungjám, sem oft verður mein að. (Tiorn, bls. 169)

Sandfok: Túninu spillir sandfok til stórskaða, og horfir til eyðileggíngar með framtíðinni. (Vindbelgur, bls. 241, við Mývatn).

Figure 5.1 Area around the upper end of Birningsstaðaflói. An example of areas where the Laxá has filled the lower lying parts of the lava field with sediment and nutrition, creating ideal location for fields. The difference between unflooded lava and flooded lava is very distinct.

Figure 5.2 Area downstream from the Laxá Canyon. An example of areas where the Laxá has filled the lower lying parts of the lava field with sediment and nutrition, creating ideal location for fields. The difference between unflooded lava and flooded lava is very distinct.

Appendix 5 Birningsstaðaflói – additional info

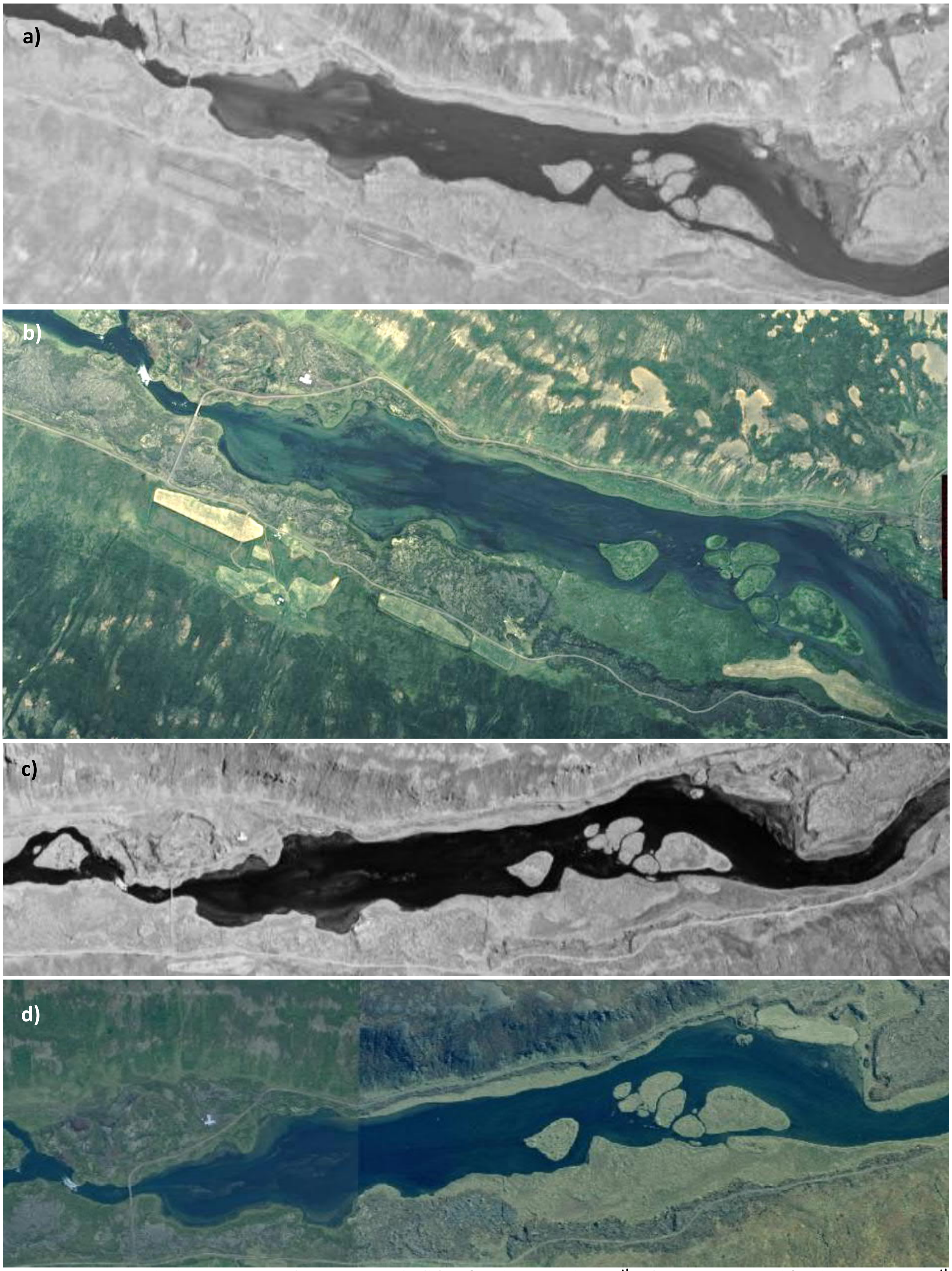

Figure 5.3 Aerial photographs of Birningsstaðaflói. a) Taken on the 16th of August 1979, b) taken on the 30th of August 1982, c) taken on the 25th of July 1990 (Landmælingar Íslands, n.d.) and d) taken in 2007 (downstream part) and 2009 (Loftmyndir ehf, n.d.-a).

Landsvirkjun

Háaleitisbraut 68
103 Reykjavik
landsvirkjun.is

landsvirkjun@lv.is
Sími: 515 90 00