Groundwater investigations at Virkisjőkull, Iceland: Data Report 2012

Earth Hazards Programme

Open Report OR/12/088

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Groundwater investigations at Virkisjőkull, Iceland: Data Report 2012

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Summary

This report describes field experiments into the groundwater environment around the Virksjőkull glacier in southeast Iceland, which were carried out between September 2011 and September 2012. The report describes these experiments and presents the resulting data: it is not intended to provide any interpretations of the data, but to be a record of project activities and field results.

BGS has set up a multidisciplinary observatory at Virkisjökull, which provides an excellent opportunity to characterise and quantify groundwater in the sandur aquifer and its interaction with glacial meltwater. For more information on the wider geoscientific research being carried out at Virkiskjőkull see http://www.bgs.ac.uk/research/glacierMonitoring/home.html. Climate data, including rainfall, and meltwater river flow data are being collected, and considerable datasets are being developed related to glacial mass, glacier movement, and surface topography and geomorphology.

The following groundwater-related activities have been carried out and are reported here:

- In three short field surveys in September 2011, February 2012 and April 2012, the focus was on:
    - Collecting samples of shallow (<1m deep) groundwater, meltwater and ice for chemistry, stable isotope and residence time analysis
    - Testing ground surface permeability on the sandur and the immediate pro-glacial area.
- In summer 2012, a longer field campaign focussed on:
    - Drilling shallow (10-15 m deep) boreholes into the unconsolidated sandur, as three short transects away from the meltwater river, and testing the boreholes to measure aquifer permeability
    - Drilling two shallow (6-18 m deep) boreholes into volcanic bedrock between the glacier front and the sandur, to help investigate whether groundwater flow through the bedrock plays a significant role in glacier drainage.
    - Collecting groundwater and additional meltwater samples for chemistry, stable isotope and residence time analysis
    - Installing sensors to monitor groundwater level, temperature and conductivity throughout the year.
    - Hand-constructing very shallow (<1m deep) piezometers to extend the borehole transects and to investigate the immediate river-groundwater zone
    - Further testing of ground surface permeability on the sandur.

1 Introduction

There is growing interest internationally in the important role that groundwater may have in buffering changes in meltwater river discharge due to increased melting of glaciers. Glaciers are a key water resource in many populated areas, including high latitude regions such as Alaska, and lower latitude mountain ranges like the Himalayas and the Andes. Glacial deposits, particularly proglacial deposits and outwash plains, are often highly permeable and may form significant aquifers, but little detailed hydrogeological investigation has been done in active glacial environments. Key questions include: how do meltwater dynamics affect groundwater recharge in glacial catchments? How much does groundwater buffer changes in meltwater river discharge due to increased glacier melting? How do climate, glacier mass balance and groundwater interact?

The sandur (outwash plain) in front of the Virkisjökull glacier in Iceland, one of many similar glaciers draining the Oraefajőkull and Vatnajőkull icecaps (Figure 1), is typical of many glacial environments. It is tens to hundreds of metres thick, poorly consolidated, highly permeable, and may contain similar volumes of groundwater to the volume of water stored as ice in the glacier. BGS has set up a multidisciplinary observatory at Virkisjökull, which provides an excellent opportunity to characterise and quantify groundwater in the sandur aquifer and its interaction with glacial meltwater. For more information on the wider geoscientific research being carried out at Virkiskjőkull see http://www.bgs.ac.uk/research/glacierMonitoring/home.html. Climate data, including rainfall, have been collected at Virkisjőkull since late 2009, and data for three locations around the glacier are available since October 2011. River levels in the meltwater channel draining Virkisjőkull have also been monitored since October 2011. Considerable datasets continue to be developed related to glacial mass, glacier movement, and surface topography and geomorphology. As well as investigating meltwater-groundwater interactions in the sandur, it may also be possible in future to use the Virkisjőkull observatory to investigate the role that groundwater plays in glacier movement; the role of groundwater in the transfer of meltwater from the glacier snout through the immediate proglacial area to the sandur; and the role of groundwater in overall glacial catchment hydrology. The data provided by new glacial groundwater observation and monitoring at Virkisjőkull will help fill the gap in understanding of hydrological fluxes and stores in glacial environments during a period of rapid climate change, not only in Iceland but potentially in other high latitude and even lower latitude mountainous regions.

Groundwater investigations at Virkisjőkull began in September 2011. In three short field surveys in autumn 2011 and spring 2012, preliminary investigations looked at the permeability of the surface of the sandur; and at chemistry, stable isotope and residence time indicators for shallow (<1m deep) groundwater, meltwater and ice. In tandem with the groundwater investigations, a stream gauge was installed and various experiments carried out to measure river flow. These hydrological data will be reported separately.

In summer 2012, a longer field campaign focussed on drilling shallow (10-15 m deep) boreholes into the unconsolidated sandur, as three short transects away from the meltwater river; testing the boreholes to measure aquifer permeability; collecting groundwater samples for chemistry, stable isotope and residence time analysis; and installing sensors to monitor groundwater level, temperature and conductivity throughout the year. Additional activities included hand-constructing very shallow (<1m deep) piezometers to extend the borehole transects and to investigate the immediate river-groundwater zone; some further surface testing focussed on the permeability of the meltwater channel bed; and collecting further meltwater and very shallow (<1m deep) groundwater samples for stable isotope analysis. Two additional shallow boreholes were also drilled into the volcanic bedrock that lies between the glacier front and the sandur, to help investigate whether groundwater flow through the bedrock plays a significant role in glacier drainage.

Figure 1 Location of the Virkisjőkull observatory in southeast Iceland

2 Borehole drilling

Eight boreholes were drilled into the sandur at Virkisjőkull between 17 and 22 August 2012. A further two boreholes were drilled into bedrock between the glacier front and the sandur, on 23 August 2012. Accurate locations and elevations of the casing top and ground surface of each borehole were measured using a differential GPS.

2.1 SANDUR BOREHOLES

The eight boreholes drilled into the sandur form three transects leading away from the active meltwater channel (Figure 2). One transect is close to the upper (nearest the glacier) edge of the sandur; one approximately 750m lower down the sandur, near the road bridge where flow in the meltwater river is being monitored; and one approximately 1km further down the sandur. The boreholes in each transect are spaced between approximately 75 and 350 m apart. The closest borehole to the active meltwater channel, as of August-September 2012, is approximately 30m distant and the furthest is approximately 650m distant.

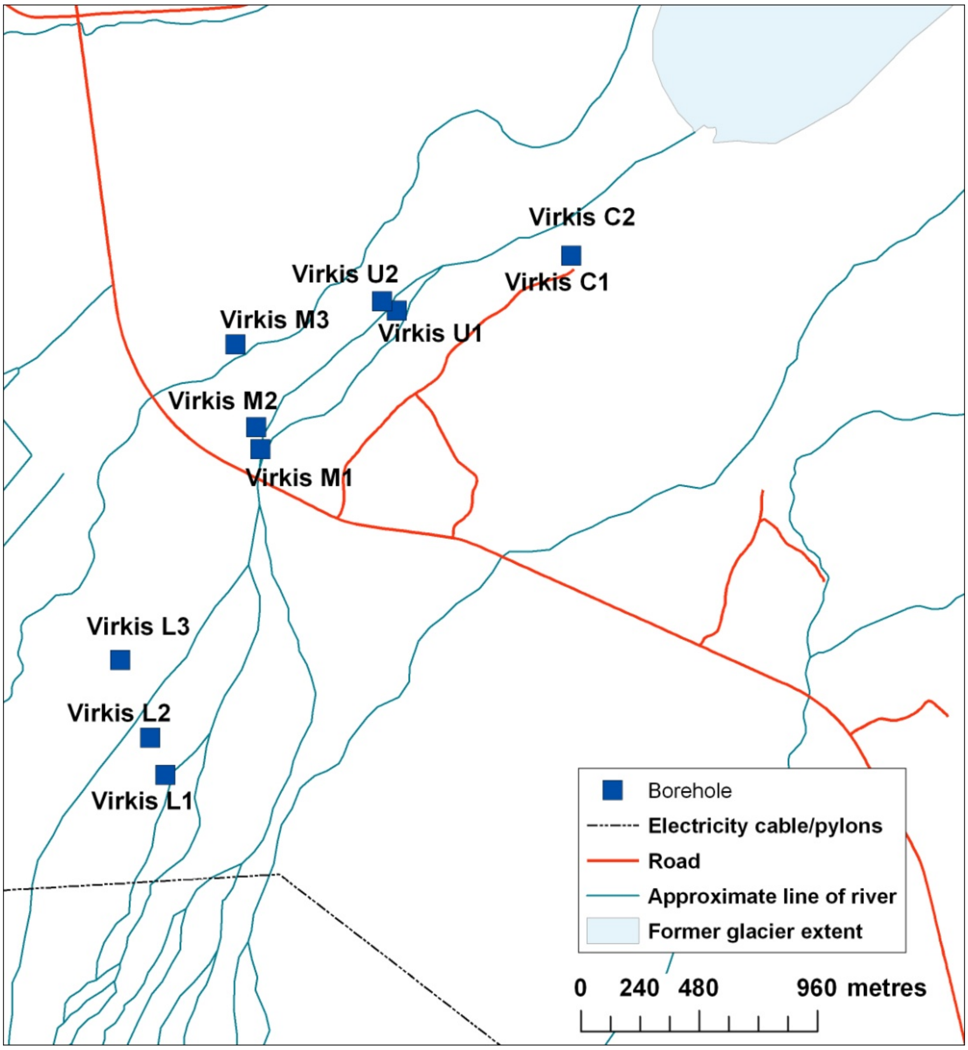


Figure 2 Location of Virkisjokull boreholes. Note that the main and subsidiary river channels are relatively mobile and have changed since this map was drawn.

The sandur boreholes were drilled to between 9 and 15m depth. The completed piezometer depths after construction range from 8.2 to 14.9m below ground level. The locations, depths and a summary of the construction of each of the boreholes are presented in Table 1.

The boreholes were drilled using the Odex drilling technique. This technique was designed to drill through unconsolidated deposits, and uses a combination rotary down-the-hole hammer with simultaneous emplacement of temporary casing. A special swing-out eccentric hammer bit is used to ream the bottom of steel casing, which is then pulled down the hole as the hammer bit is advanced. All the boreholes were drilled with approximately 150mm diameter steel casing. Once drilled to the required depth, 88 mm diameter uPVC liner (0.5mm or 1.0mm screen and plain casing) was installed and held in place by a washed 2-5mm gravel pack around the whole length of the liner (except in one case where gravel pack was just installed against the length of the screen – Table 1). The temporary steel casing was then jacked out, leaving approximately 2m length of casing in the ground in most cases (Table 1), with approximately 0.5m left standing above ground. The boreholes were completed by emplacing approximately 0.5m length of bentonite pellets over the top of the gravel pack between the uPVC liner and the steel casing. The ground around the casing was then dug out to approximately 0.5m depth and infilled with bentonite pellets.

During drilling, the drill cuttings were observed and samples collected for further interpretation and analysis. The samples were later washed and used, alongside drilling observations, to produce borehole lithological logs, which are presented in Appendix 1.

Once drilled, the boreholes were flushed by airlifting for between 20 minutes and 1 hour, until the water stopped clearing. In half the boreholes, the water cleared up to almost or totally clear; in the other half, the water remained slightly silty after both airlifting and test pumping.

The boreholes were completed with steel caps which can be bolted on. An example of a completed borehole is shown in Figure 3.

2.2 BEDROCK BOREHOLES

The two bedrock boreholes are sited within 1m of each other in the area between the glacier snout and the sandur (Figure 2). One borehole was drilled to 18m and the other to 6m depth. Like the sandur boreholes, they were drilled using the Odex technique (see Section 2.1), but steel casing was only emplaced through the unconsolidated moraine deposits and the uppermost section of weathered bedrock; below this the boreholes were drilled open hole. No uPVC liner was installed.

Both bedrock boreholes intercepted about 3m of moraine deposits overlying volcanic rock. A very large void was encountered in the deeper borehole between 15 and 18m depth, which caused loss of air circulation and prevented drilling any deeper.

Figure 3 Piezometer being installed in a newly drilled borehole (top) and examples of a completed borehole (bottom) at Virkisjőkull

Table 1 Summary of boreholes at Virkisjőkull

Borehole ID	Northing	Easting	Elevation of casing top (mOD)	Date completed	Drilled depth (mbgl)	Completed depth (mbct)	Height of steel casing top (magl)	Approx. base of steel casing (mbgl)	Depth of screened sections (mbct)	Total screen length (m)	Gravel pack
Virkis U1	63.95905556	-16.83663889	93.87	17/08/2012	15	14.9	0.5	2	10.9-13.9	3	All of liner
Virkis U2	63.95941667	-16.83783333	94.15	18/08/2012	15	15.2	0.6	2	9.2-10.2; 12.2-13.2	2	All of liner
Virkis M1	63.95419444	-16.84830556	78.20	19/08/2012	15	15.35	0.45	2	11.4-14.4	3	All of liner
Virkis M2	63.955	-16.84858333	78.55	20/08/2012	15	15.2	0.45	2	12.2-14.2	2	Around screen
Virkis M3	63.95802778	-16.85008333	81.22	21/08/2012	15	15.23	0.55	2	8.25-14.25	6	All of liner
Virkis L1	63.94247222	-16.85708333	59.08	21/08/2012	15	12.43	0.45	7	5.5-11.5	6	All of liner that hadn't collapsed
Virkis L2	63.94383333	-16.85822222	60.29	22/08/2012	9	8.78	0.55	2	4.8-7.8	3	All of liner
Virkis L3	63.94669444	-16.8605	63.06	22/08/2012	9	8.87	0.45	2	4.9-7.9	3	All of liner
Virkis C1	63.96083333	-16.82202778	123.03	23/08/2012	18	13.75	0.4	6	n/a	n/a	none
Virkis C2	63.96083333	-16.82202778	123.08	23/08/2012	6	5.5	0.4	5.5	n/a	n/a	none

In all of the boreholes, c. 0.5m of bentonite pellets was emplaced above the washed 2-5mm gravel pack between the uPVC liner and the steel casing. In borehole M2, the only borehole where gravel pack was not emplaced through all of the liner, the bentonite seal was topped with backfill of drilling chippings, and another 0.5m of bentonite pellets was emplaced on top of this. For all the boreholes, the ground around the steel casing at the surface was then dug out to approximately 0.5m depth and bentonite pellets were emplaced around the outside of the steel casing.

3 Sandur aquifer hydraulic testing

Constant rate test pumping was carried out on all of the sandur boreholes between 19 and 29 August 2012. All the tests were carried out with a suction pump with a maximum capacity of about 2 litres/second (l/s), but the range of flow rates achieved during the tests was between 0.5 and 1.8 l/s. The tests were carried out for at least 3.5 hours. The longest test was six hours. During the test on borehole U1, pumped water was discharged to the meltwater river; at all the other boreholes, the pumped water was discharged to the ground as far as possible from the pumped borehole, given the available discharge pipe length, which was always less than 20m away from the borehole. The pumped water infiltrated rapidly into the ground, but no evidence of re-circulation of pumped water was observed in any of the tests.

A summary of test pumping results is presented in Table 2. Detailed results are presented in Appendix 2. An example of the test pumping setup is shown in Figure 4.

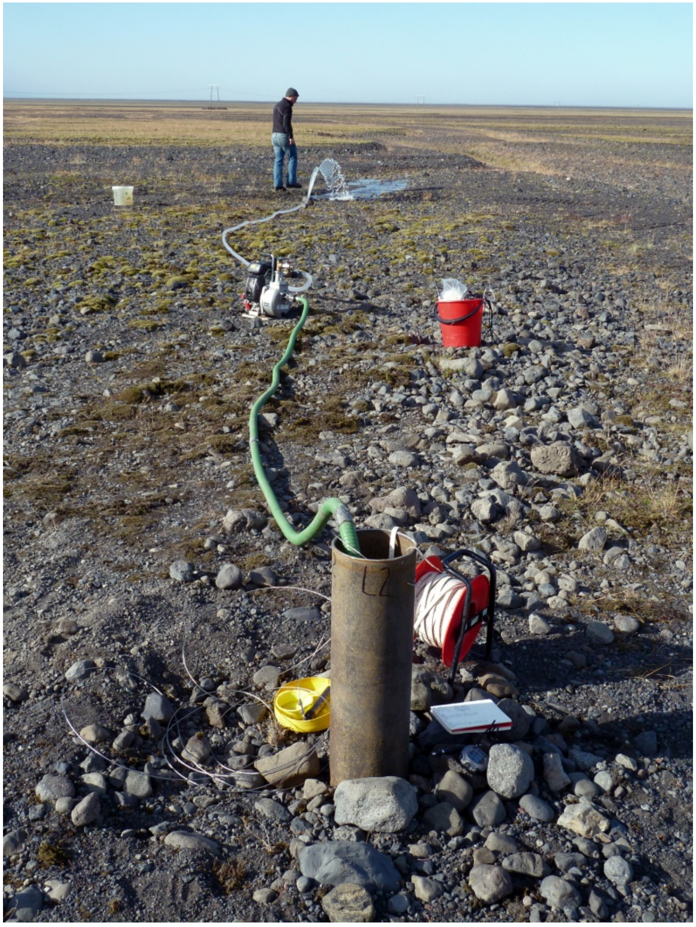


Figure 4 Example of test pumping setup on a borehole on the Virkisjőkull sandur

Table 2 Summary of test pumping results on sandur boreholes at Virkisjőkull

Borehole ID	Test date	Test length (min)	Average test yield (m^3/d)	Rest water level (mbct)	Maximum drawdown (m)	Specific capacity ($m^3/d/m$)	Transmissivity (m^2/day)	Notes
Virkis U1	19/08/2012	300	95.04	3.19	3.81	25	100	
Virkis U2	20/08/2012	225	138.24	3.55	0.7	200	600	
Virkis M1	21/08/2012	300	112.32	2.26	3.46	30	200	
Virkis M2	22/08/2012	225	95.04	2.6	3.7	25	150	
Virkis M3	23/08/2012	230	120.96	4.41	0.85	140	600	
Virkis L1	25/08/2012	360	43.2	1.67	7.02	6	80	The borehole construction restricts water inflow and significantly reduces apparent transmissivity. Probably similar to L2 and L3.
Virkis L2	28/08/2012	244	157.248	1.49	0.38	415	2500	
Virkis L3	29/08/2012	215	150.336	2.25	0.42	360	2000	

4 Hand-installed piezometers

Twelve very shallow (<1m) hand-installed piezometers were put in place during the summer 2012 field campaign. Accurate locations and elevations of the casing top and ground surface of each piezometer were measured using a differential GPS. Their locations are shown in Figure 5. Location details, and a summary of piezometer construction, are presented in Table 3. An example of a shallow piezometer is shown in Figure 6.

The piezometers are a rapid way of being able to monitor groundwater levels in areas where groundwater is very close to the ground surface: these are largely in the lower sandur (close to the lower borehole transect) and/or adjacent to the active meltwater channel. They are intended to be relatively temporary, because their construction and location means they are not protected from flooding or other damage. Also, because the groundwater level in the sandur appears to fluctuate significantly, and because the piezometers were installed during what may be the period of highest groundwater levels annually (i.e., the period of highest melt and meltwater flow), the groundwater level may lie below the base of the piezometers for much of the year.

Groundwater levels in the piezometers were monitored during the summer 2012 field campaign. These data are presented in Appendix 3.

Automatic loggers were not left in the piezometers over the winter, but if the piezometers are still available for use in future field campaigns, they can continue to provide extra groundwater information during those campaigns.

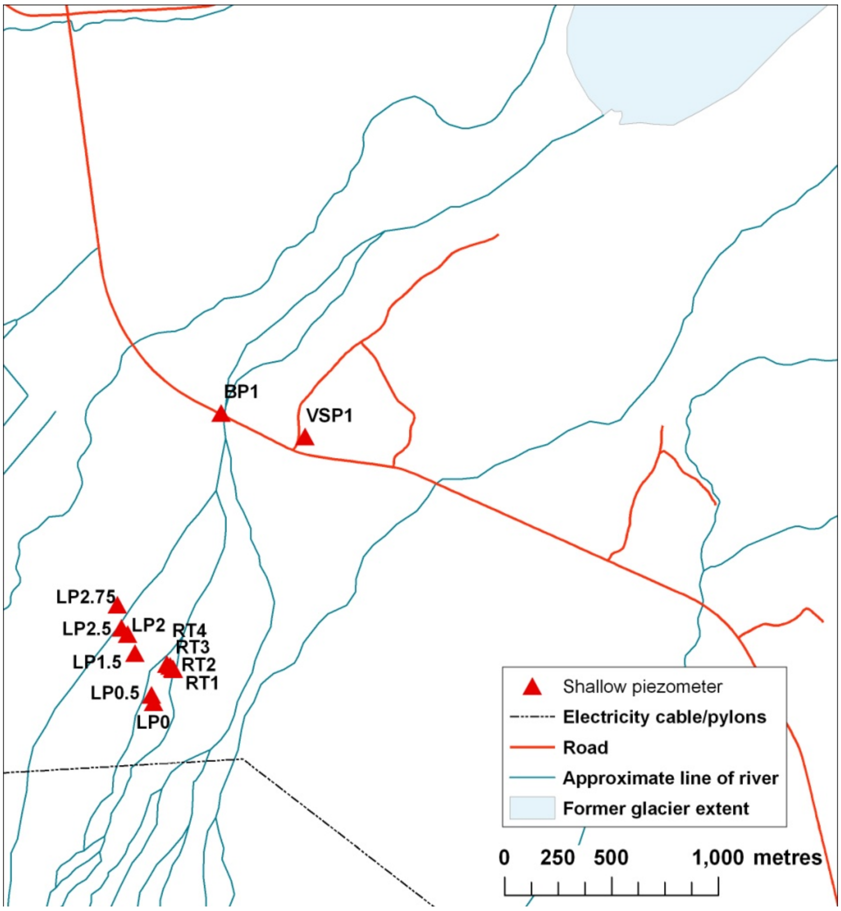


Figure 5 Location of hand-installed piezometers at Virkisjőkull

Table 3 Summary of hand-installed piezometers at Virkisjőkull

Piezometer ID	Northing	Easting	Elevation of casing top (mOD)	Date completed	Completed depth (mbct)	Height of casing top (magl)	Depth (mbgl)
LP0	63.94122222	-16.85627778	56.74	25/08/2012	0.6	0.4	0.2
LP0.5	63.94152778	-16.85644444	57.58	25/08/2012	0.99	0.44	0.55
LP1.5	63.94330556	-16.85788889	59.17	22/08/2012		0.43	
LP2	63.94411111	-16.85852778	59.68	22/08/2012		0.35	
LP2.5	63.94438889	-16.85911111	59.49	22/08/2012	0.53	0.3	0.23
LP2.75	63.94536111	-16.85941667	61.18	25/08/2012	1.22	0.4	0.82
BP1	63.95325	-16.84888889	75.76	20/08/2012	0.98	0.53	0.45
RT1	63.94258333	-16.85427778	58.21	30/08/2012	0.585		
RT2	63.94261111	-16.85433333	58.53	30/08/2012	0.69		
RT3	63.94272222	-16.85458333	58.72	30/08/2012	0.78		
RT4	63.94280556	-16.85488889	58.80	30/08/2012	0.78		
VSP1	63.95213889	-16.84097222	75.46	04/09/2012	0.96		

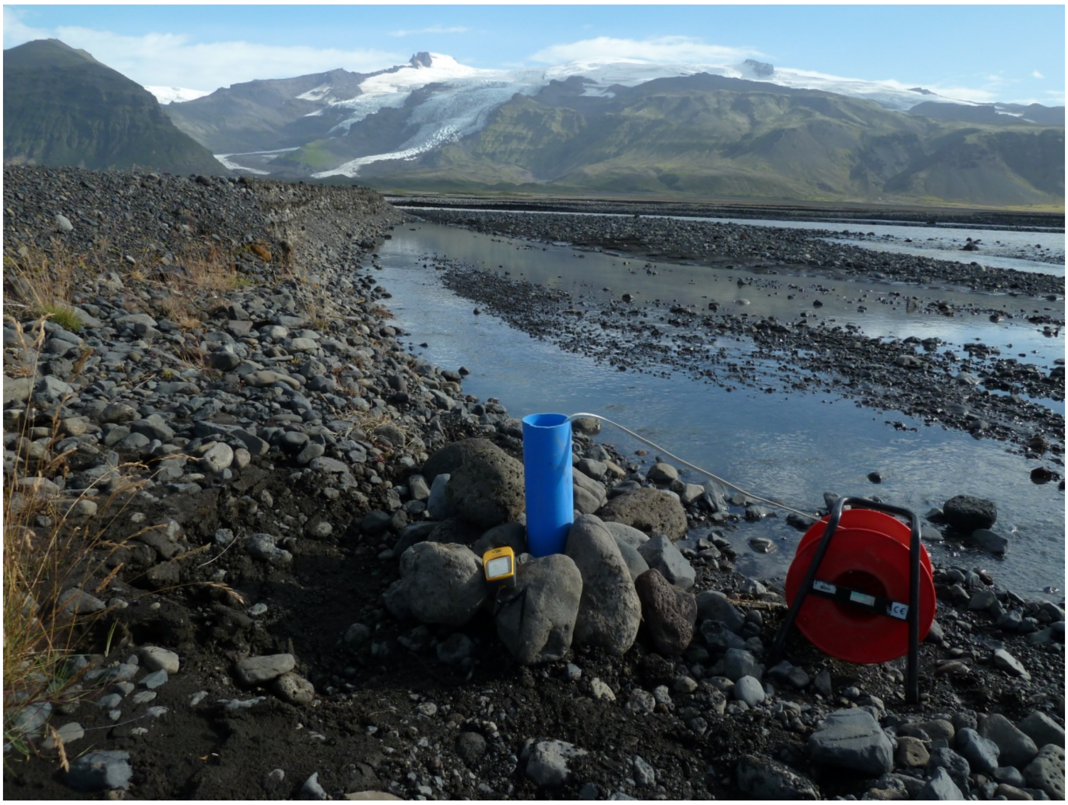


Figure 6 Example of a hand-installed, very shallow piezometer at Virkisjőkull

5 Groundwater level and temperature monitoring

Monitoring of groundwater levels and temperature in the sandur was carried out during the summer 2012 field campaign, and is continuing over the winter of 2012-13 by means of automatic loggers.

The loggers being used are mainly In-Situ Inc. Rugged TROLL 100s, which measure pressure and temperature. They have a pressure range of 0-9m. There is also one In-Situ Aqua TROLL 200, which additionally measures conductivity (SEC or specific electrical conductance). Pressure measured by the loggers is adjusted for air pressure based on measurements made by two In-Situ Rugged Baro TROLLS on site, and converted to groundwater level.

5.1 GROUNDWATER LEVEL MONITORING DURING SUMMER 2012 FIELD CAMPAIGN

During the summer 2012 field campaign, groundwater level monitoring was done in available boreholes and shallow piezometers both manually, using a hand-held dipper, and automatically using downhole loggers. The downhole loggers also measured groundwater temperature.

Loggers were installed in each borehole to collect data during test pumping (see also Section 3), and then left in place to continue monitoring. Between 2 and 2.5 weeks of groundwater level and temperature data were collected during the field campaign from the newly drilled boreholes. For Loggers were also used to collect groundwater level and temperature data over five days from four shallow piezometers across a short transect (<50m) away from the river on the lower sandur, to investigate in more detail river-groundwater interactions in the zone immediately adjacent to the river. These measurements served to field test the loggers that were then left in place over the winter (see Section 5.2), and also provided very valuable initial evidence to improve our initial conceptual model of the sandur groundwater system and of groundwater-meltwater interaction.

A summary of groundwater level data collected during the summer 2012 field campaign is presented in Appendix 3.

5.2 ONGOING GROUNDWATER MONITORING

A summary of the installed groundwater sensors at Virkisjőkull is given in Table 4. These were field tested during the summer 2012 field campaign (see Section 5.1) and have been left in place to monitor groundwater levels, temperature and, in one case, groundwater conductivity (SEC).

Table 4 Summary of groundwater sensors installed in Virkisjőkull boreholes for monitoring during winter 2012-13

Borehole ID	Sensor type	Date and time Winter1213 log started	Groundwater level at start of Winter1213 log (mbct)	Depth of logger sensor (mbct)
Virkis U1	Rugged TROLL 100	07/09/2012 10:00	3.08	7.38
	AquaTROLL 200	09/09/2012 18:00	3.203	9.59
	Baro TROLL	07/09/2012 10:00	n/a	n/a
Virkis U2	Rugged TROLL 100	7/09/2012 10:15	3.49	7.00
	Baro TROLL	09/09/2012 18:00	n/a	n/a
Virkis M1	Rugged Troll 100	07/09/2012 09:30	2.38	6.95
Virkis M2	Rugged Troll 100	07/09/2012 09:30	2.55	7.73
Virkis M3	Rugged Troll 100	07/09/2012 09:45	4.30	6.98
Virkis L1	Rugged Troll 100	07/09/2012 08:45	1.74	8.40
Virkis L2	Rugged Troll 100	07/09/2012 08:45	1.425	7.80
Virkis L3	Rugged Troll 100	07/09/2012 09:00	2.25	7.90
Virkis C2	Rugged Troll 100	07/09/2012 11:00	2.04	5.25

6 Water chemistry, stable isotopes and residence time

Water chemistry, stable isotope composition and residence time indicators provide essential tools to investigate groundwater sources, movement and interactions with surface water. A range of samples was collected at Virkisjőkull during four field campaigns, and analysed at BGS laboratories, combined with field measurements of selected parameters.

Different samples were collected at different sites, depending on the water source (e.g. glacier ice, glacier melt, river water or groundwater). At many sample sites, field measurements were made of pH, dissolved oxygen (DO), redox potential (Eh), water temperature, specific electrical conductance (SEC) and alkalinity by titration. At most sites, field measurements of SEC and temperature were made. Where possible, pH, DO and Eh were measured in an in-line flow cell to minimise atmospheric contamination and parameters were monitored (typically for 10 to 15 minutes) until stable readings were obtained.

Samples for major and trace element analysis were filtered through 0.45µm filters and collected in factory-new polyethylene bottles rinsed with sample water before collection. One filtered aliquot was acidified to 1% v/v with Aristar HNO_3, for analysis of major cations, total sulphur and Si by ICP-MS (inductively coupled plasma-mass spectrometry). A second filtered aliquot was left unacidified for analysis of anions by ion chromatography (NO_3-N, Cl, Br, F). Samples were also collected in chromic-acid-washed glass bottles for dissolved organic carbon (NPOC) analysis, after filtration using the same 0.45µm filters as for the samples for ionic analysis. Samples for stable-isotopic analyses (δ^2H and $\delta^{18}O$) were collected in either glass or polyethylene bottles rinsed with samples water before collection. Analysis was carried out by mass spectrometry. Samples for CFC and SF_6 dissolved gas analysis were collected in glass bottles, submerged under flowing groundwater to prevent atmospheric contamination. Samples for noble gases were collected in copper tubes from flowing groundwater.

The samples collected in each field campaign between September 2011 and September 2012 are summarised in Table 5, and shown on the map in Figure 8. Preliminary interpretation of the analysis results is presented in Appendix 4.

Table 5 Summary of water samples collected at Virkisjőkull and surrounding areas during four field campaigns from September 2011 to September 2012

Field campaign	Sept 2011	Feb 2012	Apr 2012	Sept 2012
Samples collected at Virkisjokull[1]				
Rainwater	1 (1,1,0)			
Ice	2 (2,2,0)			
Meltwater on or immediately in front of glacier	3 (3,3,0)		3 (1,3,1)	2 (0,2,0)
Meltwater river or lake	6 (4,6,3)	5 (5,5,5)	7 (7,7,7)[2]	4 (0,4,0)
Very shallow groundwater from pits (<1.5m depth)	2 (2,2,0)	3 (3,3,1)	3 (2,3,0)	1 (0,1,0)
Shallow groundwater from springs/groundwater fed streams				7 (1,7,1)
Shallow groundwater from boreholes (<15m depth)				9 (9,9,9)
Deep groundwater from boreholes (up to 150m depth)[3]				1 (1,1,1)

[1] Numbers given in brackets are subtotals of the total number of samples taken in each category, respectively, for: ionic analysis; stable isotope analysis; and dissolved gas analysis (CFC/SF_6 and sometimes noble gases).

[2] Four of these were collected from meltwater rivers draining glaciers other than Virkisjőkull

3 Deep borehole in volcanic bedrock approximately 2.7km from Virkisjőkull site

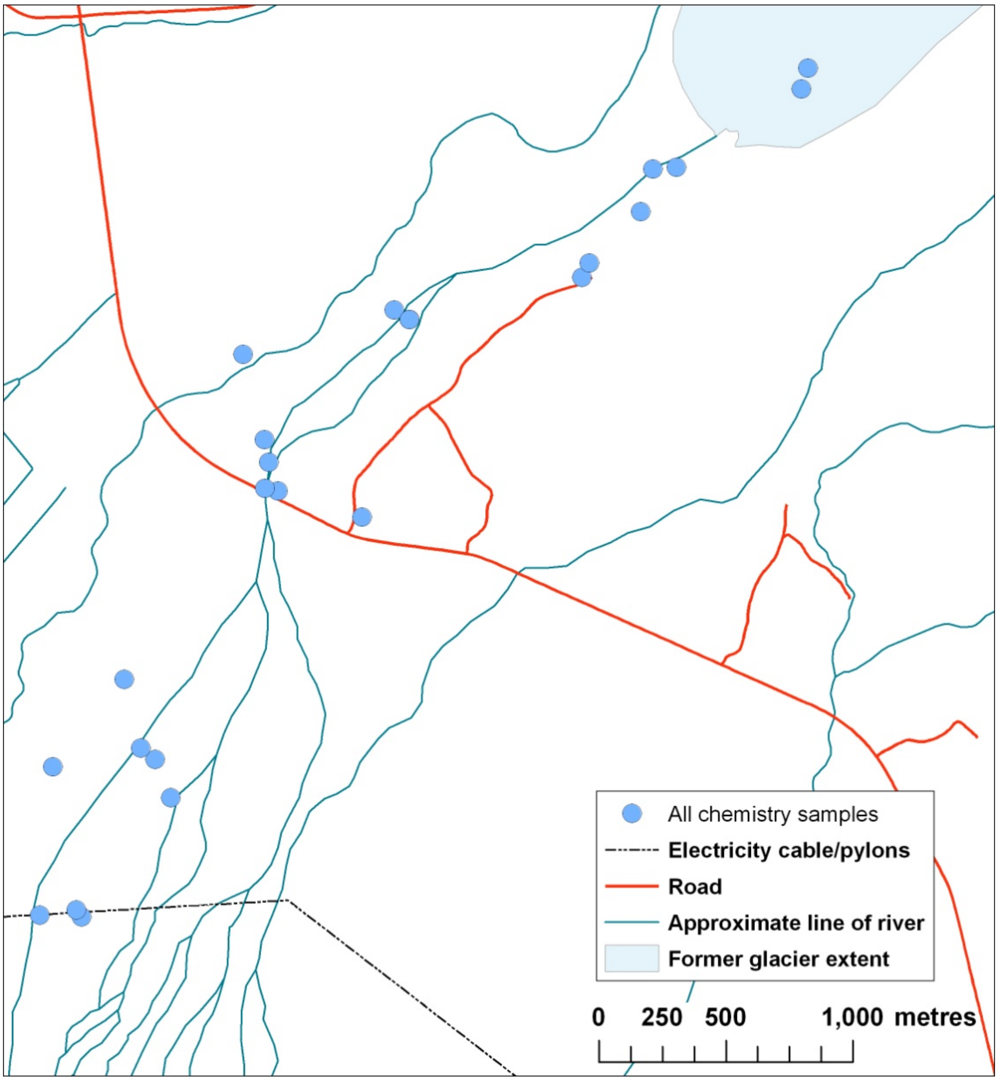


Figure 7 Location of water chemistry samples collected at Virkisjőkull

7 Surface permeability

A number of field tests of ground surface (to approximately 0.15m depth) permeability have been made using a Guelph permeameter at Virkisjőkull: twenty at various sites across the sandur and twelve in the pro-glacial area. Sites on the sandur were selected to investigate the variability in surface permeability across the sandur surface, and also specifically to try to identify unsaturated sediments which are equivalent to those sediments which form the bed of the active meltwater river channel.

At each site a shallow hole was dug, up to approximately 150mm deep and as close as possible to 50mm in diameter; the permeameter was inserted in the hole, and in most cases the hole was backfilled with gravel. For some of the tests, water was added to the hole before the test for approximately 10 minutes to wet the sediment, but for most of the tests this wasn't done. At all sites, a test with a head of 5cm was run. In some cases the test was repeated if necessary until a steady rate of head fall was recorded. At most sites, a brief description of the surface sediment texture was made. At some sites, samples for later particle size analysis were also collected.

A summary of surface permeability measurements at Virkisjőkull and saturated permeability values estimated using the Laplace method (Reynolds et al. 1983) is presented in Table 6. The estimated permeability values span a wide range, even for sediments of similar types and in similar settings. These may be **upper estimates** of surface permeability, in part because the Laplace method tends to return a high estimate (Reynolds et al. 1983), and in part because of the limitations of the Guelph permeameter on these very high permeability sediments. The effective hydraulic conductivity (permeability) range of the Guelph permeameter is lower than many of the measurements at Virkisjőkull (Table 6): the manufacturers quote an effective range of 0.01 to 10 m/d (Soil Moisture Equipment Corp. 2012), while field tests on Quaternary glacial deposits in Scotland (which are likely to be similar to many of the sediment types at Virkisjőkull) gave an effective range of 0.001 to 40 m/d (MacDonald et al. 2012).

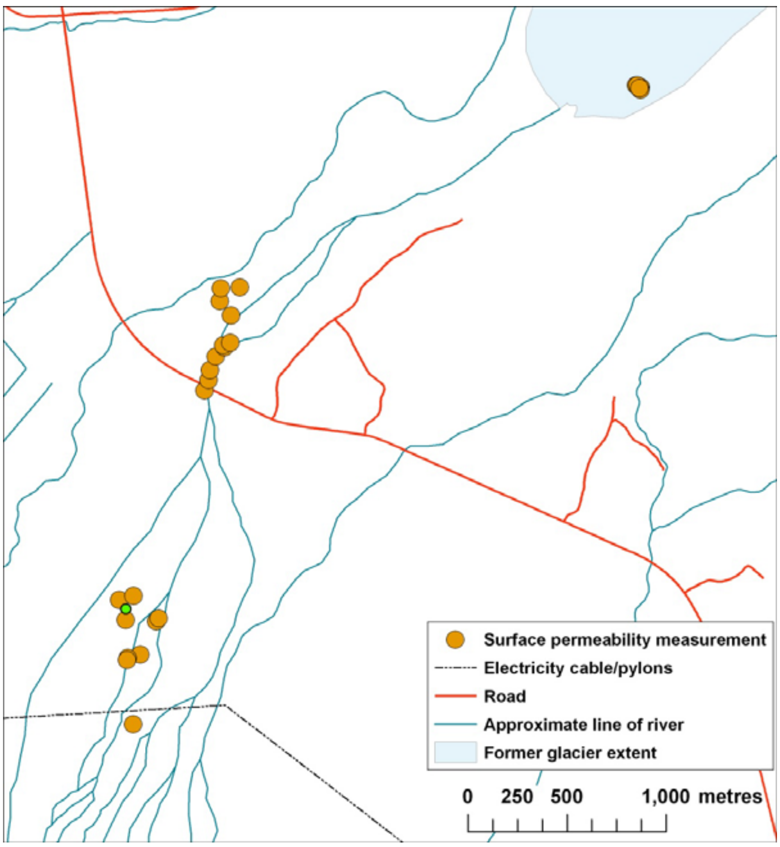


Figure 8 Location of surface permeability measurements at Virkisjőkull

Table 6 Summary of surface permeability measurements at Virkisjőkull

Test ID	Northing	Easting	Date	Hole depth (mm)	Hole diam-eter (mm)	5 cm head infiltration rate (cm/sec)	Site description	Kfs (cm/ min)	Kfs (m/d)
Sandur									
Site 1	63.95299	-16.84898	19/09/11	120	65	0.12	Made ground	1.03	14.83
Site 2	63.95345	-16.84853		140	70	0.85	General sandur	6.71	96.62
Site 3	63.9539	-16.84837		100	60	0.86	General sandur	7.60	109.4
Site 4	63.95451	-16.84773		140	65	1.07	General sandur	8.64	124.4
Site 5	63.95491	-16.84679		120	60	0.3	Sand	2.54	36.58
Site 6	63.955	-16.8469		140	60	0.5	Sand bar	4.14	59.62
Site 7	63.957	-16.8471		140	50	0.04	Silt and sand	0.38	5.47
Site 8	63.95511	-16.84616		100	120	1.2	General sandur	5.06	72.86
Site 9	63.95634	-16.84602		120	60	0.69	General sandur	5.38	77.47
Site 10	63.95759	-16.84697		120	50	0.74	Abandoned channel	6.56	94.46
Site 11	63.9576	-16.845		150	100	0.45	Abandoned channel	2.15	30.96
28/8(1)	63.94364	-16.85847	28/08/12	110	80	0.21	Inter-channel	1.53	22.03
28/8(2)	63.94381	-16.857	28/08/12	140	80	0.45	Abandoned channel	3.28	47.23
30/8(1)	63.94114	-16.85653	30/08/12	150	60	0.08	Abandoned channel edge	0.76[1]	10.96
30/8(2)	63.938	-16.8575	30/08/12	150	100	0.7	Abandoned channel centre	4.11[1]	59.20
30/8(3)	63.941	-16.85781	30/08/12	150	70	0.12	Abandoned channel	0.99[1]	14.27
30/8(4)	63.94092	-16.85789	30/08/12	150	100	0.25	Abandoned channel	1.47[1]	21.18
30/8(5)	63.94272	-16.85789	30/08/12	150	70	0.42	Abandoned channel	3.46[1]	49.84
7/9(1)	63.94261	-16.85475	07/09/12	110	60	0.8	Abandoned channel edge – sand bank	7.55[1]	108.7
7/9(2)	63.94275	-16.8545	07/09/12	120	70	1.07	Abandoned channel edge – sand bank	8.81[1]	126.9
Pro-glacial area									
Site A[2]	63.96612	-16.80354		130	50	0.02	Clayey till	0.01	0.14
Site B				100	50	1.75	Pyroclastic substrate	14.61	210.4
Site C	63.96598	-16.8031		100	100	0.05	Pyroclastic substrate	0.23	3.31
Site D[2]	63.96598	-16.8031		120	50	0.06	Glacial till	0.03	0.43
Site E	63.96602	-16.80306		120	50	0.08	Pyroclastic substrate	0.63	9.07
GP1			18/04/12	80	60	0.21	Pyroclastic substrate	1.38	19.87
GP2			18/04/12	100	50	0.01	Pyroclastic substrate	0.07	1.01
GP4	63.96611	-16.80342	18/04/12	90	60	0.1	Pyroclastic substrate	0.63	9.07
GP5	63.96592	-16.80311	18/04/12	70	60	0.24	Pyroclastic substrate	1.48	21.31
GP6	63.966	-16.8032	18/04/12	60	50	0.04	Pyroclastic substrate	0.28	4.03

[1] Hole wetted before test
[2] Guelph permeameter inner ring only used

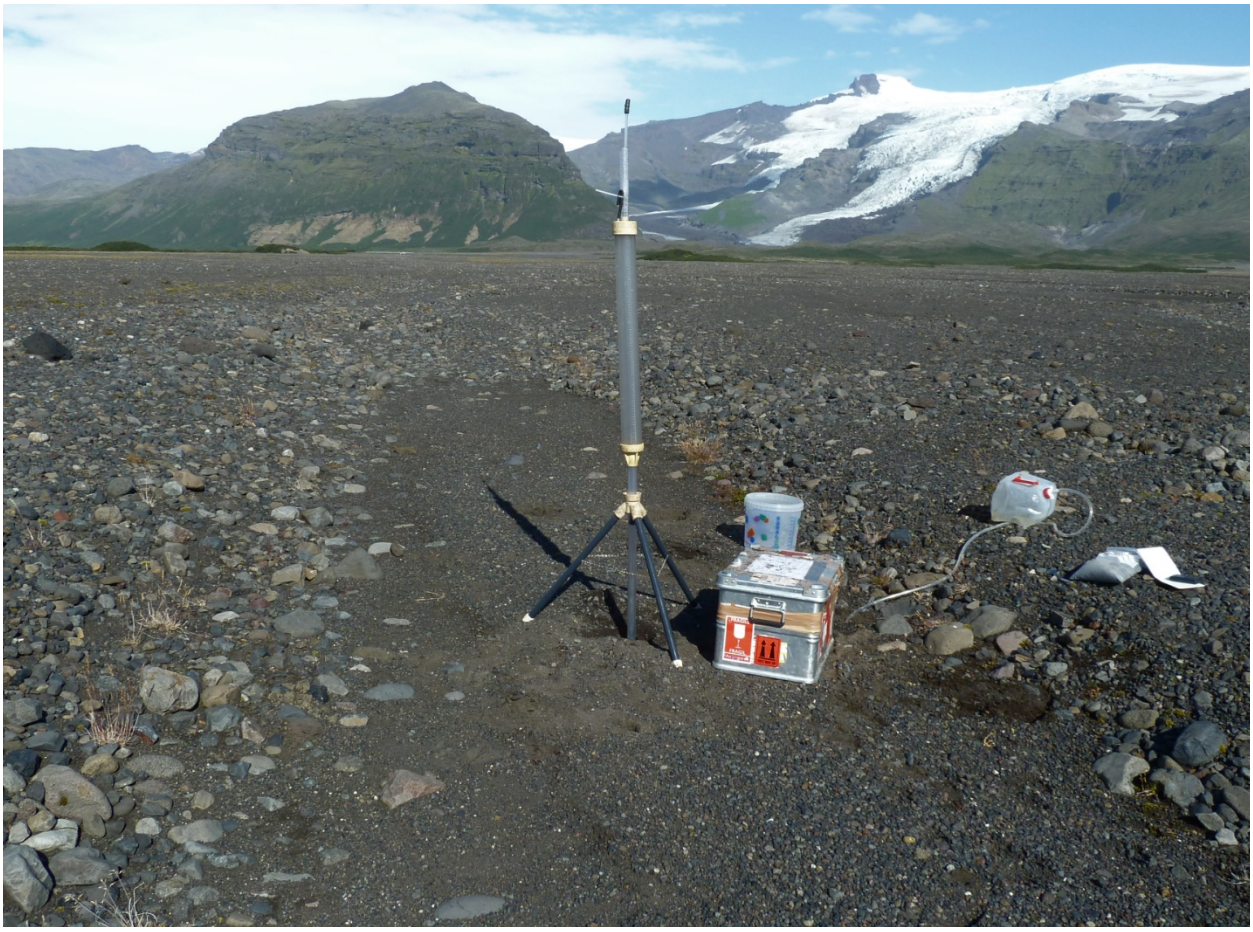


Figure 9 Example of field setup for surface permeability tests using Guelph permeameter

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

MACDONALD A M, MAURICE L, DOBBS M R, REEVES H J AND AUTON C A. 2012. Relating in situ hydraulic conductivity, particle size and relative density of superficial deposits in a heterogeneous catchment. *Journal of Hydrology*, 434-43. 130-141.

REYNOLDS W D, ELRICK D E AND TOPP G C. 1983. A re-examination of the constant head well permeameter method for measuring saturated hydraulic conductivity above the water table. *Soil Science* 136, 250-268.

SOIL MOISTURE EQUIPMENT CORP. 2012. Operating instructions for Guelph permeameter. December 2012. Accessed from HTTP://WWW.SOILMOISTURE.COM/PDF/82800K1.PDF on 20 February 2012.

Appendix 1 Borehole logs

Abbreviations used in the following logs are:

mbgl – metres below ground level
rod – rod number during drilling. Each rod was 3m long
water – note of where water was encountered on drilling
screen – perforated screen

Virkis U1


mbgl
rod
water
screen
1
well sorted fine to coarse sand
1
mod well sorted very coarse sand/granules to small pebbles
2
mod to poorly sorted, very coarse sand/granules to large pebbles
3
water
bimodal: med-coarse sand and med to large pebbles
2
4
mod well sorted coarse sand/granules to medium pebbles
5
mod well sorted coarse sand/granules to medium pebbles
6
mod to poorly sorted med sand to large pebbles
3
7
8
mod sorted med sand to med pebbles
9
coarse sand with some small pebbles, a lot of silt/fine sand
4
10
11
mod to poorly sorted fine sand to large pebbles, less silt/fine sand than above
12
granules to medium pebbles
5
13
14
mod sorted fine to coarse sand
15

Virkis U2

mbgl	rod	water		screen	Description
	1				Mod sorted coarse sand to medium pebbles with some large pebbles
1					
2					
3					
	2				Well sorted coarse sand to small pebbles with some medium pebbles
4					
5					Mod sorted, fine to very coarse sand and granules and medium to large/very large pebbles
		water			
6					
	3				Poorly sorted, fine to very coarse sand and granules up to large/very large rounded pebbles
7					
8					Mod sorted, fine to very coarse sand and granules up to medium to large pebbles. Higher propertion of fine material than previous 2 bags - maybe 50% finer fraction. Very muddy sample pre-wash, clumped together
9					
	4				Mod sorted, fine to very coarse sand and granules up to medium to large pebbles. Maybe 50%finer fraction.
10					
			pumice		Large fines component - very clumpy, slurry-like on drilling. At least 50-70% well sorted fine to medium sand with larger clasts up to large pebbles
11					
			pumice		At least 50-70% well sorted medium to coarse sand, larger clasts up to large pebbles
12					
	5		pumice		Slightly muddy but flowing pre-wash sample. Mod sorted, c. 50% medium to coarse sand with c. 10-30% larger clasts from small to large pebbles
13					
			pumice		Mod sorted, 50-70% coarse sand to granules, larger fraction medium to large pebbles
14					
			pumice		Muddy pre wash sample, mod sorted, 50-75% medium sand to granuleslarger fraction medium to large pebbles
15					Fines noted on drilling. Mod sorted, c. 50-60% medium to coarse sand, with very small proportion within that of granules and fine sand. Larger fraction medum to large pebbles

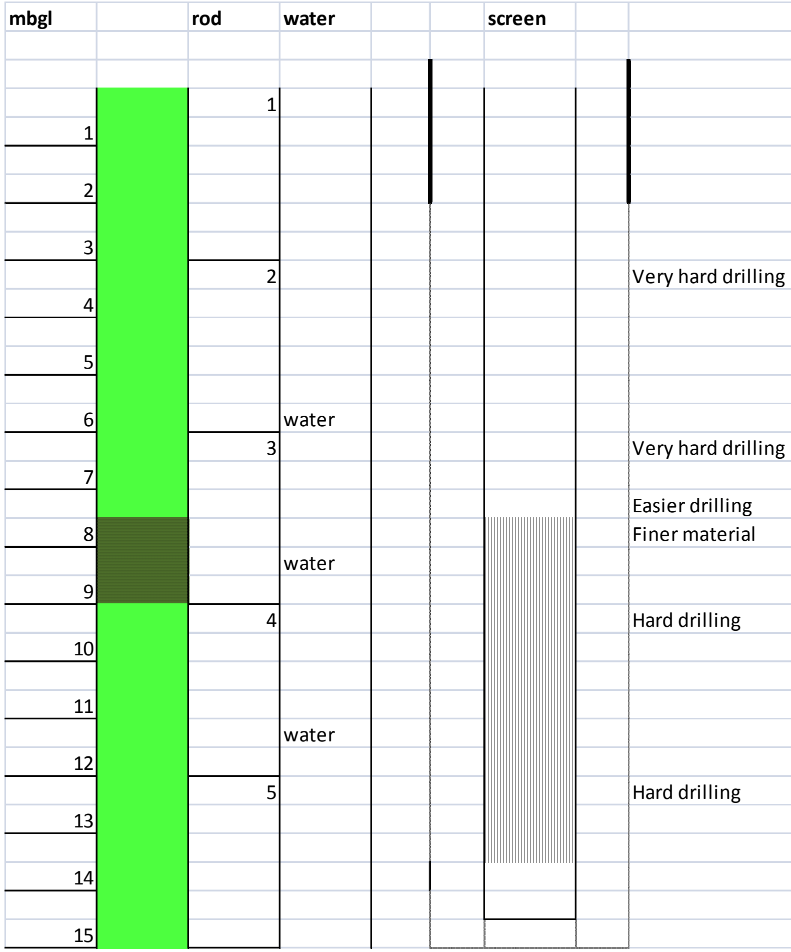
Virkis M1

mbgl		rod	water			screen		
		1						Fines on drilling; poorly sorted; remainder is medium to very coarse sand to c. 50% small to large pebbles
1								
2								
3			water					
		2						Poorly sorted, med to very coarse sand with small to medium pebbles
4								Mod sorted, dominantly med to very coarse sand to small pebbles with c. 10-20% large pebbles
5								
6								
		3		Pumice				Muddy before washing, remainder is mod sorted: finest fraction is coarse sand with granules to med pebbles and c. 10% large pebbles.
7				Pumice				Very muddy before washing, remainder is mod to poorly sorted fine to coarse sand with small to large pebbles. Higher fine sand fraction than previous bags
8								
9								
		4		Pumice				Very muddy, lots fines before washing, poorly sorted, remainder of sample is 50-70% fine to coarse sand (high proportion of fine sand) and small to large pebbles
10								Lots fines on drilling, poorly sorted, remainder of sample is very fine to coarse sand and granules, c. 10% large pebbles and rest small to med pebbles
11								
12								
		5		Plant stalk				Fines before washing; mod sorted, rest= c. 90% < small pebbles: 5-10% fine sand, 10% med & occ lg pebbles, dominant fraction coarse sand & some granules
13								
								Mod sorted, 10% med sand, 50-70% coarse sand to granules, rest is small to large pebbles
14								
								Fines before washing/on drilling; remainder is very well sorted coarse sand with occ small to med pebble
15				Ash? Organic?				Poorly sorted, coarse sand to large pebbles with large component of slurry/fine oily material (ash?)

Virkis M2

mbgl		rod	water			screen		
		1						
1								
2								
			water					
3								
		2						Stteady drilling throughout rod, no softer/easier layers. Generally poorly sorted, sand to pebbles
4								
5								
6								
		3						Softer, faster drilling throughout rod 3 - more fines indicated, within overall moderately sorted sand to pebbles
7								
8								
9								
		4						Drill progress slower than rod 3, large chips.
10								
								Easy drilling - finer material
11								
								Harder drilling - harder band
12								
		5						Hard drilling
13								
			water					Hard drilling
14				Woody material				
15								

Virkis M3


mbgl
rod
water
screen
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
1
2
3
4
5
water
water
water
Very hard drilling
Very hard drilling
Easier drilling
Finer material
Hard drilling
Hard drilling

Virkis L1

mbgl		rod	water			screen		
		1						Mod to well sorted, c. 70% coarse sand to granules, c. 20% small pebbles, c. 10% medium with occ large pebble
1								
2								
3			water					
		2						Mod to well sorted, c. 70% coarse sand to granules, c. 20% small pebbles; remainder med pebbles with occ large pe
4								
5								
6								
		3						Mod to well sorted, c. 50-60% coarse sand to granules, c. 20% small pebbles, remainder med to large pebbles
7								
8								Mod to poorly sorted, c. 50% med sand to granules, c. 30-40% small to med pebbles
9								
		4		pumice				Mod to well sorted, c. 70% med to coarse sand, remainder small to med pebbles
10								
11								
12								
		5		pumice				Lots of fines on drilling; remainder is well sorted, very uniform med sand with some fine and coarse sand
13								
14								
15								

Virkis L2

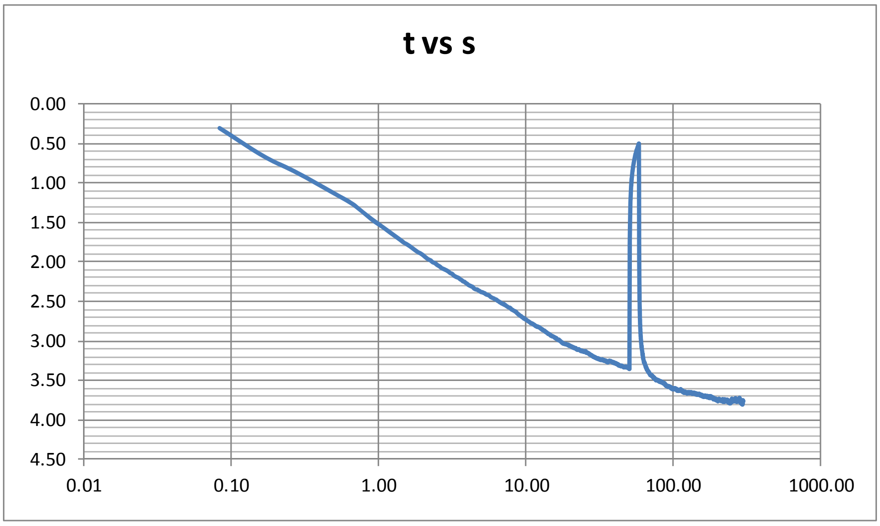
mbgl		rod	water			screen		
		1						Easy drilling. Moderately to well sorted, dominantly coarse sand and granules with some pebbles
1								
2								
			water					
3								
		2						Easy drilling. Moderately to well sorted, dominantly coarse sand to granules with some pebbles
4								
5								
			water					Some finer material, otherwise moderately to well sorted, dominantly coarse sand to pebbles
6								
		3						Moderately to poorly sorted, medium sand to granules to medium pebbles
7								Some finer material
8								
9								

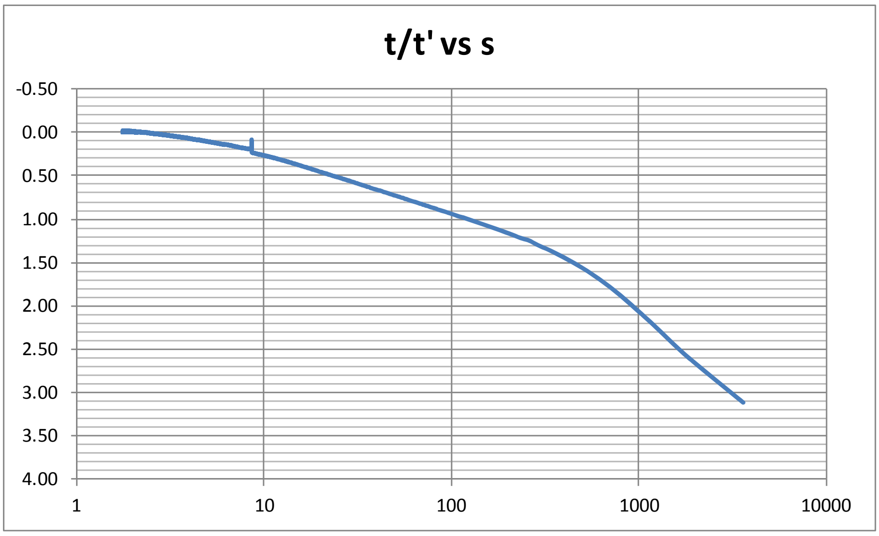
Virkis L3

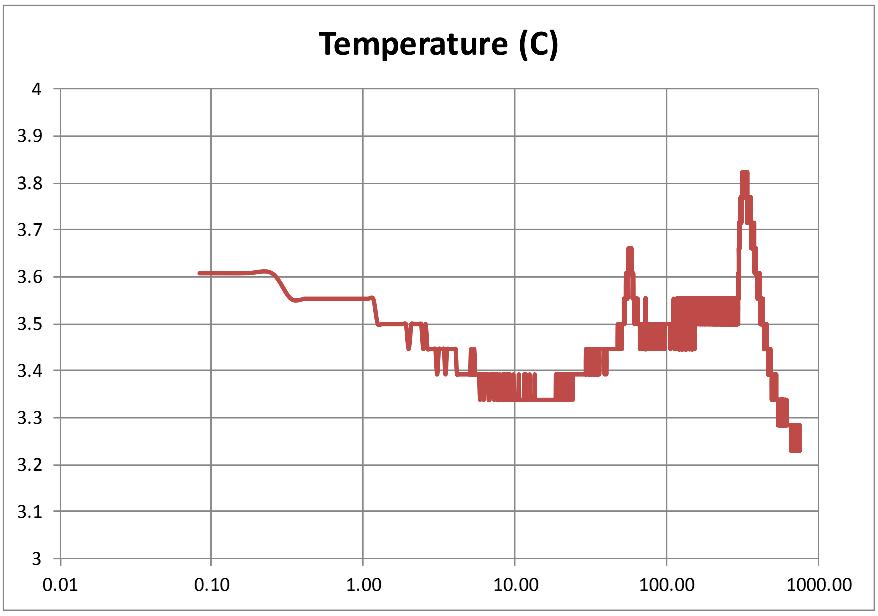
mbgl		rod	water			screen		
		1						Easy drilling. Moderately to well sorted, dominantly coarse sand and granules with some pebbles
1								
2								
			water					
3								
		2						Firmer drilling for 0,5m then lots of fine material, with medium sand to granules and some pebble
4								
5								
			water					
6								
		3						Moderately to poorly sorted, medium sand to granules to medium pebbles
7								
8								Increase in finer material, with sand to pebbles
9								

Appendix 2 Test pumping results

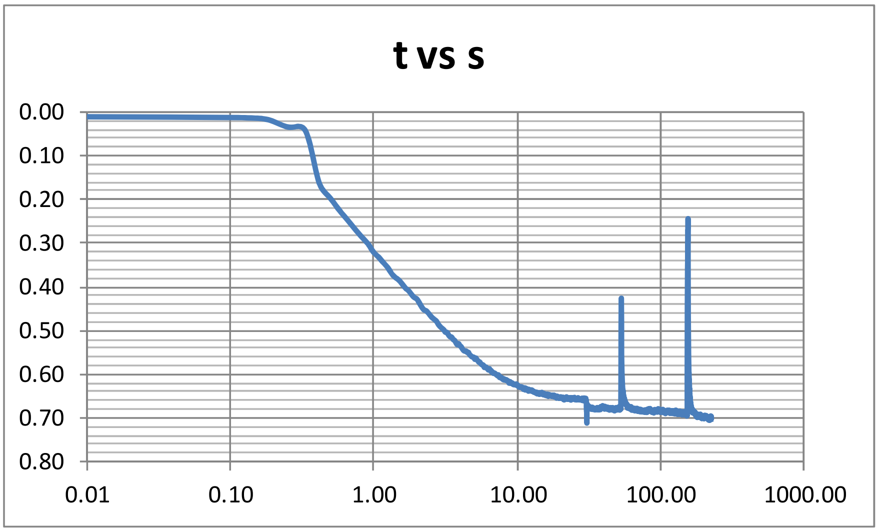
U1

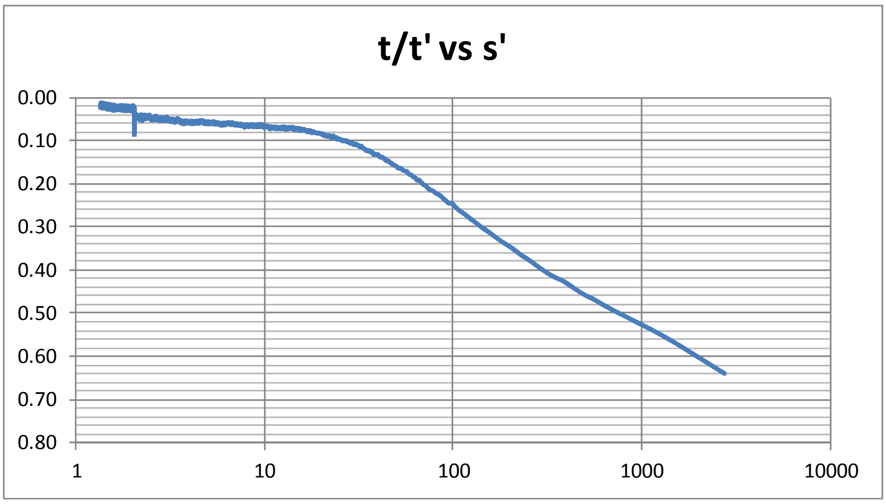






U2


t vs s
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.01
0.10
1.00
10.00
100.00
1000.00


t/t' vs s'
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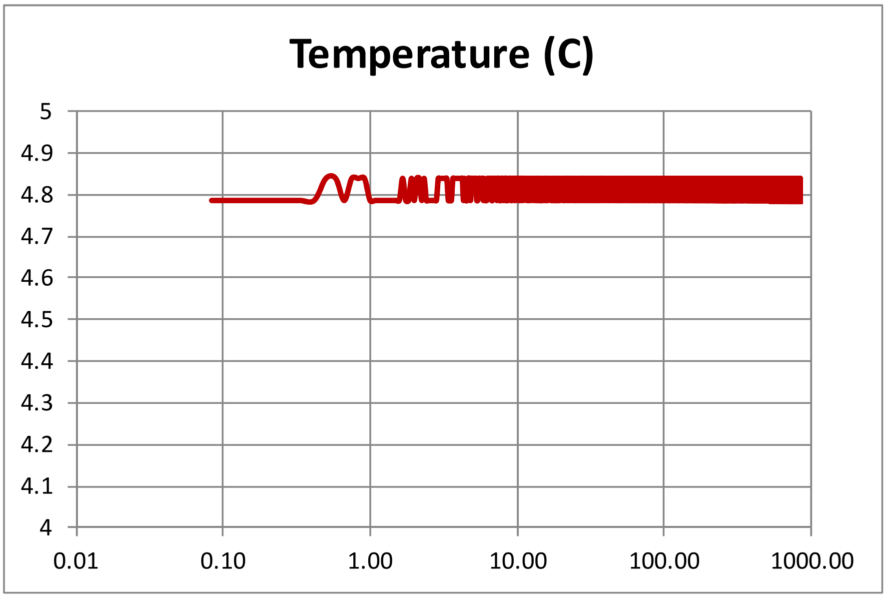
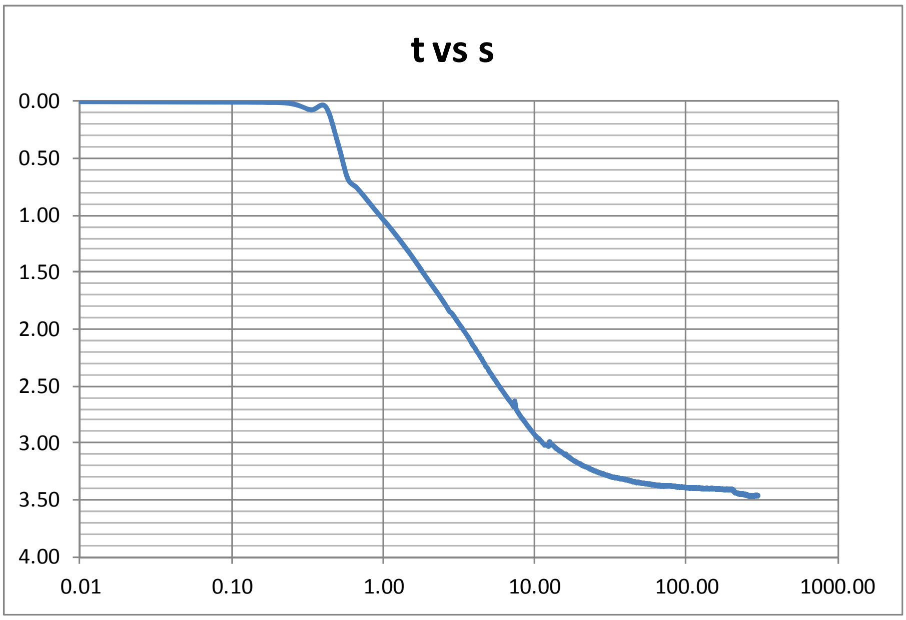
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
1
10
100
1000
10000


Temperature (C)
5
4.9
4.8
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4
0.01
0.10
1.00
10.00
100.00
1000.00

M1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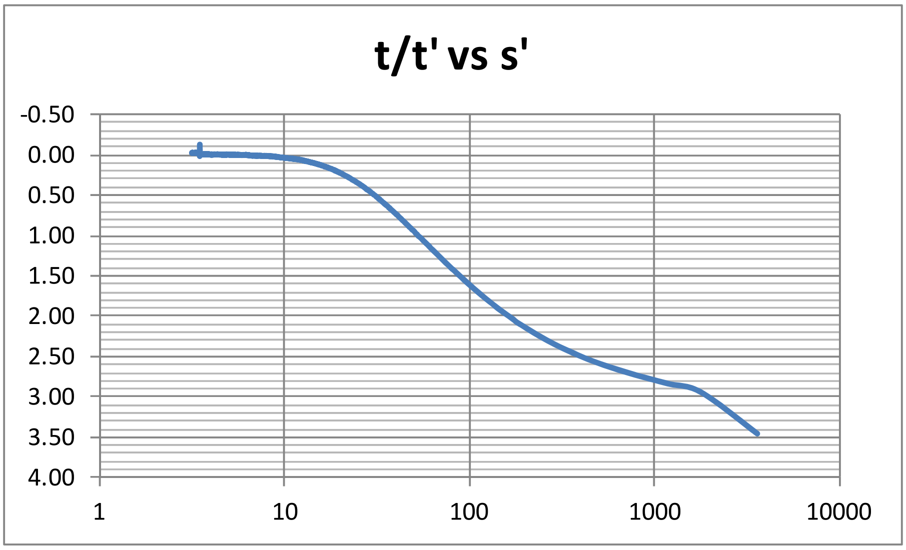
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
0.01
0.10
1.00
10.00
100.00
1000.00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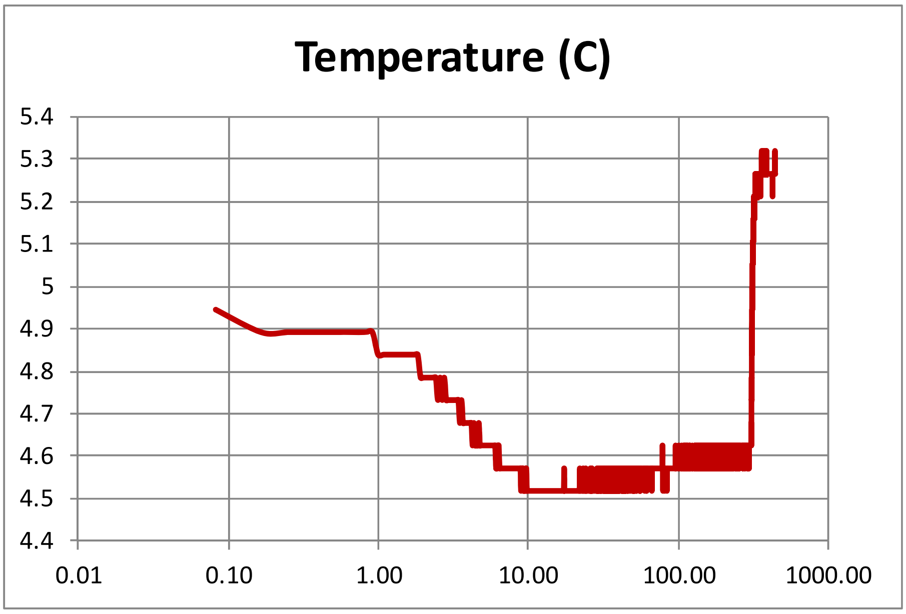
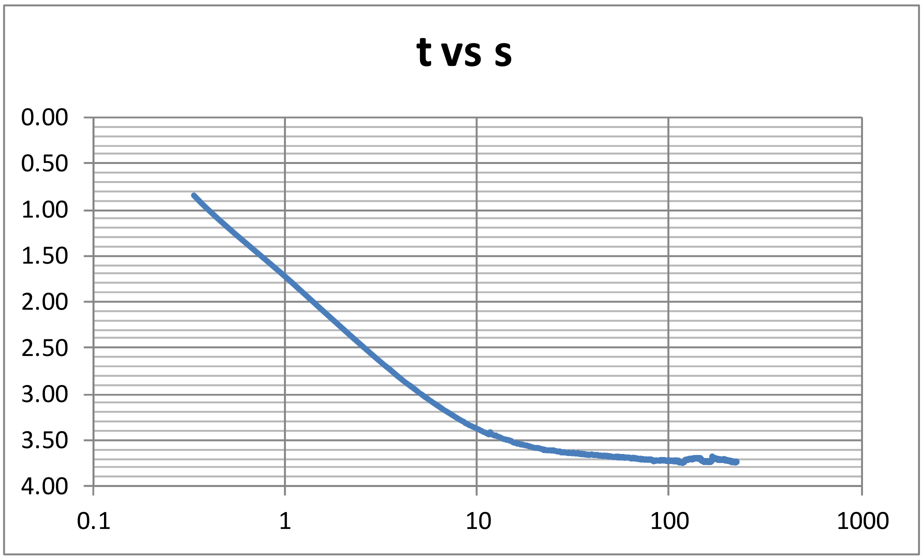
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
1
10
100
1000
10000


Temperature (C)
5.4
5.3
5.2
5.1
5
4.9
4.8
4.7
4.6
4.5
4.4
0.01
0.10
1.00
10.00
100.00
1000.00

M2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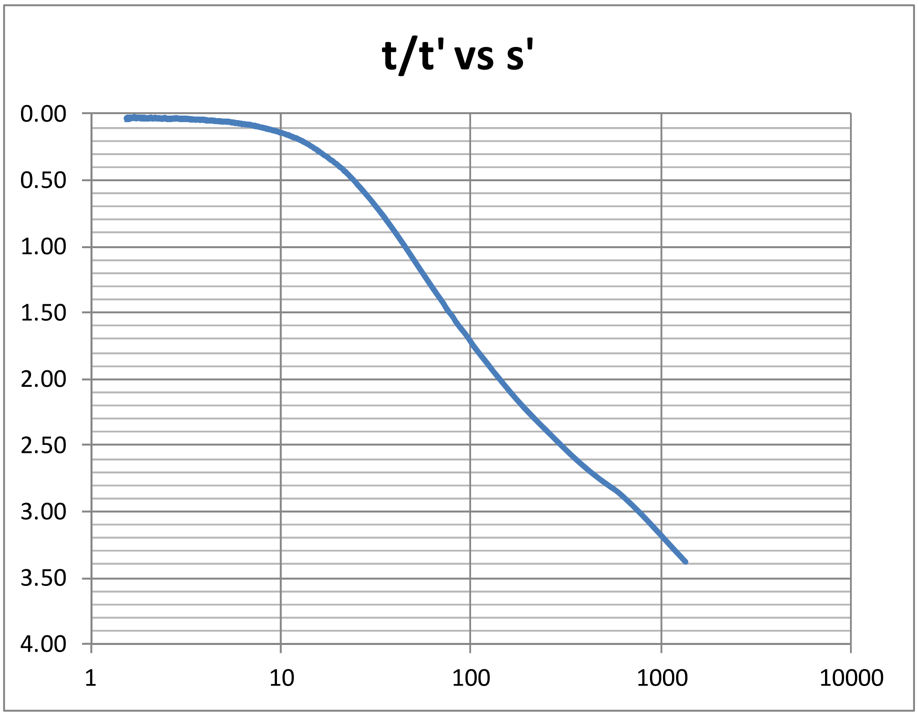
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
0.1
1
10
100
1000


t/t' vs s'
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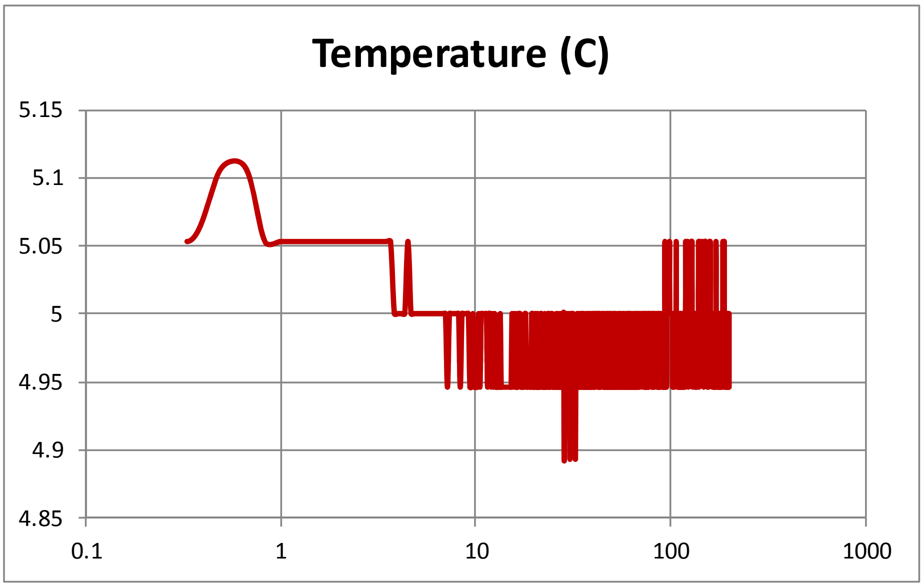
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
1
10
100
1000
10000


Temperature (C)
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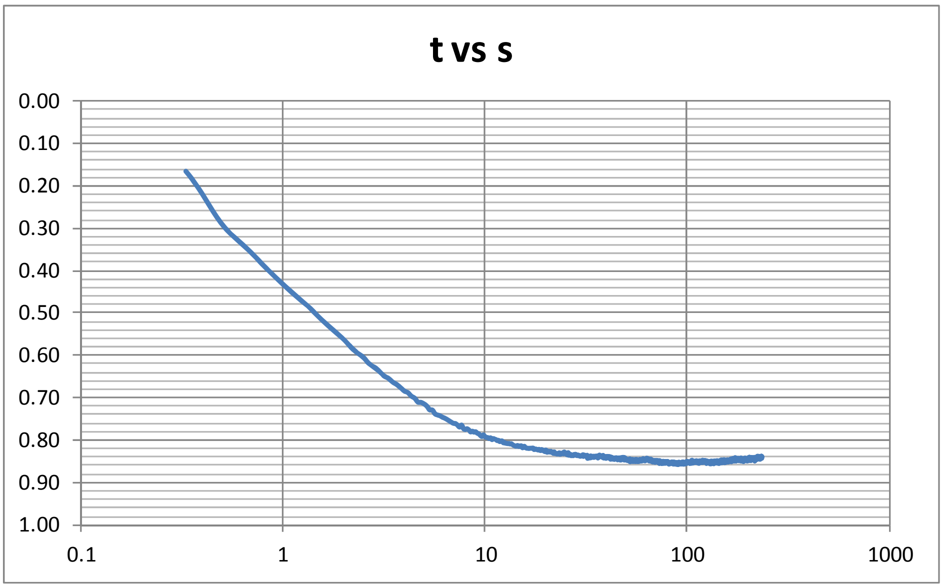
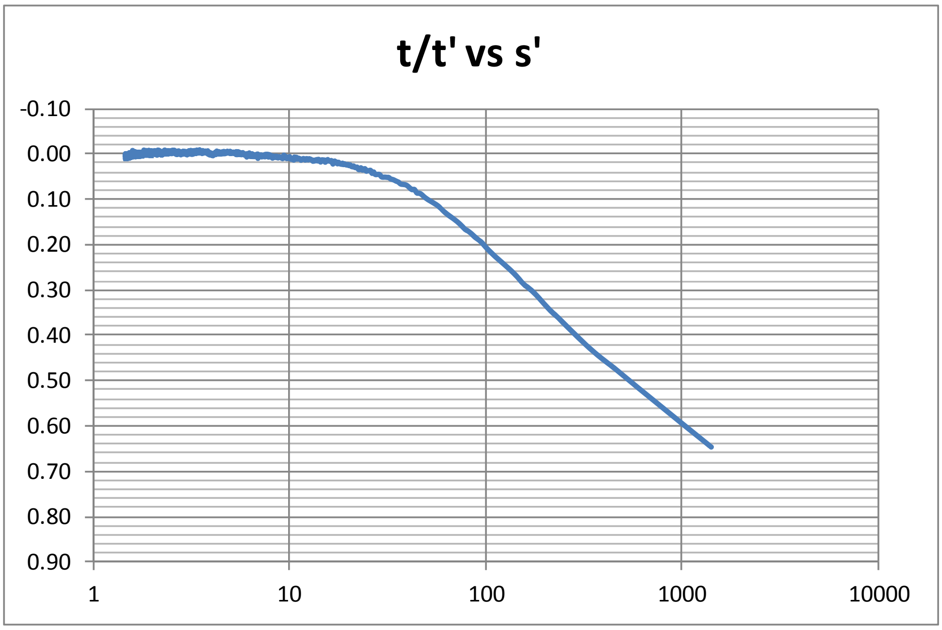
5.1
5.05
5
4.95
4.9
4.85
0.1
1
10
100
1000

M3


t vs s
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
0.1
1
10
100
1000


t/t' vs s'
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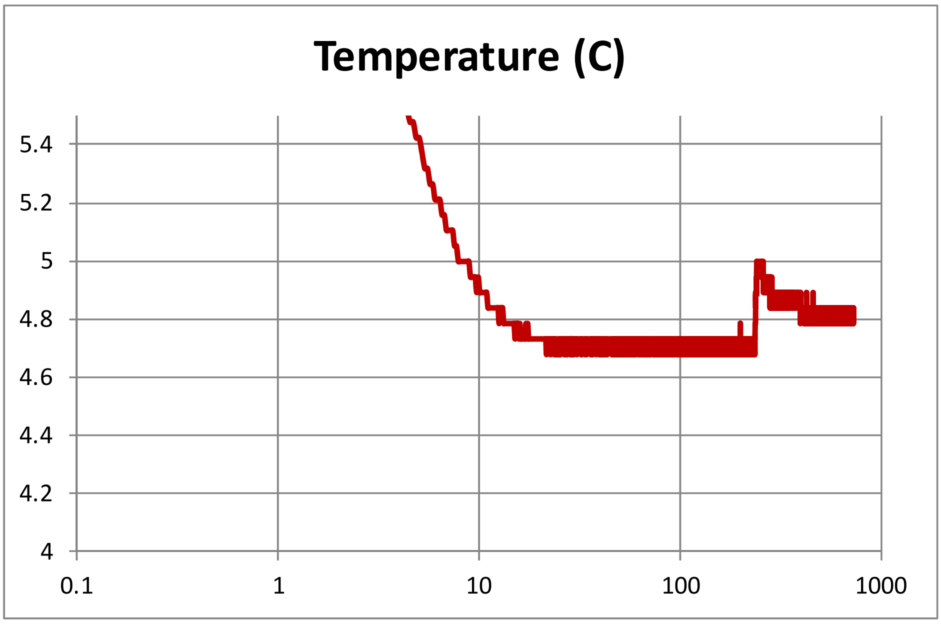
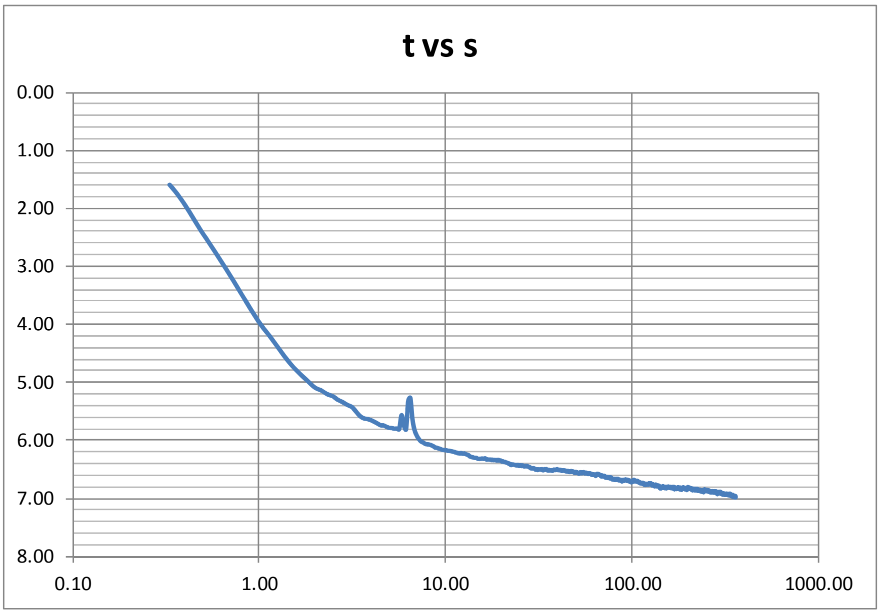
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1
10
100
1000
10000


Temperature (C)
5.4
5.2
5
4.8
4.6
4.4
4.2
4
0.1
1
10
100
1000

L1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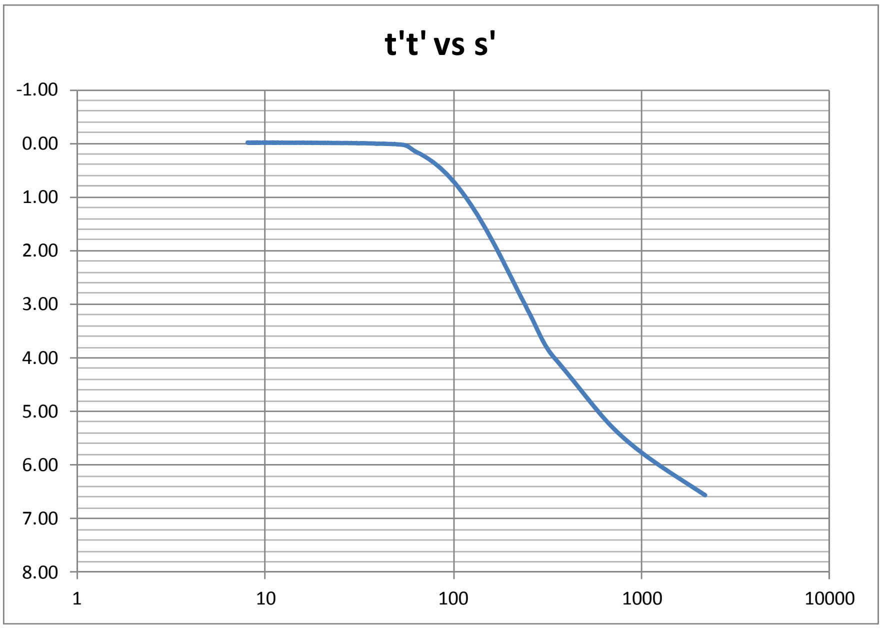
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
0.10
1.00
10.00
100.00
1000.00


t't' vs s'
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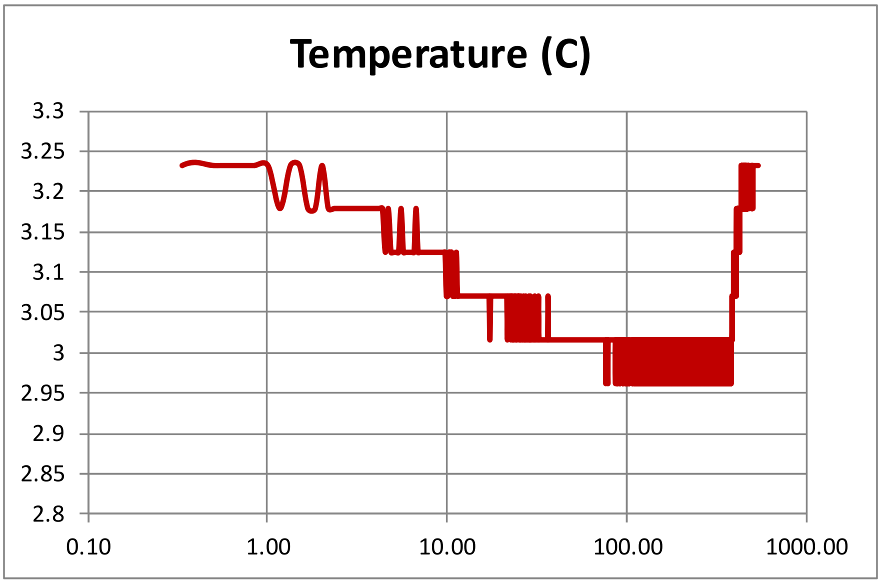
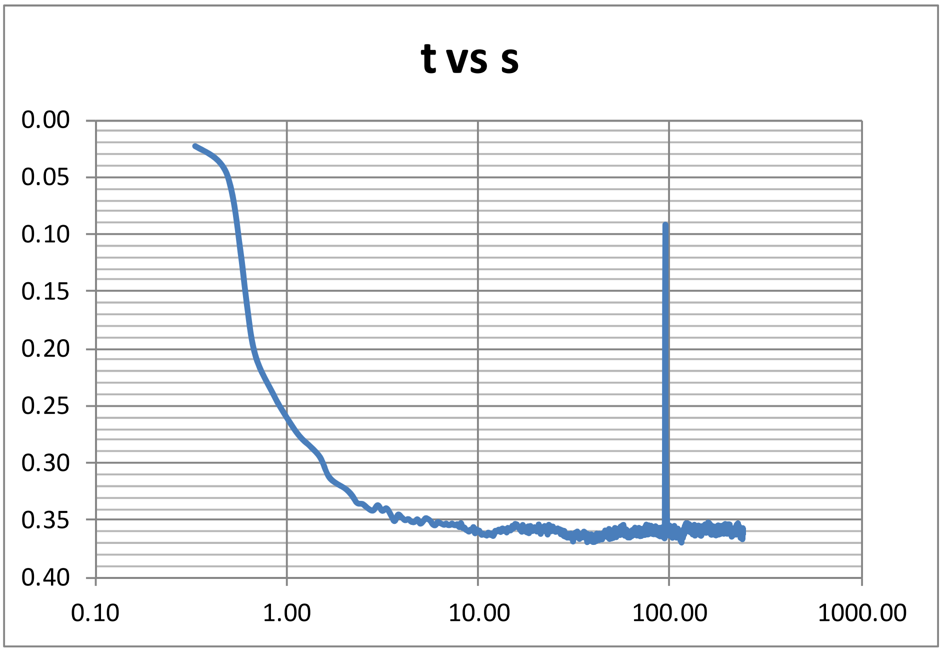
2.00
3.00
4.00
5.00
6.00
7.00
8.00
1
10
100
1000
10000


Temperature (C)
3.3
3.25
3.2
3.15
3.1
3.05
3
2.95
2.9
2.85
2.8
0.10
1.00
10.00
100.00
1000.00

L2


t vs s
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0.25
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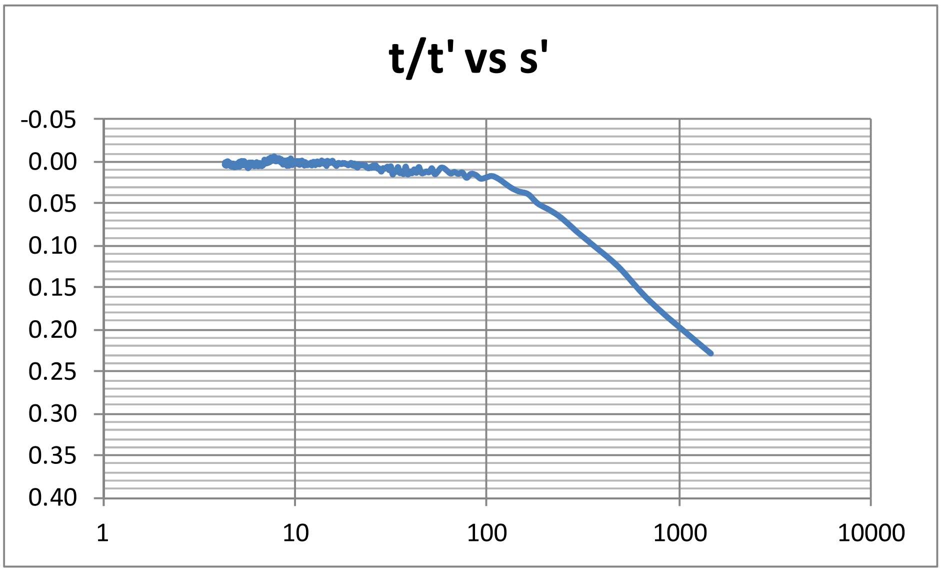
1.00
10.00
100.00
1000.00


t/t' vs s'
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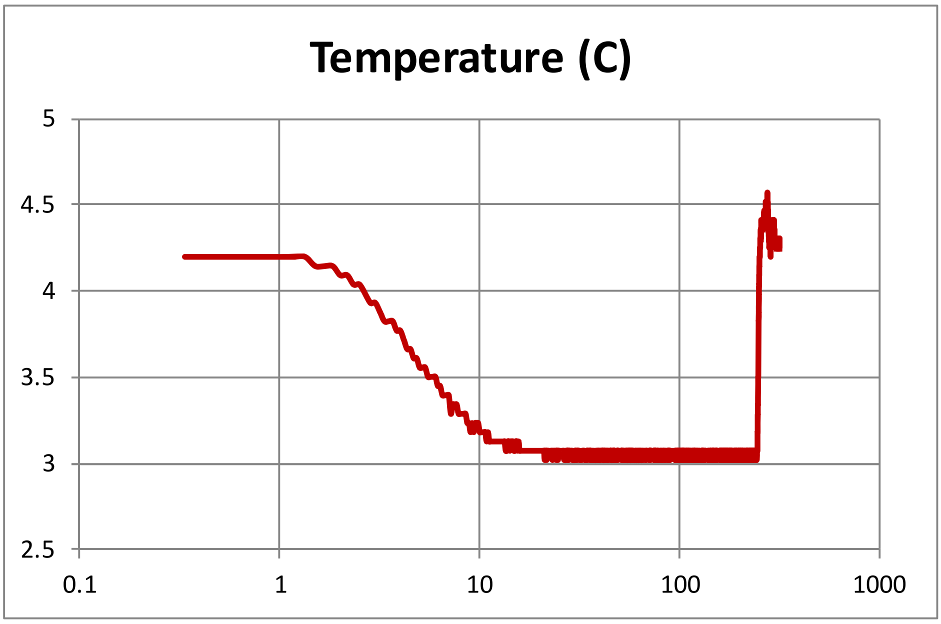
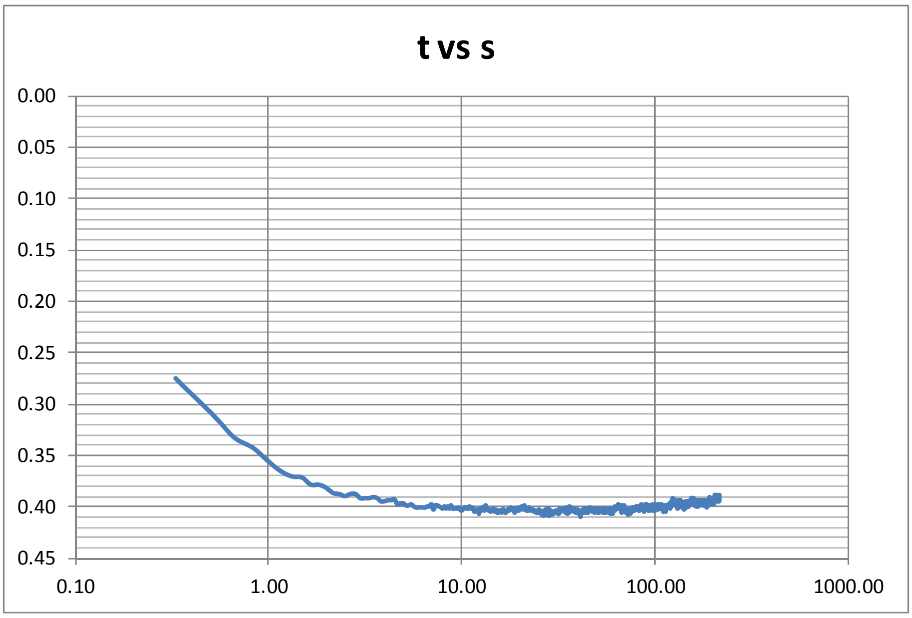
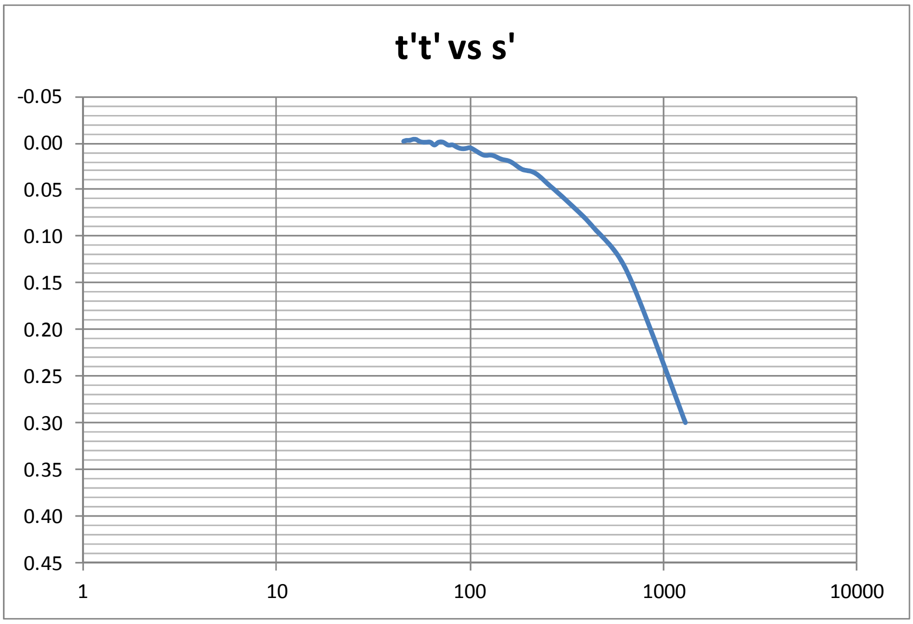
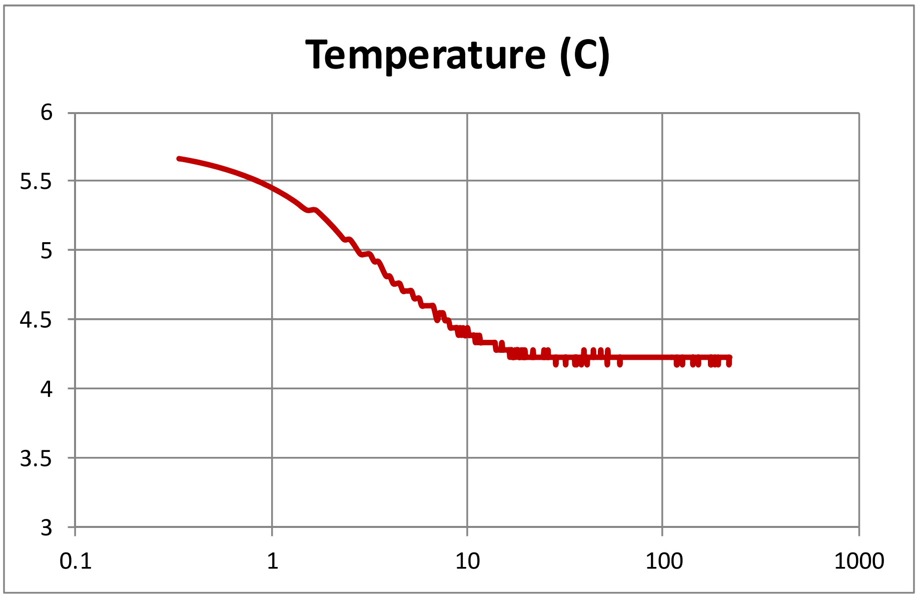
0.15
0.20
0.25
0.30
0.35
0.40
1
10
100
1000
10000


Temperature (C)
5
4.5
4
3.5
3
2.5
0.1
1
10
100
1000

L3

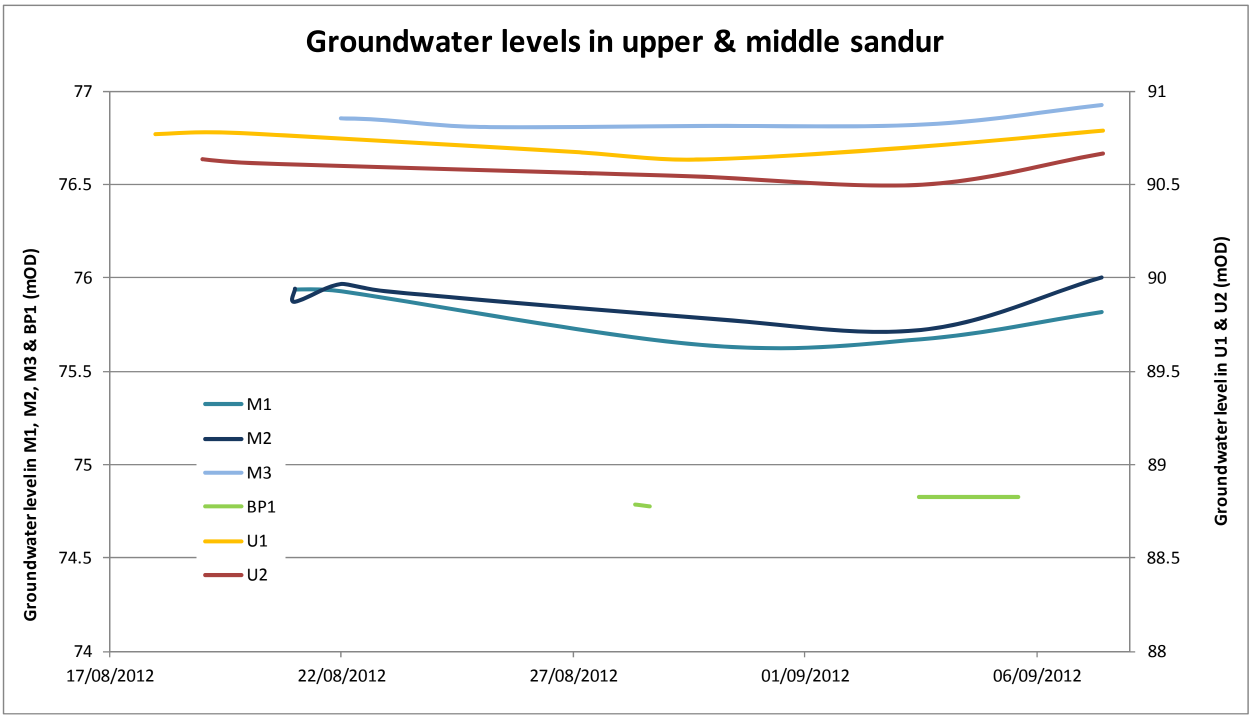

t vs s
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.10
1.00
10.00
100.00
1000.00

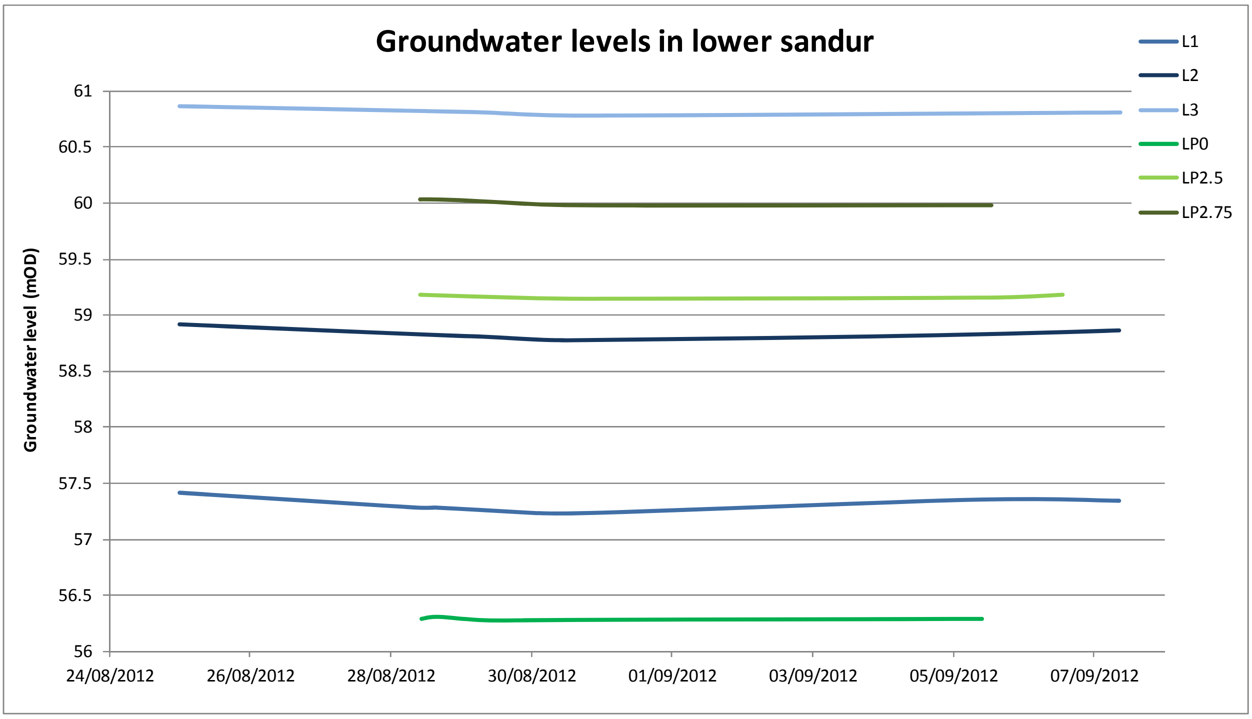

t't' vs s'
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
1
10
100
1000
10000


Temperature (C)
6
5.5
5
4.5
4
3.5
3
0.1
1
10
100
1000

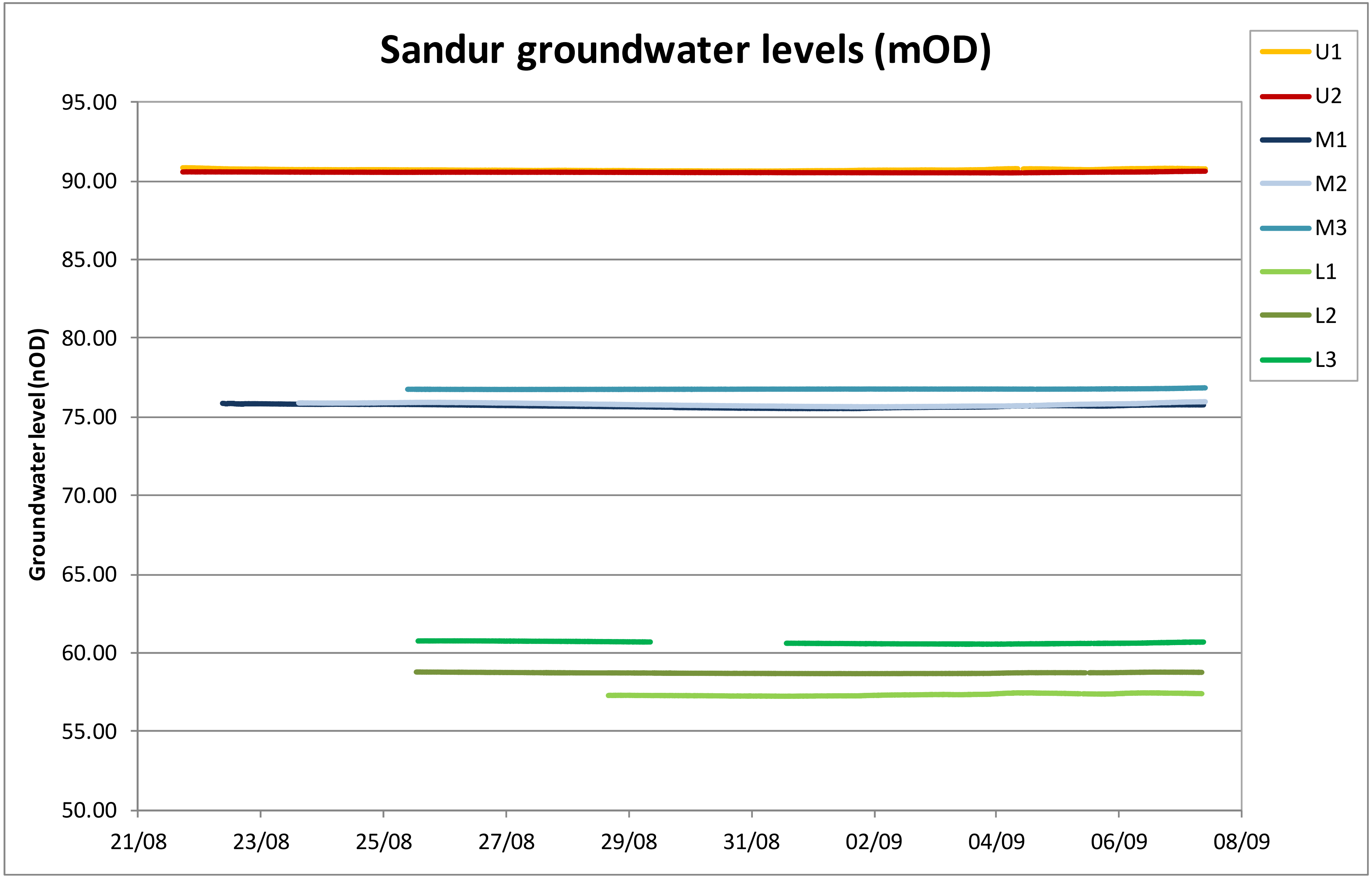
Appendix 3 Groundwater level and temperature monitoring during summer 2012 field campaign

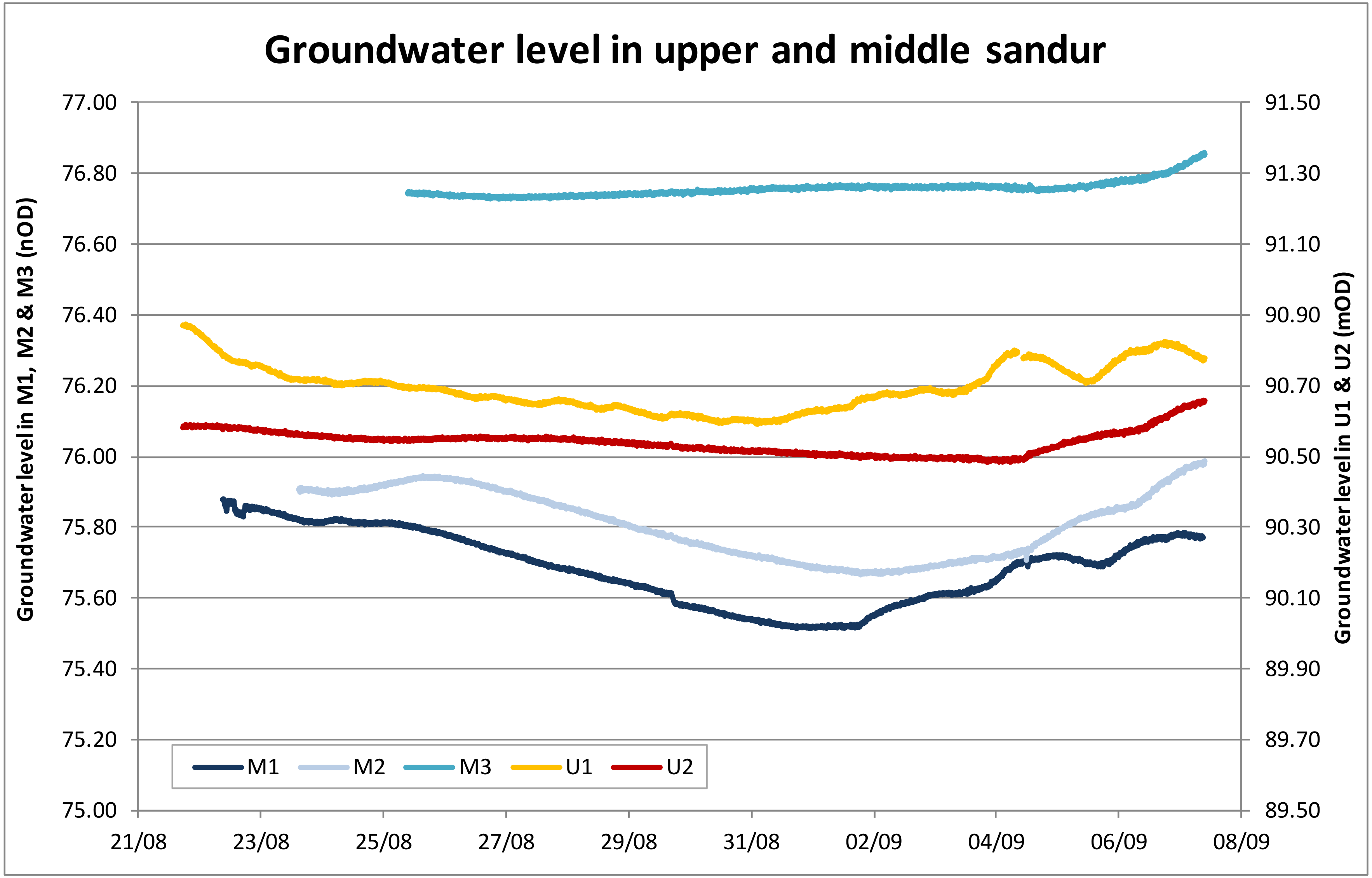
A3.1 Manual dips/spot measurements

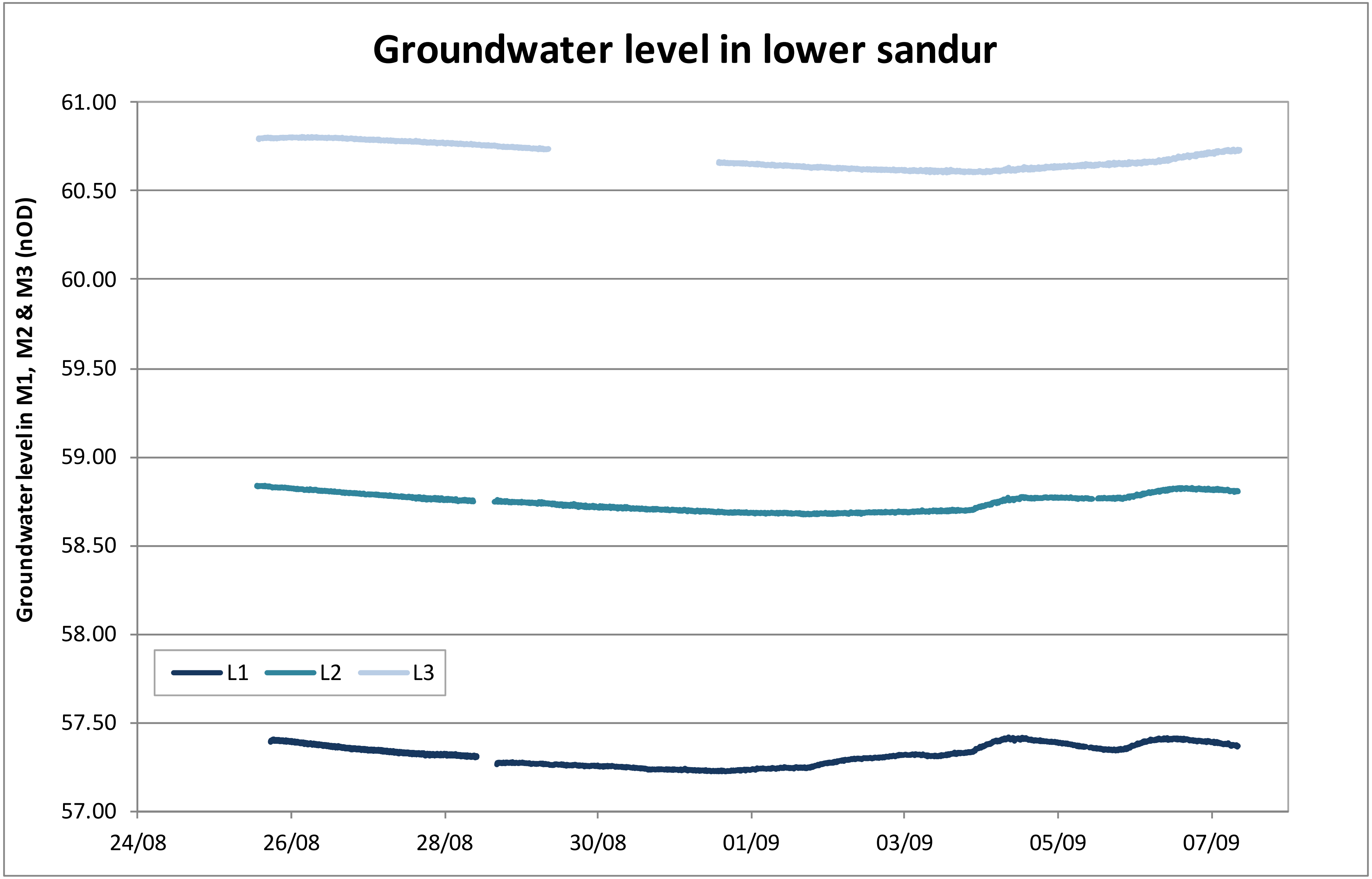


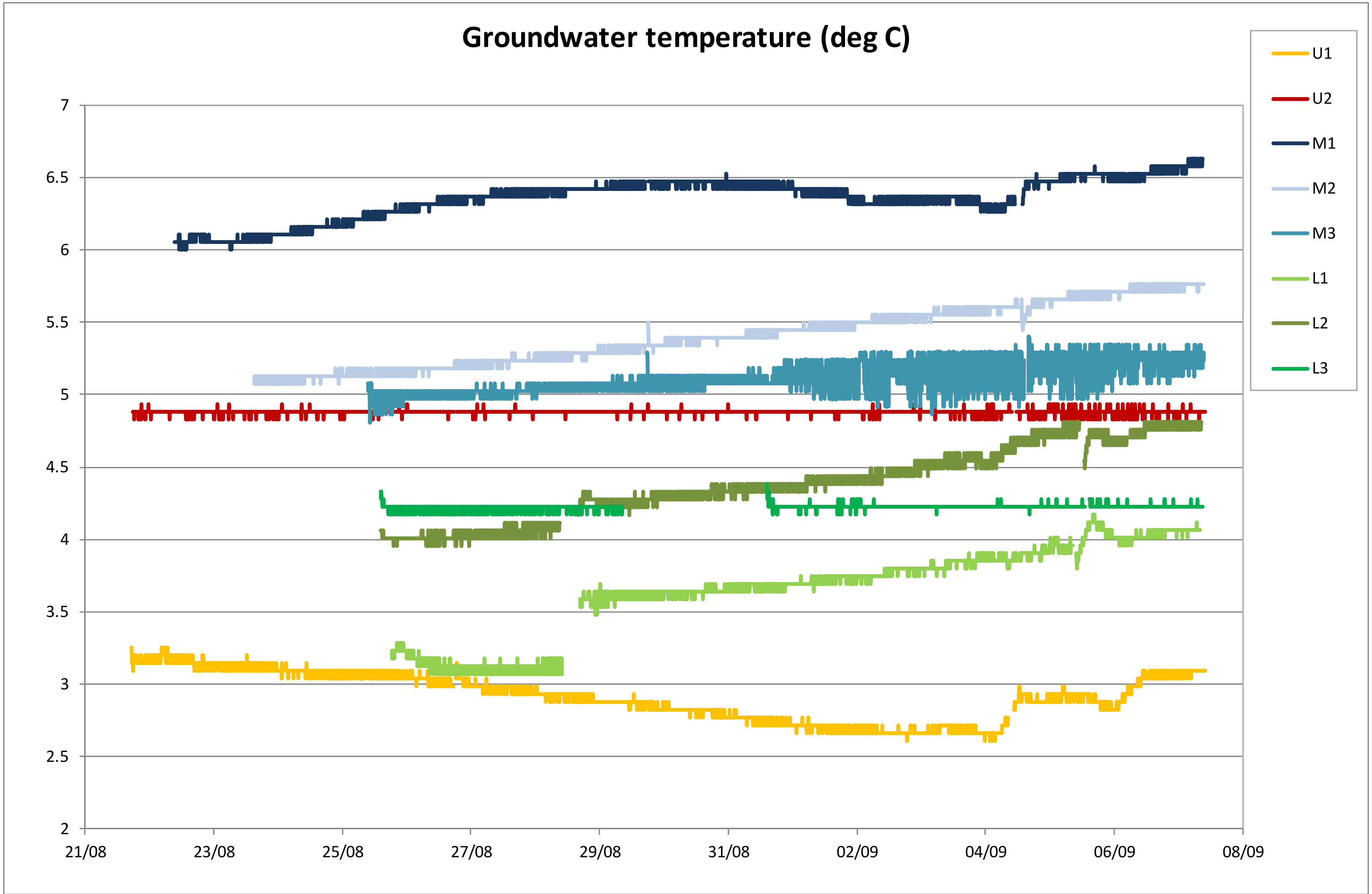


A3.2 Logger data




Groundwater level in upper and middle sandur
Groundwater level in M1, M2 & M3 (nOD)
Groundwater level in U1 & U2 (mOD)
77.00
76.80
76.60
76.40
76.20
76.00
75.80
75.60
75.40
75.20
75.00
91.50
91.30
91.10
90.90
90.70
90.50
90.30
90.10
89.90
89.70
89.50
21/08
23/08
25/08
27/08
29/08
31/08
02/09
04/09
06/09
08/09
M1
M2
M3
U1
U2

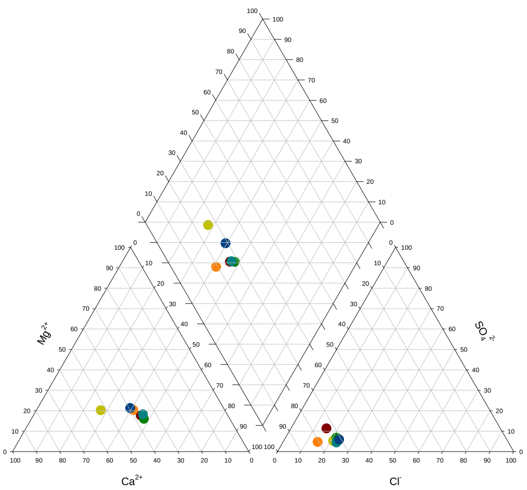

Groundwater level in lower sandur
Groundwater level in M1, M2 & M3 (mOD)
61.00
60.50
60.00
59.50
59.00
58.50
58.00
57.50
57.00
24/08
26/08
28/08
30/08
01/09
03/09
05/09
07/09
L1
L2
L3


Groundwater temperature (deg C)
U1
U2
M1
M2
M3
L1
L2
L3
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
21/08
23/08
25/08
27/08
29/08
31/08
02/09
04/09
06/09
08/09

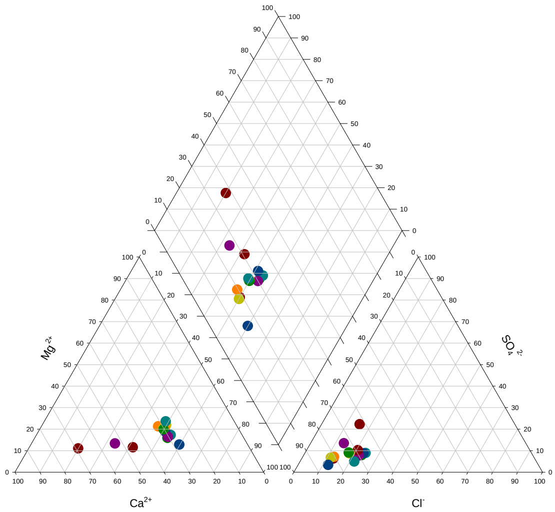
Appendix 4 Preliminary interpretation of water chemistry data

A4.1 Piper plots illustrating major ion chemistry of different water types at Virkisjőkull and nearby rivers

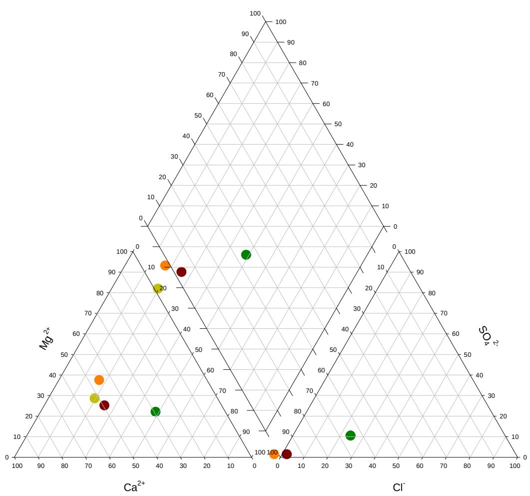
Shallow groundwater



River water



Glacier water



Note: the major ion chemistry data for the latest samples collected in September 2012, including from the boreholes, have not yet been analysed.

A4.2 Stable isotopes (d18O‰- d2H‰) in different water types at Virkisjőkull and nearby rivers