Riverine discharge and conductivity in rivers draining potential eruptions sites within the Vatnajökull glacier. Background data and observations.

Eydís Salome Eiríksdóttir, Iwona Monika Galeczka, Rebecca Anna Neely and Sigurdur Reynir Gíslason

Background conductivity in Icelandic rivers.

The conductivity of river waters reflects water discharge, temperature, dissolved charged constituents and potentially dissolved volatiles and metals from eruption within or in the vicinity of the Vatnajökull Glacier. Under normal conditions conductivity is inversely correlated to discharge but increased discharge due to volcanic unrest or floods from geothermal areas underneath glaciers cause conductivity to increase.

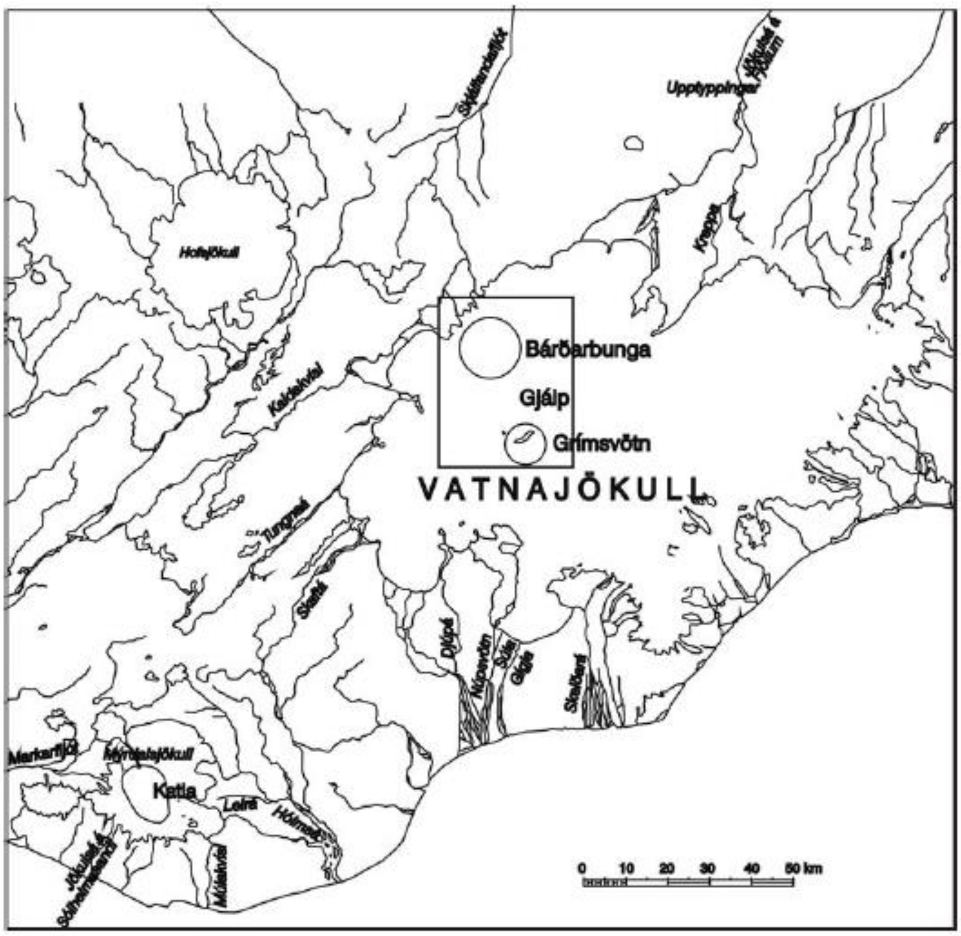

Figure 1. Location of rivers draining Vatnajökull and Mýrdalsjökull. Data from some of these rivers are in table 1.

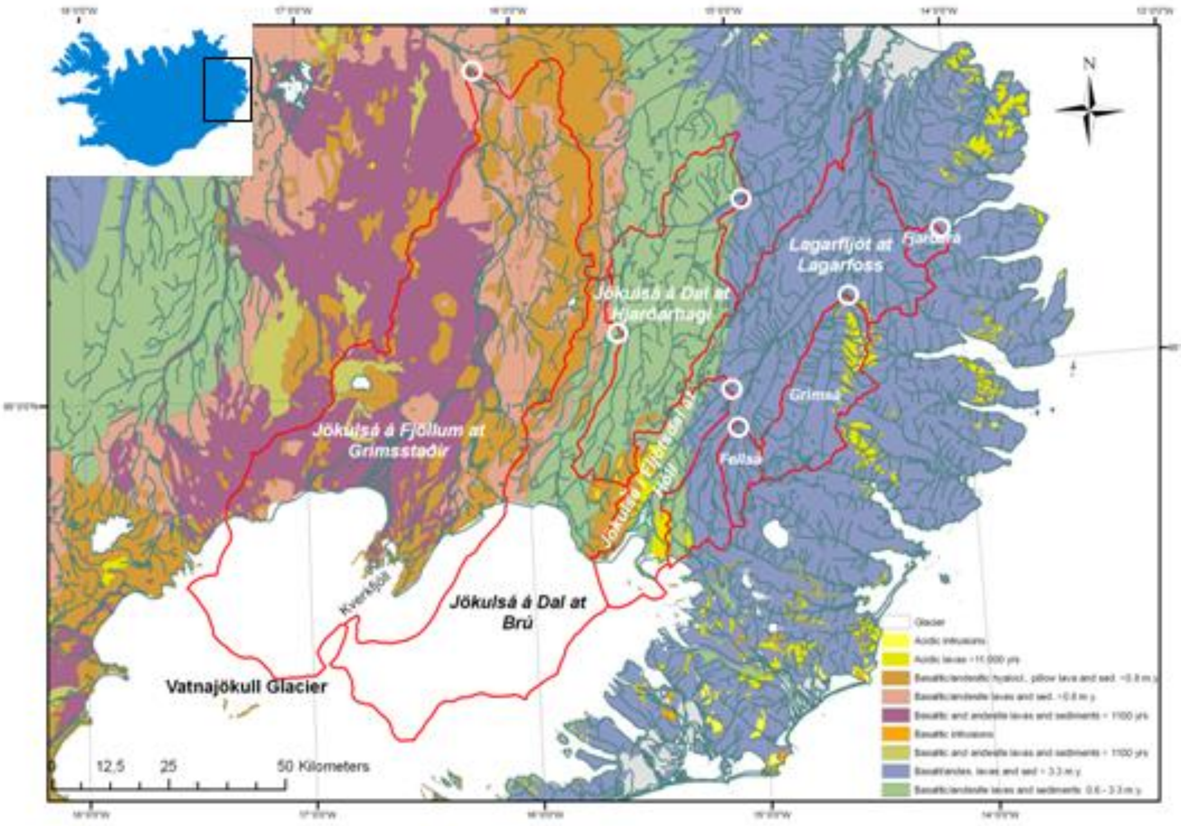

Figure 2. Location of rivers draining northern part of Vatnajökull and few non-glacial rivers in eastern Iceland. Data from these rivers are in table 1.

Monitoring of glacial rivers draining Vatnajökull and Mýrdalsjökull (Gislason et al, 2004a; 2004b; 2007; Kristmannsdóttir et al., 2006) have shown that the chemical composition of these rivers vary seasonally, and even daily, as a response to seasonal glacial melting. This is reflected in the conductivity of the river water which tends to be high at low discharge and decreases as discharge increases. Table 1 shows average discharge and conductivity of selected rivers in Iceland.

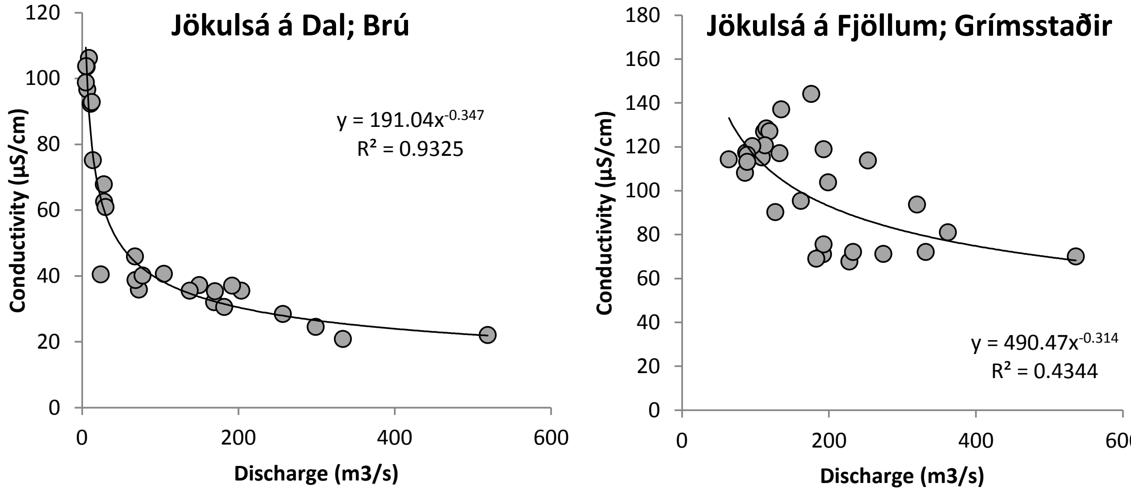

Fig. 3. There is an inverse relationship between discharge and conductivity at normal conditions.

Table 1. Average discharge and conductivity of rivers in Iceland. Rivers draining Vatnajökull glacier are in red (Gislason et al 2004a; 2004b; Gislason et al. 2007; Kristmannsdottir et al. 2006)

Sample	**Discharge**	**Conductivity**
Number	**m³/sek**	**µS/cm**
Fellsá	10.4	36.2
Fjarðará v/ Fjarðarselsvirkjun	3.8	33.1
Grímsá	30.3	55.0
Jökulsá á Dal; Brú	114.7	63.9
Jökulsá á Dal; Hjarðarhagi	156.7	62.3
Jökulsá á Fjöllum; Grímsstaðir	176.6	101.0
Jökulsá í Fljótsdal; Hóll	46.6	77.4
Lagarfljót v/ Lagarfossvirkjun	133.2	55.6
Sog, Þrastarlundur	97.7	71.5
Brúará, Efstidalur	36.1	44.7
Tungufljót, Faxi	38.2	49.7
Hvítá, Brúarhlöð	118	57.3
Ölfusá, Selfoss	340	69.0
Þjórsá, Sandafell	305	78.8
Þjórsá, Urriðafoss	333	74.9
Ytri Rangá, Árbæjarfoss	42.3	109
Skeiðará	211	221
Gígjukvísl	25.2	73.3
Súla	44.4	67.8
Tungná, Hrauneyjafossstöð	215	82
Tungná, Botnaver	40	49
Skaftá, Sveinstind	139	93
Skaftá, Skaftárdalur	133	93

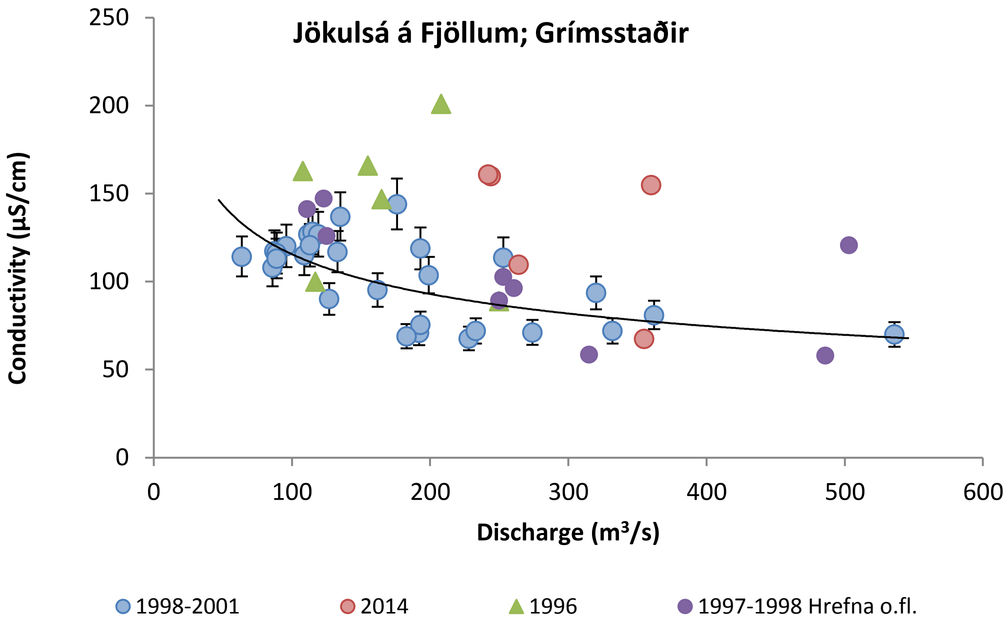

Fig. 4. Discharge dependency of conductivity in Jökulsá á Fjöllum at Grímsstaðir from different monitoring campaigns.

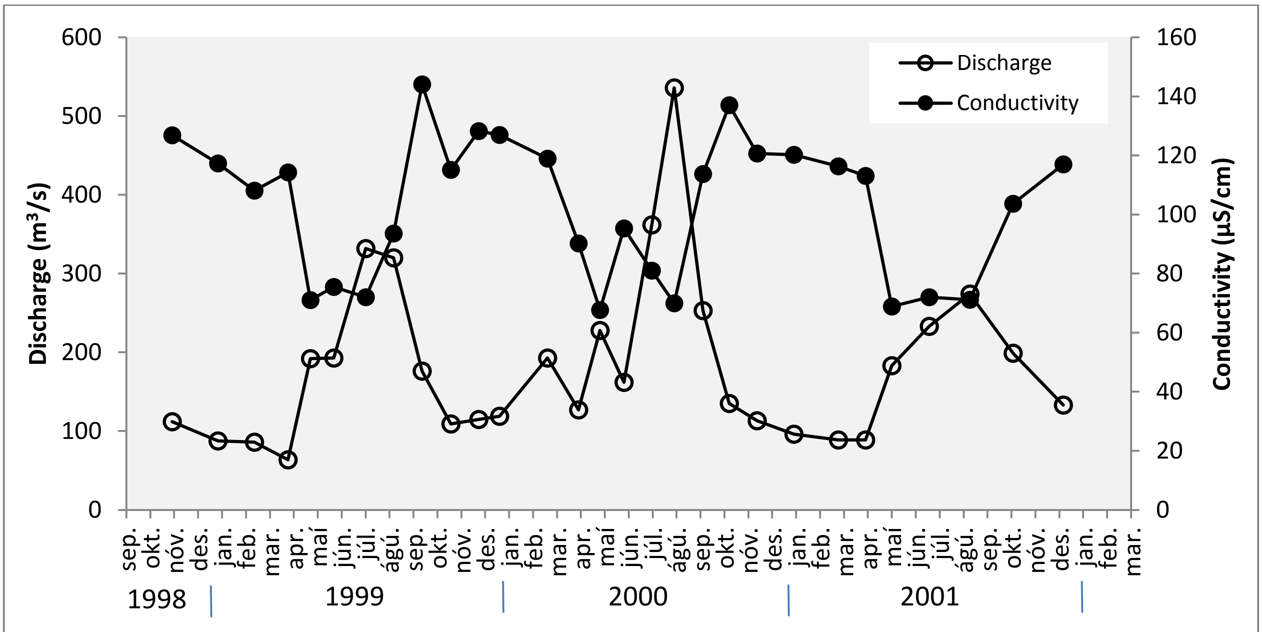

Fig. 5. Temporal changes in discharge and conductivity in Jökulsá á Fjöllum at Grímsstaðir. There is an inverse relationship between the two parameters at normal conditions.

Spatial variation in alkalinity in Iceland.

Riverine alkalinity is a measurement of the quantity of water-rock interaction that has taken place at each site. Alkalinity is an indirect measurement of the concentration of dissolved CO_2 in the water, but its concentration increases with increased chemical weathering. Dissolved CO_2 is a charged ion in neutral water (HCO_3^-) and is a large portion of the negatively charged ions making up the conductivity. Therefore alkalinity and conductivity are related under normal conditions. At normal conditions, when alkalinity and conductivity are proportional, the spatial distribution of alkalinity in rivers as shown on figure 3 reflects the conductivity in these waters (Oskarsdottir et al., 2011). The bedrock in the volcanic zone is made mostly of glassy basalt that is highly reactive when it comes in contact with water. Rivers draining the volcanic zone therefore have high alkalinity and conductivity compared with rivers draining older bedrock.

Conductivity of glacial meltwater due to volcanic eruptions however is not only due to dissolved CO_2 but rather due to other more soluble ions such as Cl^-, SO_4^{2-} and F^- brought by the volcanic gases to the water system. Water-rock interactions are relatively slow and therefore alkalinity does not usually have enough time to build up in hours before it is flooded away.

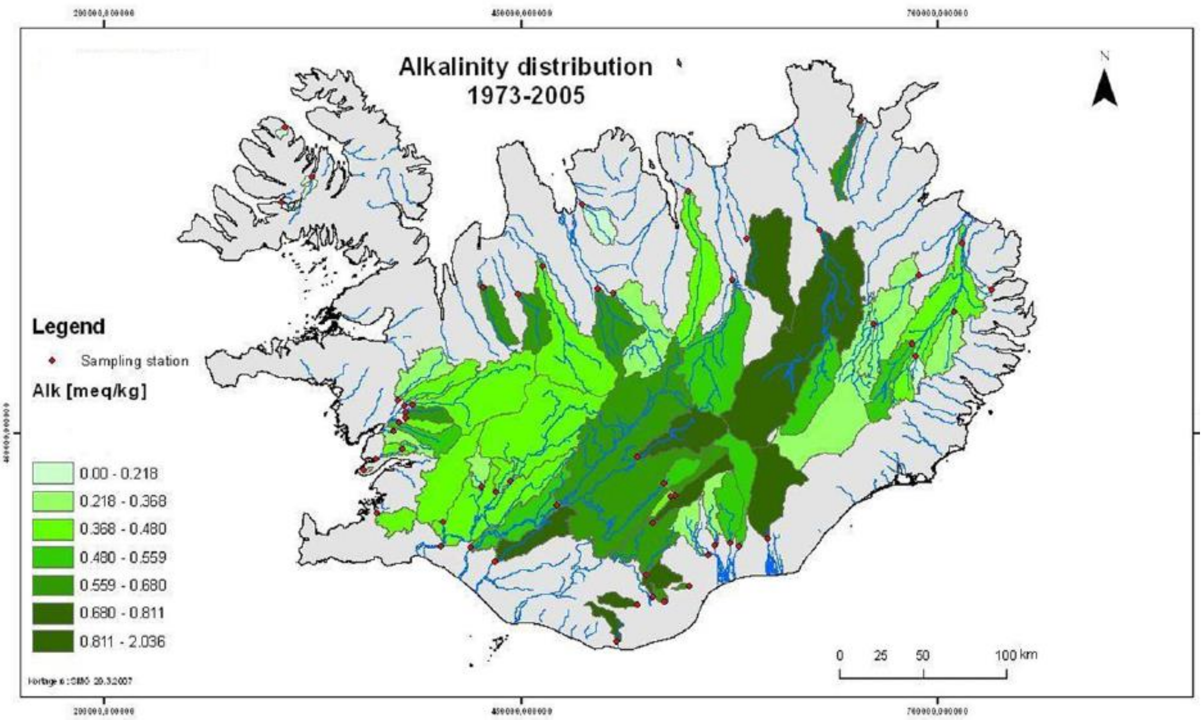

Fig. 6. Spatial distribution of alkalinity in Icelandic river waters. Alkalinity and conductivity are correlated at normal conditions but not in meltwater due to volcanic eruptions.

What can be expected in case of a flood in Vatnajökull due to eruption?

In this chapter we present data collected during glacial floods, with and without eruption.

Gjálp eruption and flood 1996

During the Gjálp eruption, waters were collected in the Grímsvötn lake for almost a month. Some leakage of geothermal water from the lake had taken place few days before main flood peak indicated by increased conductivity (see table below). When the discharge increased from 75 to 8100 m^3/s, the conductivity increased almost 3.5 times and it was stable during the rest of the flood as it can be seen in table and plot below. Data taken from Gislason et al, 2002.

Table 2. Discharge and conductivity in Skeiðará river during the Gjálp 1996 eruption.

Sample	River	Date and time	Days from eruption	Discharg. ***m^3/s	conductivity µS/Cm
96-S004	Skeiðará	06/10/1992 08:55	6.5	210	72
96-S007	Skeiðará	07/10/1992 18:20	7.9	205	80
96-S017	Skeiðará	12/10/1992 18:15	12.9	119	88
96-S024	Skeiðará	16/10/1992 10:08	16.5	158	82
96-S035	Skeiðará	21/10/1992 17:00	21.8	139	84
96-S044	Skeiðará	28/10/1992 09:15	28.5	108	96
96-S054	Skeiðará	02/11/1992 09:40	33.5	75	114
96-S056	Skeiðará	03/11/1992 10:40	34.5	75	115
96-S057	Skeiðará	03/11/1992 17:00	34.8	75	115
96-S057b	Skeiðará	04/11/1992 03:00	35.2	75	138
96-S058	Skeiðará	04/11/1992 09:25	35.5	***8100	472
96-S059	Skeiðará	04/11/1992 13:15	35.7	22200	486
96-S060	Skeiðará	04/11/1992 16:40	35.8	30800	479
96-S061	Skeiðará	04/11/1992 21:45	36.0	46600	402
96-S062	Skeiðará	05/11/1992 00:30	36.1	51900	422
96-S063	Skeiðará	05/11/1992 03:15	36.2	45000	412
96-S064	Skeiðará	05/11/1992 06:45	36.4	29700	401
96-S065	Skeiðará	05/11/1992 10:24	36.5	16300	391
96-S067	Skeiðará	05/11/1992 17:00	36.8	5800	375
96-S069	Skeiðará	06/11/1992 11:00	37.6	450	385

*** Flood discharges are integrated discharge of all the river channels

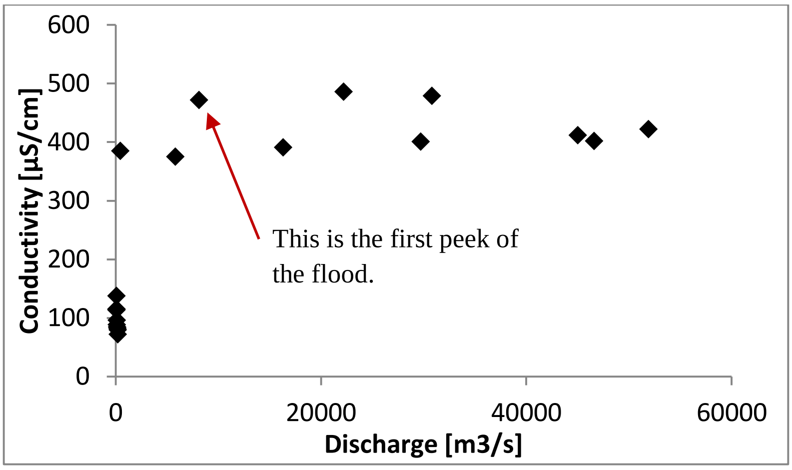

Fig. 7. Discharge vs. conductivity during Skeiðará flood in 1996 following the Gjálp eruption. Flood water was between 400 and 500 µS/cm and background conductivity around 100 µS/cm.

Skaftá glacial flood in 2002

During the Skafta 2002 flood draining eastern Skafta cauldron, the conductivity increased with discharge (Table 3 and Fig. 8). This flood was not associated with a volcanic eruption. For comparison, we show the conductivity vs. discharge for the normal stage of the river during the 2003-2006 monitoring period excluding all small glacier floods. There is substantial difference between discharge and conductivity dependence during normal stage of the river and during the glacial flood.

Table 3. Discharge and conductivity in Skaftá during a flood in the eastern Skaftá cauldrons in 2002 (Gislason et al. 2007).

Sample number Númer (Sample)	Location)	Dagsetning (Date)	Disch. m^3/sek	Conductivity µS/m
02SK001	Ása-Eldvatn af brú	18.9.2002 18:20		
02SK001	Ása-Eldvatn, Sveinstindur	18.9.2002 08:44	349	209
02SK002	Skaftá, Sveinstindur	18.9.2002 16:40	522	206
02SK003	Skaftá, Sveinstindur	18.9.2002 23:30	603	210
02SK004	Skaftá, Sveinstindur	19.9.2002 11:00	625	214
02SK005	Skaftá, Sveinstindur	19.9.2002 19:30	628	208
02SK006	Skaftá, Sveinstindur	20.9.2002 08:25	517	228
	Skaftá við upptök	20.9.2002 15:05		
02SK007	Skaftá við upptök, Sveinstindur	20.9.2002 19:35		352
02SK008	Skaftá, Sveinstindur	20.9.2002 20:50	452	316
02SK009	Skaftá, Sveinstindur	21.9.2002 20:30	312	138
02SK010	Skaftá, Sveinstindur	22.9.2002 13:00	237	90
02SK011	Skaftá, Sveinstindur	23.9.2002 13:18	172	84
02SK012	Skaftá, Sveinstindur	24.9.2002 09:50	145	67
02SK013	Skaftá, Sveinstindur	25.9.2002 08:30	137	68

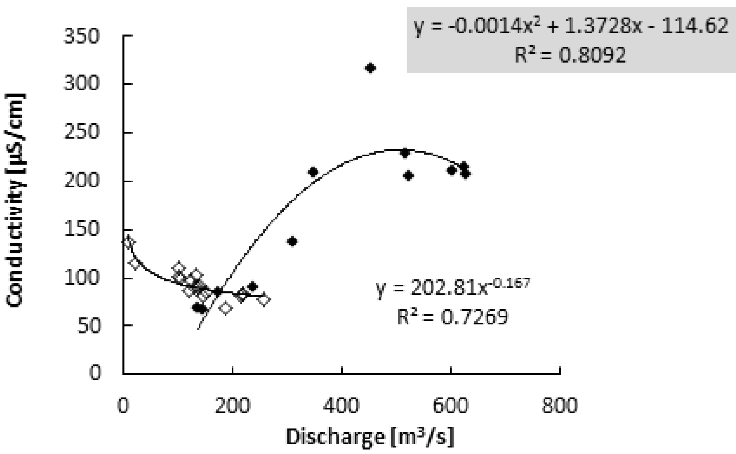

Fig. 8. Conductivity vs. discharge for the Skaftá at Sveinstindur monitoring station. Black filled diamonds (equation gray background) represent conditions during Skaftá 2002 glacial flood open diamonds (transparent equations) represent normal stage of the river during 2003-2006 monitoring period excluding floods.

Grímsvötn eruption and Skeiðará flood Oktober 2004

On 28th October 2004 Lake Grímsvötn started draining into River Skeiðará. Following four days of draining, with subsequent rise in discharge and conductivity, an eruption started in Lake Grímsvötn on 1st November. The volume of the flood peak was 0.45 km^3 and further 0.35 km^3 of floodwater discharged until 7th of December as a result of melting due to the eruption. Data taken from chapter 5 in Sigfusson 2009.

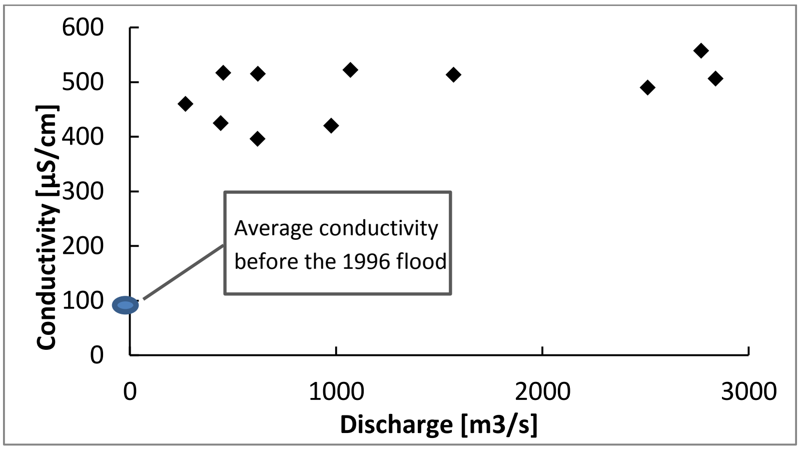

Fig. 9. Discharge vs. conductivity during the Skeiðará flood in 2004. Flood water was between 400 and 500 µS/cm.

Eyjafjallajökull April 2010 eruption, Markarfljót flood.

Markarfljót flooded shortly after Eyjafjallajökull started erupting on the 14th of April 2010. No discharge data are available but this is how the conductivity increased with time.

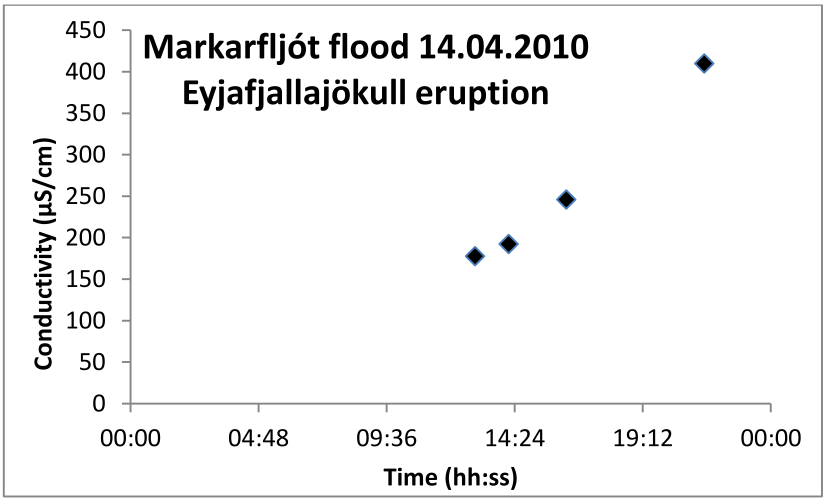

Fig. 10. Conductivity during the onset of the flood in Markarfjót, at the new bridge, during Eyjafjallajökull eruption April 14th 2010.

Múlakvísl flood July 2011

During the Múlakvísl flood in 2011, geothermal water released from the Katla cauldrons on Mýrdalsjökull caused a fivefold increase of the river water conductivity during the peak of the flood. The flood was not related to volcanic unrest but due to sub glacial geothermal melting. Unfortunately, no real time discharge measurements were carried out due to the destruction of the bridge where discharge meter was located. Data taken from Galeczka et al. 2014.

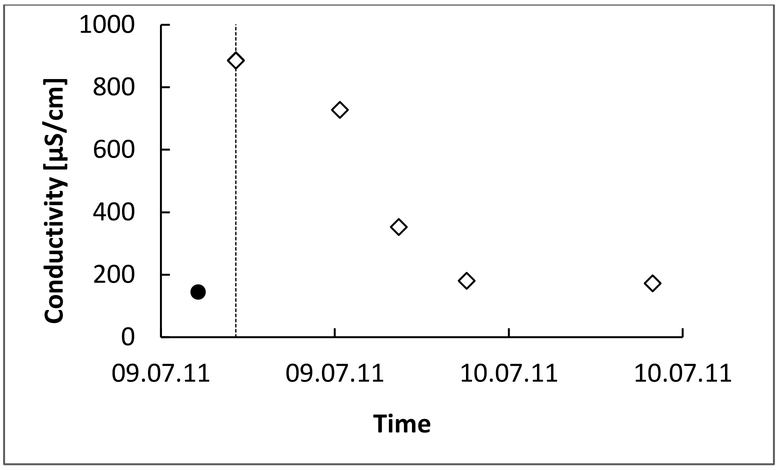

Fig. 11. Conductivity vs. time during the Múlakvísl 2011 glacial flood. Vertical line represents the flood peak, black filled dot shows the background conductivity measured few months after the flood.

Kaldakvísl July 2011

In the Kaldakvísl flood in July 2011, conductivity increased during the peak of the flood, similarly as in Múlakvísl. The flood was caused by draining Hamarinn cauldrons in NW part of Vatnajökull glacier and not by volcanic unrest. Data from Galeczka et al. 2014.

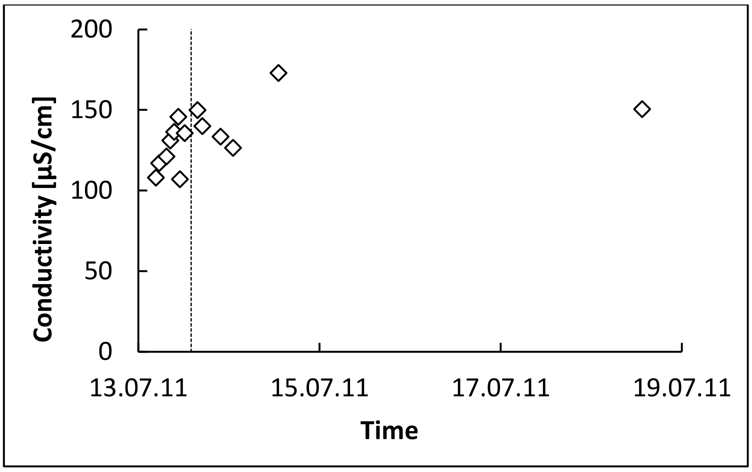

Fig. 12. Conductivity vs. time during the Kaldakvísl 2011 glacial flood. Vertical line represents the flood peak.

Summary of observation during the eruption in Holuhaun, north of Dyngjujökull.

First eruption under the glacier 23rd of August 2014 at around 13:00 UTC (Saturday), water presumably drained down to Grímsvötn. No sign of discharge out of Grímsvötn and no marked change in conductivity in Gígja and Núpsvötn?

Second eruption. At 00:02 UTC August 29th 2014 (Friday) signs of a lava eruption were detected on web camera images from Mila. The eruption ended about 4 hours later. There was no increased conductivity or discharge caused by this eruption.

Table 2. Present travel time (at normal conditions) between Holuhraun, Upptyppingar Bridge, Upptyppingar Station and the Bridge at Grímstaðir.

Station	**distance**	**velocity**	**travel time**	
	km	m/s	hours	
Holuhraun	0	0.83	0.0	
Upptyppingar Bridge	31	0.83	10.4	
Upptyppingar monitoring station (V289)	40	**0.83**	13.4	Based on offset in conductivity between Upptyppingar stations.
Grímsstaðir monitoring station	111	**1.6**	26.4	Based on offset in discharge between Upptyppingar V289 and Grímsstadir, thirteen hours

Twelve hours after the onset of the eruption August 29th strange "noise" is detected in the conductivity at the Upptyppingar Bridge due to exposure of the conductivity meter to air at the highest discharge. The meter is floating on the water in the channel and during high discharge it can be lifted out of the water for short periods at the time creating the noise on the graph. The maximum background conductivity is similar or slightly higher (~200 µS/cm) than the conductivity measured at the monitoring station at Upptyppingar about nine km downstream. According to the conductivity diagrams below it takes the water about 3 hours to travel the distance between the two monitoring spots, translating to about 0.83 m/s.

The maximum conductivity in Jökulsá á Fjöllum at Grímsstöðum (at the bridge on "Highway one") during the last two weeks is 170 µS/cm, considerably lower than at Upptyppingar. No abnormal increase in conductivity is observed at this station following the August 29th eruption in Holuhraun.

Third eruption. This eruption started around 04:00 31st of August 2014. No detectable change in the conductivity or discharge in Jökulsá á Fjöllum at Grímsstaðir nor Upptyppingar due to the onset of the eruption.

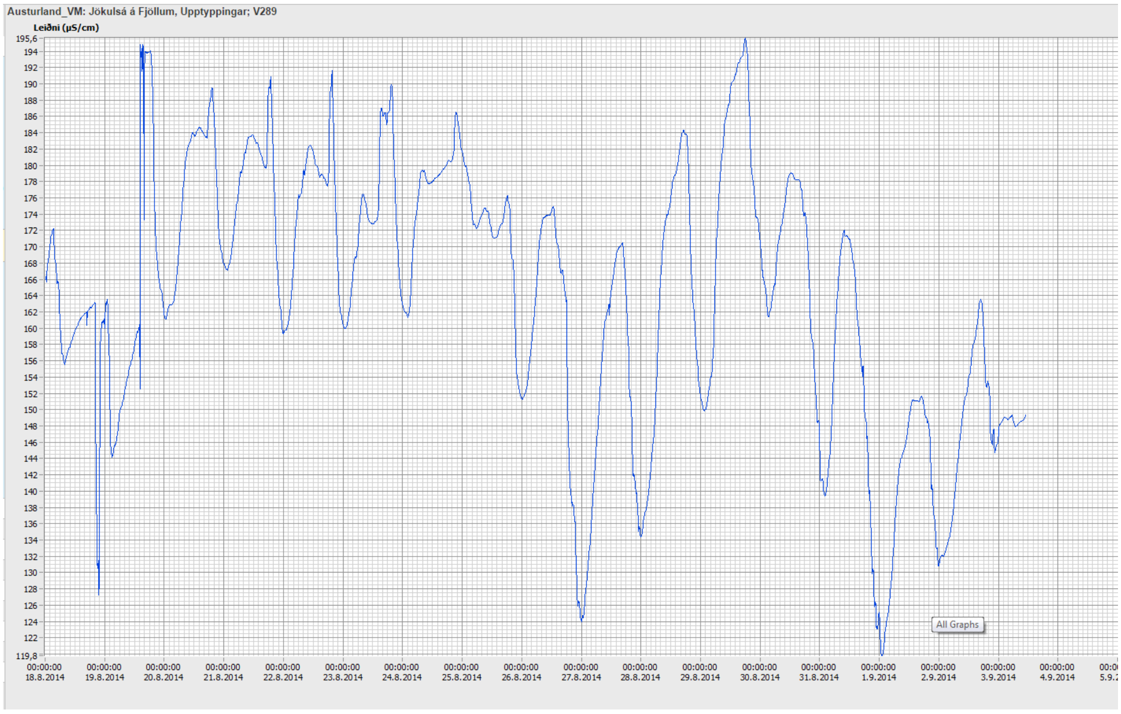

Fig 13. Jökulsá á Fjöllum at the Upptyppingar Station (data from vedur.is)

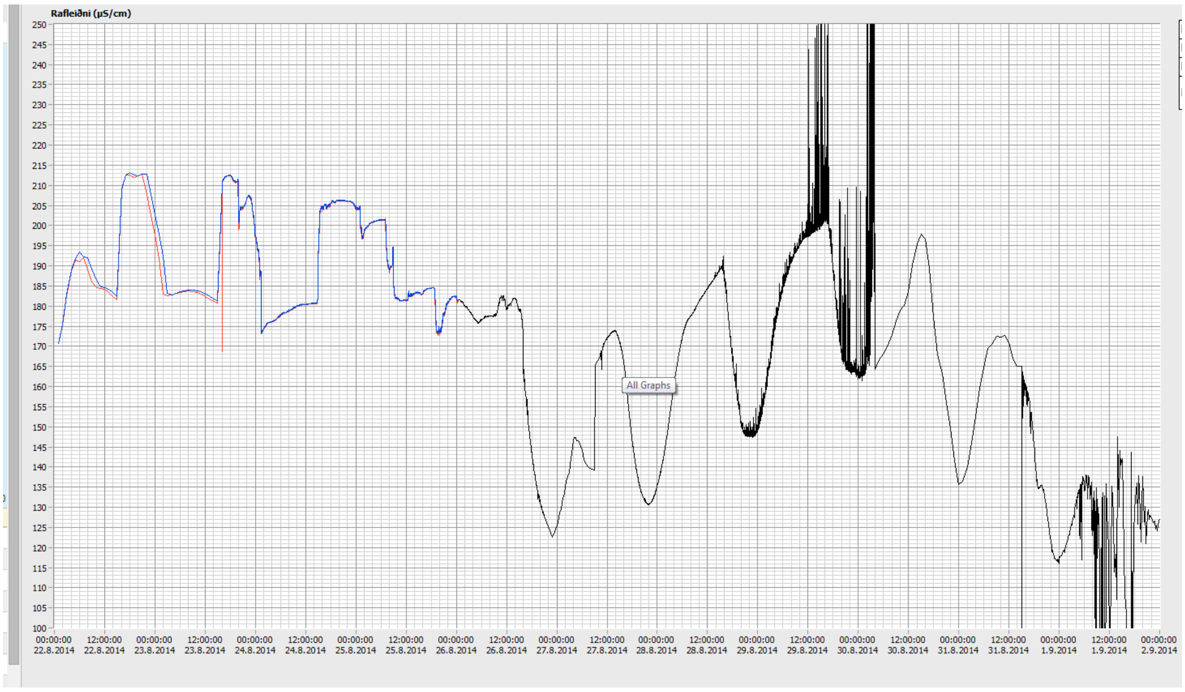

Fig 14. Jökulsá á Fjöllum at Upptyppingar Bridge, from 22/8/2014 to 1/9/2014. Noise is due to air and sand getting into the conductivity meter (data from vedur.is)

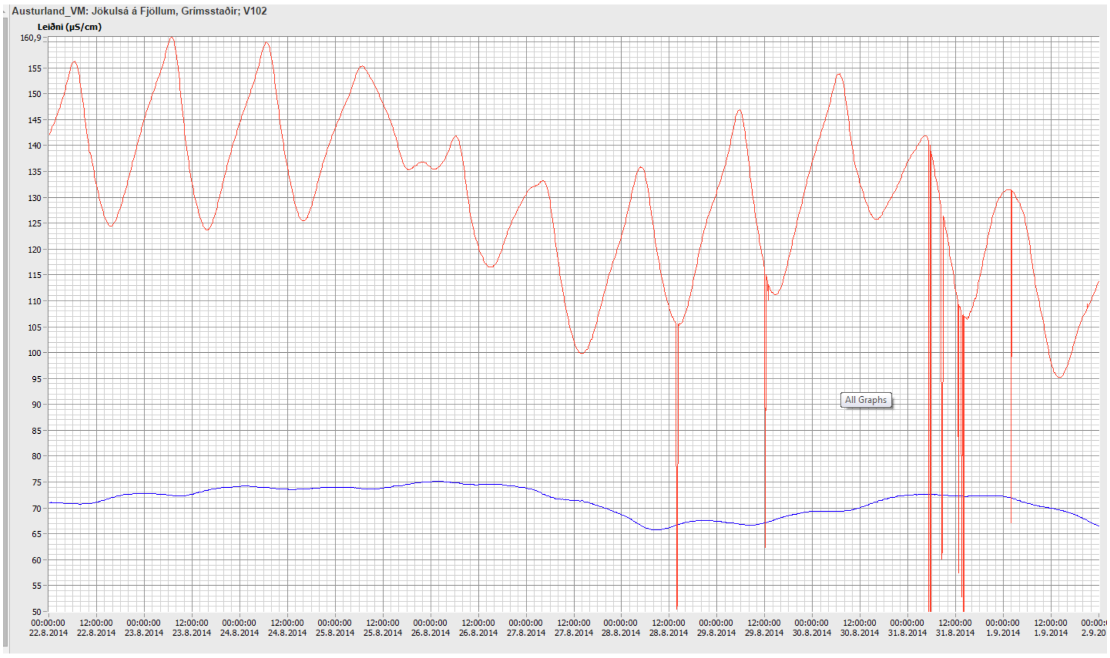

Fig 15. Conductivity of Jökulsá á Fjöllum at Grímsstadir from 18/8/2014 to 1/9/2014 at road no. 1. Noise is due to air and sand getting into the conductivity meter (data from vedur.is)

Results from the first chemical analyses of Jökulsá á Fjöllum at Upptyppingar

Water samples were collected in Jökulsá á Fjöllum at Upptyppingar during the first part of the unrest at Bárðarbunga. First analyses have been done on these samples and can be seen in Table 3 and in figure 16.

Table 3. First results from measurements from Jökulsá á Fjöllum at Upptyppingar done by Iwona M. Galeczka. Discharge values are taken from vedur.is and are preliminary.

Day	Sampling station	Discharge	pH	T°C	Conductivity	Cl	F	SO_4
		m^3/s		ref.	µS/s	mg/l	mg/l	mg/l
18.8.2014	JF at Upptyppingar		7.98	20	147	3.39	0.14	9.75
18.8.2014 19.30	JF at Upptyppingar	187		19.8	146	3.36	0.13	9.88
19.8.2014 14:52	JF at Upptyppingar	173	7.97	18.7	156.6	3.84	0.15	10.48
20.8.2014 13:30	JF at Upptyppingar	173	7.95	18.2	152.2	3.73	0.15	10.26
21.8.2014 9:25	JF at Upptyppingar	210	7.89	21.5	152.3	3.74	0.14	10.12
21.8.2014 18:30	JF at Upptyppingar	157	7.95	22.8	153.1	3.80	0.15	10.24

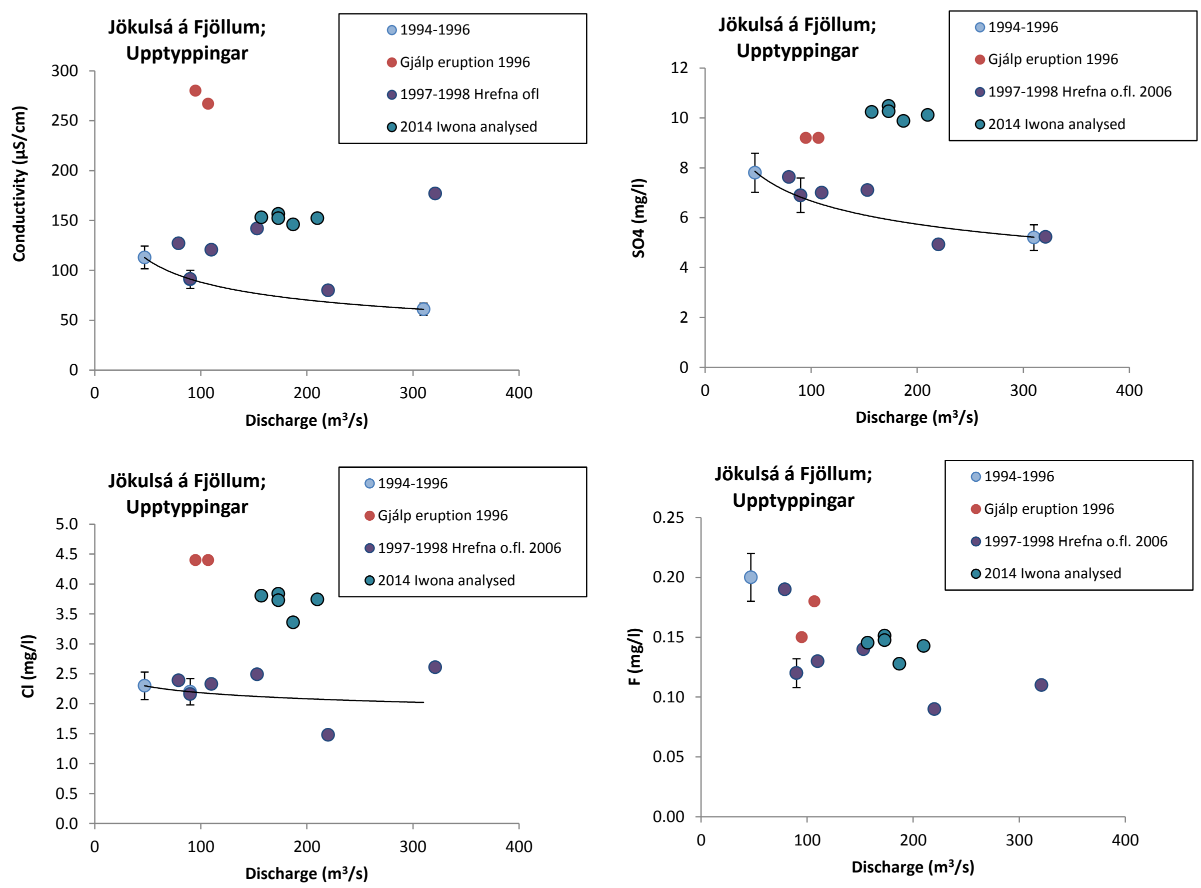

Figure 16. Results from measured samples (blue-green dots) from Jökulsá á Fjöllum at Upptyppingar vs. discharge of the river. Older data are also presented for comparison. The conductivity is higher than expected in "normal" conditions and so are the concentrations of Cl and SO_4. The concentration of SO_4 is even higher than in the event following the Gjálp eruption 1996 (Kristmannsdóttir et al., 2002).

Conductivity measured in samples taken from rivers draining NW part of Vatnajökull: Sveðja, Kaldakvísl and Skjálfandafljót during the seismic unrest before the first eruption were 47.1, 90.0 and 92.8 µS/cm, respectively. This conductivity is within the range expected in those rivers. Concentrations of anions in Sveðja were lower in the sample collected on August 20th than in a sample colledted few days after the flood in Kaldakvísl in 2011. The sample collected in Kaldakvísl on August 20th has comparable anion concentration as the flood water samples from the Kaldakvísl flood but lower conductivity. This indicates that there is very little effect of seismic activity on those particular rivers.

River Volga which drains the Kverkfjöll geothermal area has high concentration of SO_4 but relatively low concentration of Cl. The SO_4/Cl concentration ratio in River Volga and Jökulsá á Fjöllum suggest that the observed increase of these elements In Jökulsá á Fjöllum cannot stem from increased input from Volga (see increased SO_4 concentration in Volga, Table 4). High concentration of SO_4 in the water at Upptyppingar after the onset of seismic unrest, but before the volcanic eruptions, suggest some admixture of volcanic gases such as SO_2 before the volcanic eruptions.

Table 4. Chemical composition of samples taken from rivers draining the NW part of Vatnajokull 19-21.8.2014.

	Date	Conduct.	pH	Temp	Alkalinity	SO_4	Cl	F
		[µS/cm]		°C	[mmol/eqv.]	[umol/kg]	[umol/kg]	[umol/kg]
Jokulsa a Fjollum. Upptok +Volga	19/08/2014 21:45	196.4	7.04	18.2	2.226	117.67	142.61	7.53
Volga	19/082014 19:55	69.2	7.21	19.1	0.461	167.97	32.57	3.03
Sveðja	20/8/2014 20:40	47.1	7.30	22.7	0.510	23.41	8.93	1.14
Kaldakvísl	20/8/2014 18:00	90	7.87	22.8	0.945	70.81	40.45	4.89
Skjálfandafljót	21/8/2014 14:15	73.4	7.8	22.9	0.647	115.26	38.82	5.11

During the seismic unrest which started 16.08.2014 conductivity in Jökulsa a Fjöllum has been higher than the background conductivity. This increased conductivity correlates with the duration of the seismic activity and indicates that the conductivity increase is related to the seismic activity. Vigorous movements of the upper crust will induce water-rock interaction resulting in higher conductivity.

There is no clear sign of volcanic affected waters in the rivers draining the Grímsvötn reservoir.

References

Galeczka Iwona, Eric H. Oelkers, Sigurdur R. Gislason, 2014. The chemistry and element fluxes of the July 2011 Múlakvísl and Kaldakvísl glacial floods, Iceland. Journal of Volcanology and Geothermal research 273, 41-57.

Gislason S.R., A . Snorrason, H.K. Kristmannsdottir, A .E. Sveinbjornsdottir, P. Torsander, J. Olafsson, S. Castet, B. Dupré, 2002. Effects of volcanic eruptions on the CO2 content of the atmosphere and the oceans: the 1996 eruption and flood within the Vatnajökull Glacier, Iceland. Chemical Geology 190, 181-205.

Gíslason Sigurður Reynir, Árni Snorrason, Bergur Sigfússon, Eydís Salome Eiríksdóttir, Sverrir Óskar Elefsen, Jórunn Harðardóttir, Ásgeir Gunnarsson, Einar Örn Hreinsson, Peter Torssander, Níels Örn Óskarsson og Eric Oelkers, 2004a. Efnasamsetning, rennsli og aurburður straumvatna á Austurlandi V. Gagnagrunnur Raunvísindastofnunar og Orkustofnunar, RH-05-2004, 101 pp.

Gíslason Sigurður Reynir, Árni Snorrason, Bergur Sigfússon, Eydís Salome Eiríksdóttir, Sverrir Óskar Elefsen, Jórunn Harðardóttir, Ásgeir Gunnarsson, Einar Örn Hreinsson, Peter Torssander, 2004. Efnasamsetning, rennsli og aurburður straumvatna á Suðurlandi VII. Gagnagrunnur Raunvísindastofnunar og Orkustofnunar. RH-06-2004, 40 pp.

Gíslason Sigurður Reynir, Árni Snorrason Luiz Gabriel Quinn Camargo, Eydís Salome Eiríksdóttir Jórunn Harðardóttir og Svava Björk Þorláksdóttir, 2007. Efnasamsetning og rennsli straumvatna á slóðum Skaftár 2002 til 2006. RH-13-2007

Kristmannsdottir Hrefna, Axel Björnsson, Svanur Pálsson, Árny E. Sveinbjörnsdottir, 1999. The impact of the 1996 subglacial volcanic eruption in Vatnajokull on the river Jökulsa Fjöllum, North Iceland. Journal of Volcanology and Geothermal Research 92, 359-372.

Kristmannsdóttir Hrefna, Sigurður Reynir Gíslason, Árni Snorrason, Sverrir Óskar Elefsen, Steinunn Hauksdóttir, Árný Sveinbjörnsdóttir, Hreinn Haraldsson, 2006. Þróun efnavöktunarkerfis til vatnar mannvirkjum við umbrot í jökli. OS-2006/014, 54 bls.

Oskarsdottir Sigrídur Magnea , Sigurdur Reynir Gislason, Arni Snorrason, Stefanía Gudrún Halldorsdottir, Gudrún Gisladottir. Spatial distribution of dissolved constituents in Icelandic river waters. Journal of Hydrology, 397, 175-190

Sigfusson B., 2009. Reactive transport of arsenic through basaltic porous media. PhD thesis, University of Aberdeen.