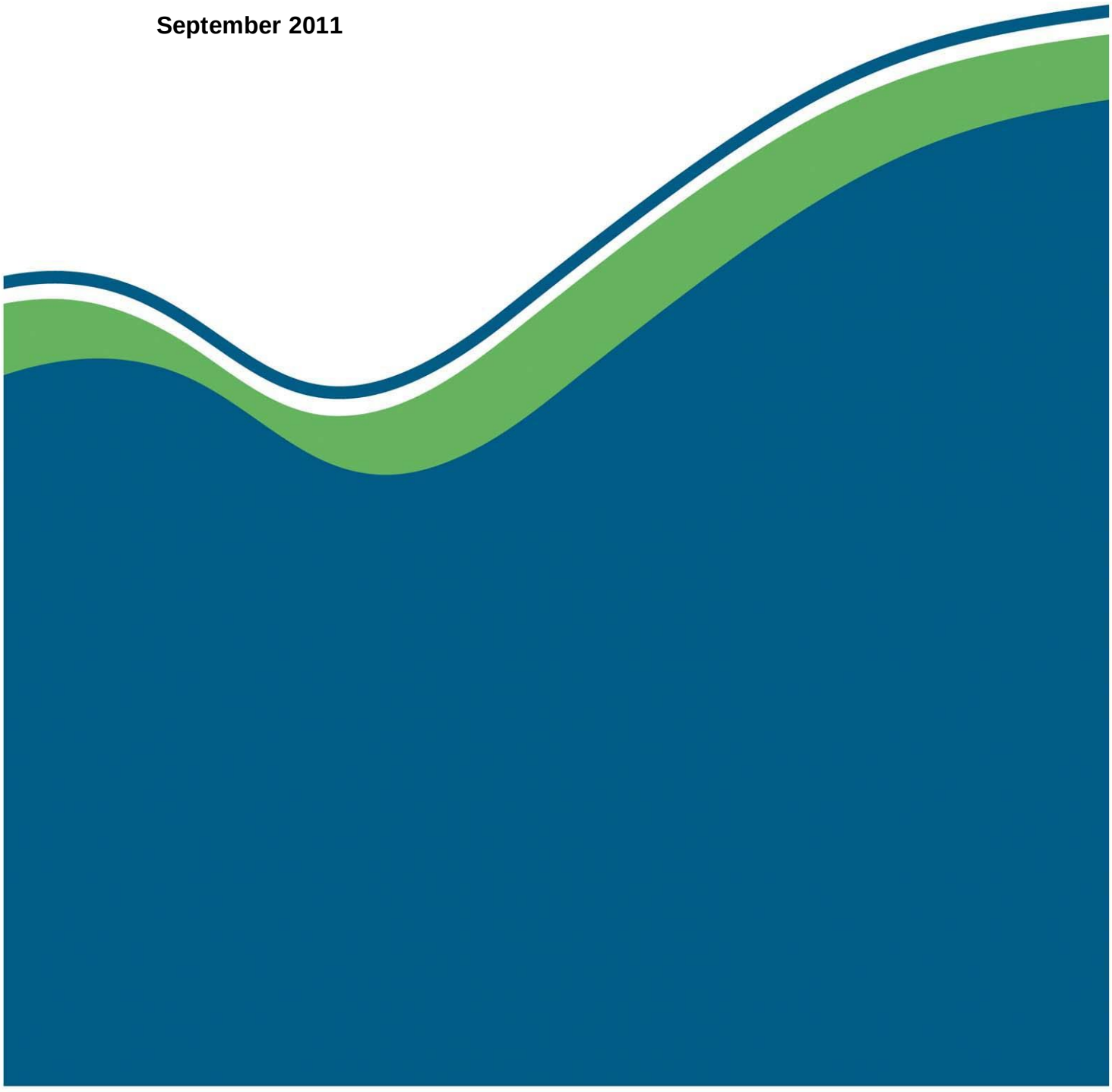
Grímsvötn volcano (Iceland) eruption May 2011: assessing the potential consequences of ash deposition in Scotland

Scottish Environment Protection Agency (SEPA)

September 2011



Acknowledgements

This report was compiled by Huw Jones, Ian Oliver and John Redshaw. Many SEPA staff contributed to the work covering aspects such as logistics, sampling, equipment deployment, data analysis, interpretation and review. Staff from across SEPA's functions (e.g. Chemistry, Operations, Hydrology and Hydrometry) contributed to the work including David Pirie, Ian Ridgway, Janet Shepherd, Ashley Roberts, Fiona Wyllie, Bill Craig, Elaine McGuire, Robin Clarke, Emily Unsworth, Tom Collins, John Millar, Ben Jackson, Gillian Telfer, Lynne Treacy, Richard Sinnott, Duncan Stewart, Maree Campbell and Graham Applegate. SEPA's Head of Chemistry, Ian Ridgway, has authorised the report.

The authors wish to thank the Met Office for providing dust deposition maps and The James Hutton Institute for providing technical support for our microscopic analysis of volcanic ash samples. We also gratefully acknowledge the volunteers from the Precipitation Monitoring Network for collection of rainfall samples analysed in this report.

Preferred citation

Scottish Environment Protection Agency (SEPA) 2011. Grímsvötn volcano (Iceland) eruption May 2011: assessing the potential consequences of ash deposition in Scotland.

Executive summary

Volcanic eruptions can damage our air, land, and water. Acidic volcanic gases dissolved in rainwater can lower the pH of receiving waters whilst dry volcanic dusts containing metals and salts can affect human health and the environment. This report details SEPA's environmental monitoring in response to the Grímsvötn volcano eruption in Iceland in May 2011 and our assessment of the potential implications of the eruption for Scotland's environment and human health.

We (SEPA) monitored rain at 47 sites across Scotland following the eruption. To do so, we re-established the precipitation monitoring network that we developed during and after the Eyjafjallajökull volcanic eruption in April 2010. This is based largely on the collection of rainfall samples by volunteer members of the public. Rainwater samples were analysed for parameters indicative of volcanic ash inputs (i.e. pH, fluoride, total iron and total manganese). Dust deposition and air quality (particulate matter content) were also monitored at various sites across Scotland.

The results of rainwater, dust and air quality analyses were compared with various environmental quality standards and human health criteria. The results present no cause for concern. The levels of metals (total iron and total manganese) in rainwater samples collected in the north of Scotland were elevated for a short period (circa one day at affected sites). Dust deposition results for the north of Scotland were also elevated during this period. These short-term elevated concentrations in rainfall and elevated dust depositions coincided with the movement of the volcanic ash cloud over Scotland. However, the results observed were considered to pose little risk.

We conducted a desk-based risk assessment of fluoride contamination of soil and herbage and the associated threats to grazing livestock. Risks were considered to be negligible and so no monitoring of these environmental receptors was conducted.

Overall, the evidence collected and assessed by us and our partner organisations indicates that the risks posed by this eruption to Scotland's environment and human health were negligible.

This second eruption substantiated our ability to respond quickly and, should a more serious event occur in future, then we will again provide appropriate sampling, analysis and interpretation.

Contents

Introduction

The Grímsvötn volcano in Iceland began erupting on 21 May 2011 at around 1800 hours GMT [1]. Previous studies have demonstrated that volcanic eruptions can potentially cause detrimental effects on the water, land and air components of the environment [2]. Water quality can be adversely affected by acidic precipitation (i.e. rainfall containing dissolved acidic volcanic gases which can lower the pH of receiving waters) and by deposition of volcanic dusts containing metals and salts. Air quality can be adversely affected by an increased concentration of airborne particulate matter, which can lead to increased respiratory problems for vulnerable people. The principal risk to land comes from deposition of volcanic dusts containing fluoride, a substance which can be toxic to livestock if it accumulates on or in herbage to concentrations above tolerable levels [2].

We (SEPA) monitored air quality and analysed dust and rainwater samples to assess the potential effects of the volcanic ash cloud on Scotland's environment.

This report outlines the monitoring methods we used and describes our assessments of the precipitation (rainwater and dust) and airborne particulate matter results.

Sampling and analysis

Rainfall network

We established a volcanic ash Precipitation (Rainfall) Monitoring Network (PMN) in Scotland in April 2010 in response to the Eyjafjallajökull volcanic eruption at that time. This network comprises some 38 sites across Scotland that are sampled mainly by volunteers (see Figure 1 and Appendix 1). We reactivated this network in response to the Grímsvötn eruption and value greatly the commitment and dedication of everyone involved in the collection and dispatch of samples. The first samples from the volunteer PMN sites arrived at our laboratories on 26 May 2011.

In addition, SEPA staff collected rainwater samples for analysis from those parts of the country not covered by the volunteer network. Samples were collected from Ayr, Dingwall, East Kilbride, Edinburgh, Elgin, Orkney, Shetland, Stornoway and Thurso and were delivered to our laboratories on 24 May 2011.

Rainwater samples were analysed for pH and fluoride and, in the case of SEPA collected samples, total iron and total manganese too.

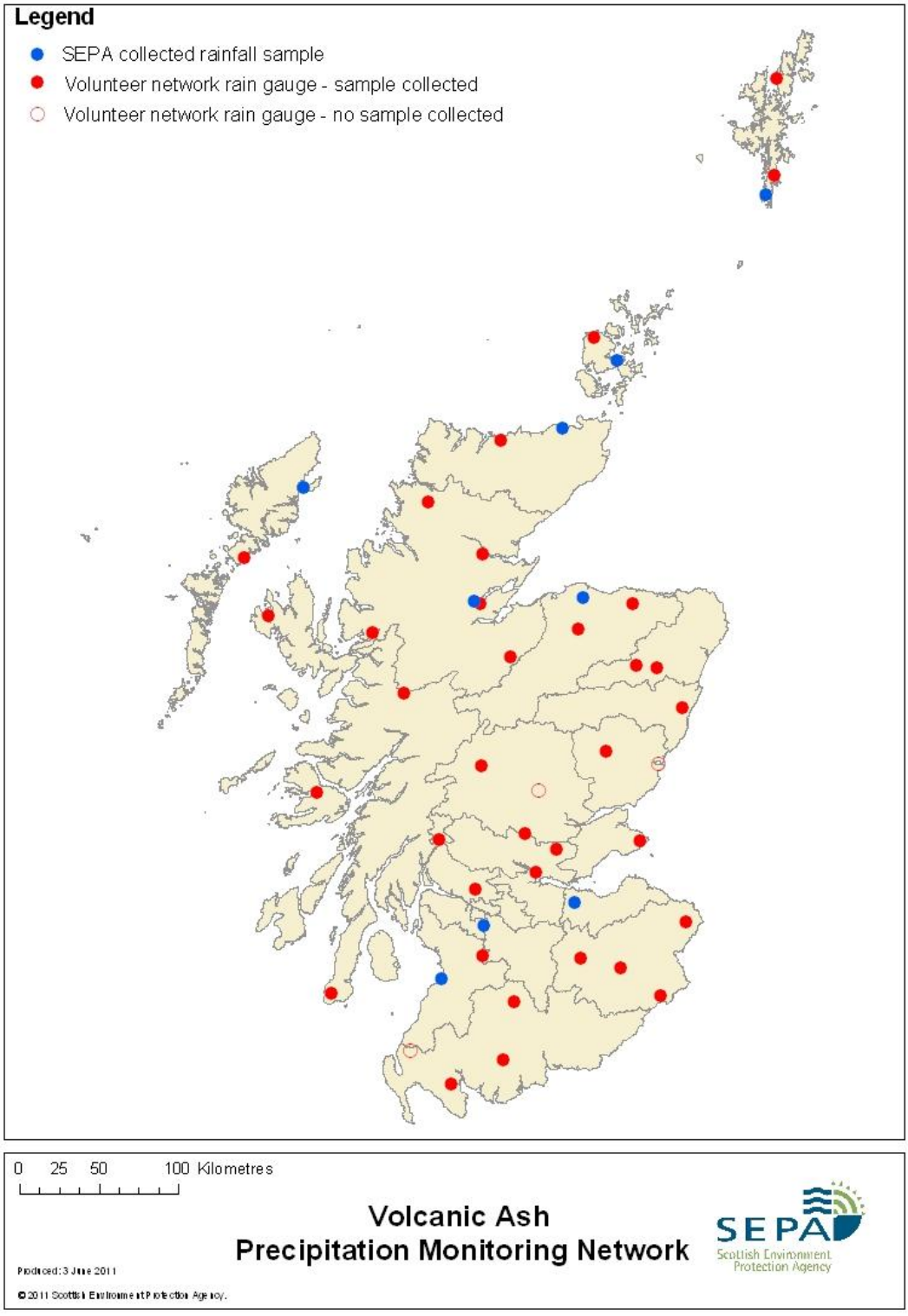


Figure 1. Rainfall monitoring locations showing sites sampled by the volunteer Precipitation Monitoring Network (PMN) and by SEPA staff.

Dust/air network

Various methods were used to sample and quantify dust deposition and assess whether the dust was volcanic in origin. These methods, including the use of sticky tiles, sticky pads and Frisbee gauges, were deployed in Shetland, the Western Isles and Thurso. Dust samples were also collected, using a clean cloth, from cars in Shetland, Orkney and the Western Isles.

Airborne particulate matter monitors (Osiris units) were deployed at six locations in Scotland (Orkney, Western Isles, Thurso, East Lothian, Edinburgh and South Lanarkshire). These units measured the concentration of airborne particulates at the sites every 15 minutes. Particulate matter is classified by the size of the particles e.g. $PM_{2.5}$ comprises particles with a diameter of 2.5 µm or less and PM_{10} comprises particles with a diameter of 10 µm or less [3].

Airborne particulate samples were also collected from monitoring stations originally established under the Ambient Radioactive Substances Monitoring Network. The high volume ambient air samplers deployed at these sites were used to sample ambient air for metals. These sites cover the regions surrounding Chapelcross, Dounreay, Hunterston and Torness. Samples collected from these sites have been stored for future analysis of metals should this be required. Figure 2 and Appendix 2 show the sites sampled for dust and particulate matter.

SEPA staff regularly reviewed data from the Scottish Air Quality Database [4] to identify any irregularities or exceptions from the norm which may have been related to volcanic ash deposition. They also received and reviewed the information in the daily dust deposition forecasts provided by the Met Office [5].

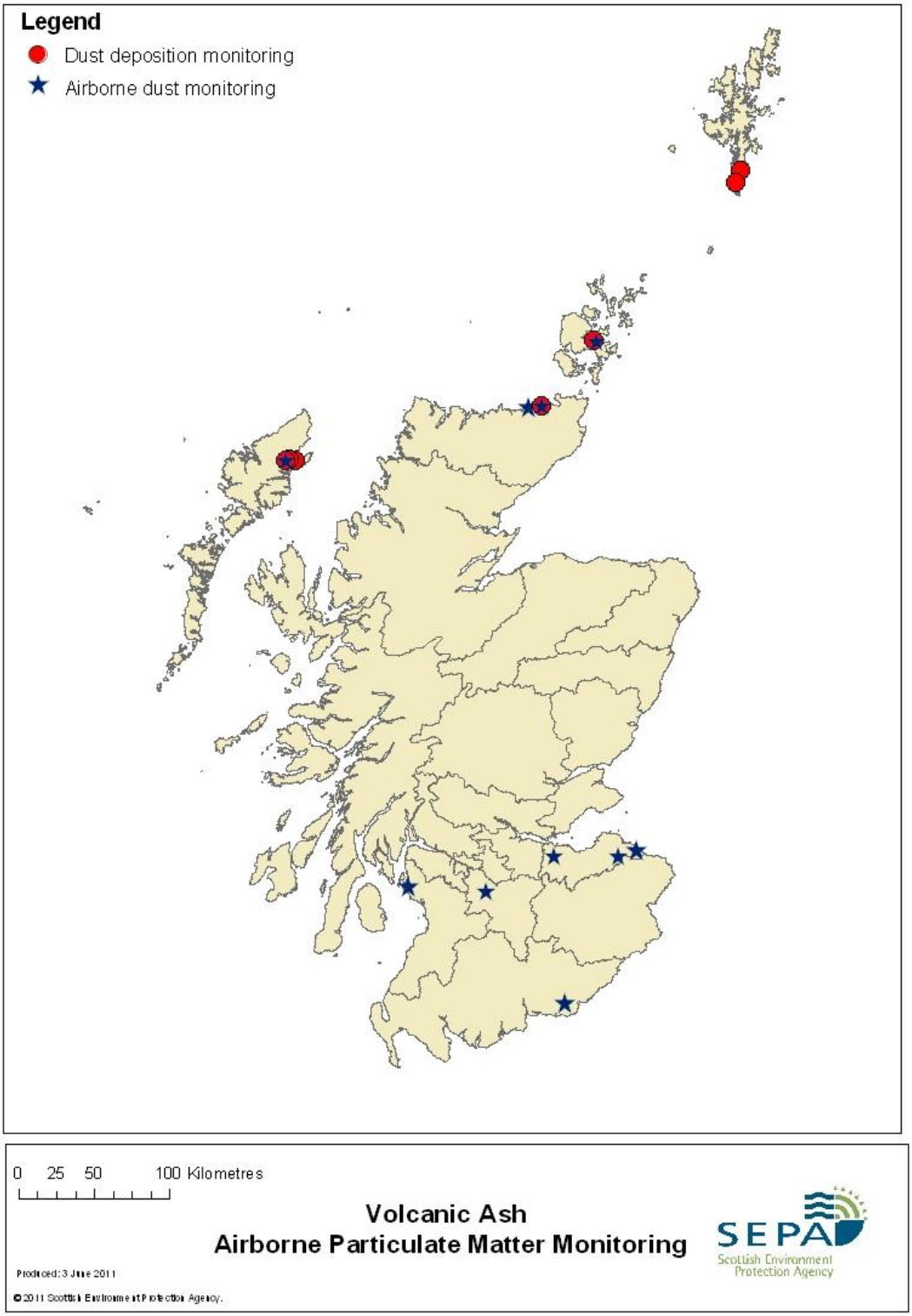


Figure 2. Location of dust and airborne particulate matter monitoring sites in Scotland. Dry deposition sites (red dots) employed one or more of the following methods of collection; tiles, sticky pads, Frisbee gauges and dust collected from vehicle surfaces. Ambient air monitoring (blue stars) was conducted using mobile Osiris units and fixed-place devices within the Ambient Radioactive Substances Monitoring Network.

Soil and herbage network

We conducted a risk assessment to determine whether the risks of soil and herbage contamination by fluoride (and subsequent uptake of fluoride by grazing livestock) were high enough to warrant environmental monitoring of these resources (see Appendix 3). The risk assessment considered the following information and parameters:

- Met Office predictions of ash deposition [5];
- herbage cover rates and animal ingestion of herbage and soil;
- a worst probable case fluoride concentration in ash, based on the maximum concentration recorded in volcanic dust depositions in Iceland following the 2010 volcanic eruption (where the fluoride concentration in ash ranged from 23 to 850 mg/kg fluoride).

The risk assessment concluded that the risks to livestock from soil and vegetation were negligible, so monitoring of these resources was not warranted on this occasion.

Results and interpretation

Rainwater samples

Results of the rainwater samples analyses (pH, fluoride, iron and manganese) are presented in Appendix 1. Threshold criteria were established and used to assess whether any parameters were of potential concern to the environment or human health (Table 1 and Table 2). These criteria are based on Environmental Quality Standards (EQS) for the protection of freshwater life [6] and Drinking Water Standards (DWS) for the protection of drinking water supplies [7].

Table 1. Generic descriptive thresholds for assessing the level of concern regarding the concentrations of chemicals in rainwater samples

Level of concern	Criterion used
Low level – not of concern	Below the DWS and the EQS
Elevated levels – not of concern	Above either DWS or EQS but not both
Elevated levels – requires further investigation	Above both DWS and EQS – or if only one applicable standard is available and the result is substantially above that standard
Result not appropriate	Reason provided

Table 2. Numeric threshold values used to assess parameter levels in rainwater samples

Substance	Freshwater EQS: Maximum Allowable Concentration*	Freshwater EQS: Annual Average*	Drinking Water Standard**	Common rainwater values
pH (pH units)	-	-	-	4-7
Fluoride (mg/l)	3	1	1.5	0.006 - 0.067 [8]
Manganese (mg/l)	0.30	0.030	0.05	-
Iron (mg/l)	-	1	0.2	-

* EQS apply to dissolved concentrations (i.e. those in filtered samples).
** refers to maximum concentration quality threshold for tap water.

All of the rainwater samples assessed were considered to be 'not of concern' in relation to pH and fluoride according to the criteria outlined in Table 1. Two rainwater samples collected in Edinburgh on 24/05/11 contained higher levels of fluoride than those found in other samples (concentrations of fluoride in many of the rainwater samples analysed were below the limit of detection of 0.03 mg/l), but even these levels were not of concern. Subsequent investigation revealed that those two samples from Edinburgh may have been contaminated from other sources of fluoride and, as such, do not reflect volcanic inputs.

Some samples collected from the north of Scotland (Table 3) contained elevated levels of iron (i.e. total iron > 1 mg/l). The sampling period showing increased iron levels in rainwater (spanning 24–27 May 2011 for various sites) coincided with the period of peak ash deposition over Scotland as predicted by the Met Office forecasts [5]. It also coincided with the period of highest airborne particulate matter concentrations detected by our particulate matter monitoring (see 'Dust deposition' section). The highest rainwater iron levels were all from sites in the north of Scotland, where the Met Office predicted volcanic dust deposition to be greatest [5]. In contrast, levels of iron were generally much lower in rainwater samples collected from southern and central Scotland. The spatial and temporal pattern of the data therefore supply strong evidence in support of the conclusion that volcanic ash (or dust) did temporarily influence rainwater in parts of northern Scotland. However, due to the rapid deployment of precipitation sampling equipment and time-limited scope for wider analysis, contributions from other potential sources of contamination cannot be ruled out entirely.

Table 3. Samples containing elevated levels of iron (i.e. total iron > 1 mg/l).

Location	Sampling period ending	Total iron (mg/l)
Thurso	24 May 2011 at 08:00	2.51
Stornoway	24 May 2011 at 15:00	1.86
Elgin	24 May 2011 at 15:00	5.78
Dingwall	25 May 2011 at 12:00	3.85
Dingwall	27 May 2011 at 15:00	3.60
Orkney	26 May 2011 at 15:00	1.96
Shetland	25 May 2011 at 08:00	6.20

The elevated levels of iron in some samples were often matched by elevated levels of manganese (see Figures 3 and 4, and Appendix 1), indicating a degree of co-variance (or linkage) for these two metals. Volcanic ash contains both iron and manganese [9] so it is likely that the elevated levels of these metals found in some rainwater samples do reflect inputs from volcanic ash.

It is interesting to note the short duration (i.e. at most one day) of elevated iron and manganese levels in rainwater in Shetland (see Figures 3 and 4). This is consistent with Met Office information, which indicated decreasing levels of volcanic ash in the atmosphere over Scotland as the ash cloud dispersed.

One early sample from Shetland (sampling period ending 24/05/11 at 08:00) contained low levels of iron and manganese (0.0943 mg/l Fe, 0.005 mg/l Mn). In contrast, the sample collected from Thurso during this period contained relatively high levels of both iron and manganese (2.51 mg/l Fe, 0.0456 mg/l Mn). Although this is only based on one sample, the difference in concentration between these two locations is consistent with the Met Office images of ash deposition [10] which

indicate that Shetland was affected by the ash plume later than the rest of northern Scotland. The Shetland sample collected on 25/05/11 contained the highest measured level of iron (Figure 3, Appendix 1), likely as a result of the migrating ash plume.

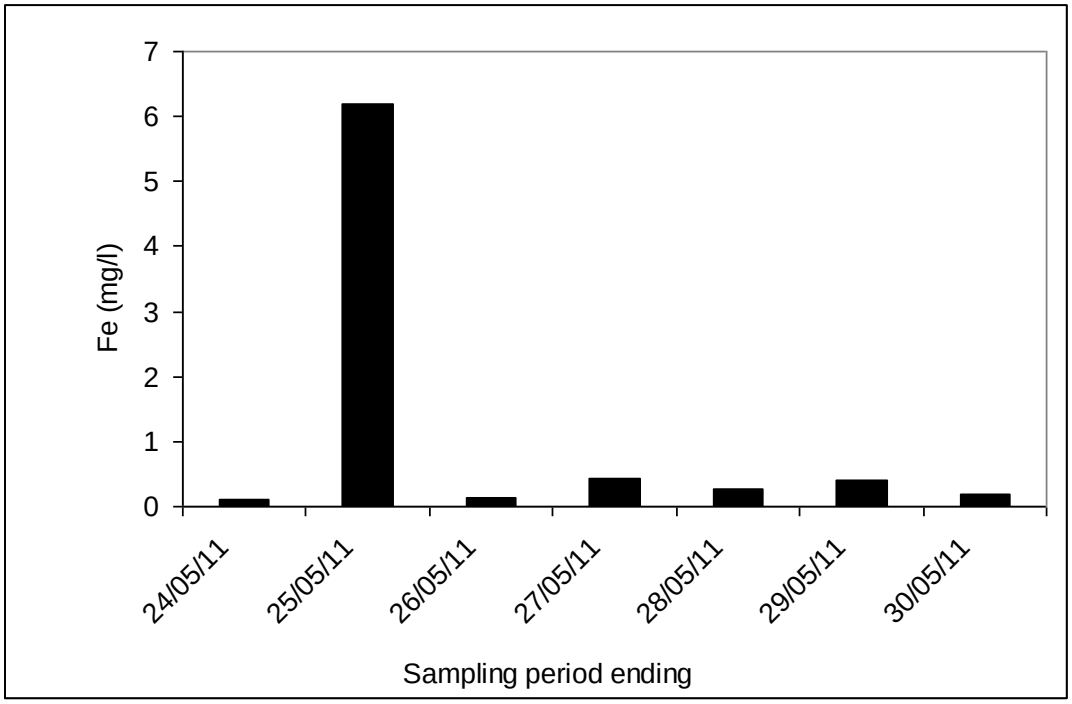


Figure 3. Total iron (Fe) concentrations in rainwater samples from Shetland.

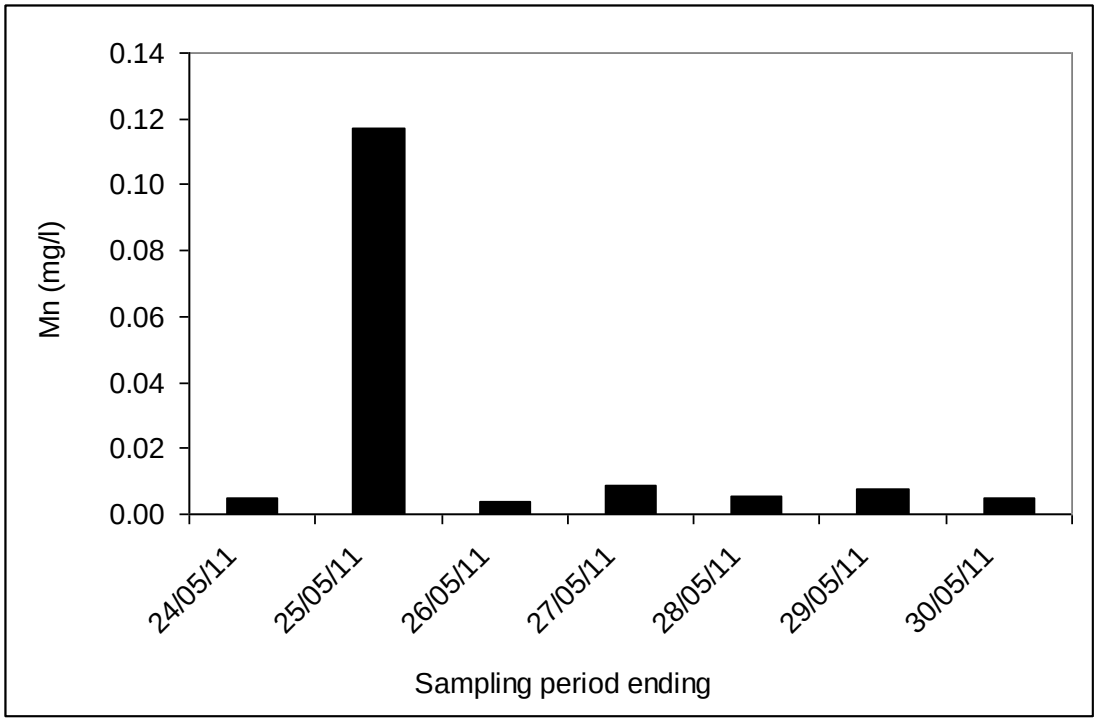


Figure 4. Total manganese (Mn) concentrations in rainwater samples from Shetland.

Dust deposition

Analysis of volcanic ash deposited on vehicles in Shetland has been described in the report "Microscopic analysis of deposited volcanic ash collected in Shetland" [11]. That report included optical microscope and scanning electron microscope images which were used to conclude that the dust deposition collected from vehicles was volcanic ash and that this ash likely originated from the Grímsvötn eruption.

The results of airborne particulate matter analysis are shown in Appendix 2. The type of airborne particulate matter monitors used (Osiris units) do not meet specifications for EU Reference Methods for PM_{10} or $PM_{2.5}$ monitoring [12] and so results cannot be assessed for compliance against Scottish Air Quality Objectives [4]. However, they may be compared with both the Objectives and the Committee on the Medical Effects of Air Pollution (COMEAP) air pollution bandings for guidance purposes [3]. For PM_{10}, the air quality objective is based on a 24 hour mean and the COMEAP bandings are based on a 24-hour running mean. All samples collected across Scotland warranted a 'low level' classification (meaning that the "effects are unlikely to be noticed even by individuals who know they are sensitive to air pollutants" [4]).

In terms of short term variability, a peak in airborne particulate matter concentration was observed from 18:00 to 22:00 on 24 May 2011 from the ambient air monitor at Thurso (Figure 5). However, 24-hour running means remained within the low classification band in Thurso throughout the sampling period (i.e. no exceedance of air quality objectives were suggested by these indicative data).

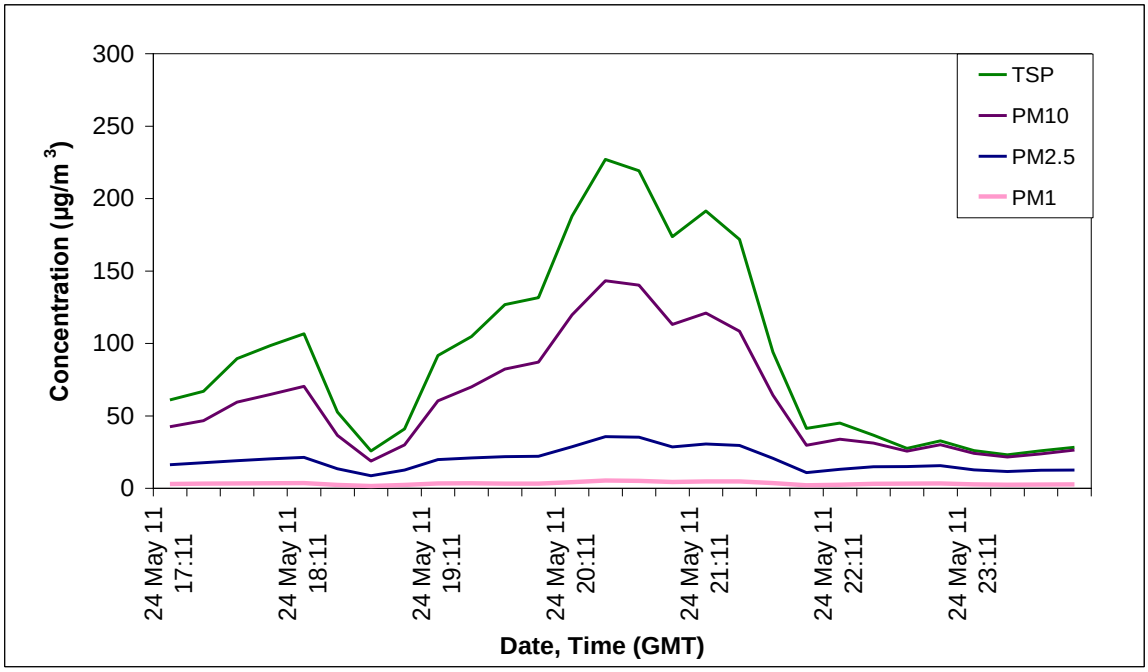


Figure 5. Airborne particulate matter monitoring at Thurso, 24 May 2011. 15 minute average TSP (Total Suspended Particulates), PM_{10} (particulate matter with a diameter ≤ 10 µm), $PM_{2.5}$ (particulate matter with a diameter ≤ 2.5 µm) and PM_1 (particulate matter with a diameter ≤ 1 µm).

Results from the Frisbee deposition gauges are presented in Table 4. Evaluation and interpretation of these samples were accomplished by assessment against limit values outlined in the Environment Agency's Technical Guidance Document M17

[13]. One result from Shetland on 23/24 May (2.06 g/m^2/day) exceeded the Limit Value for Annoyance of 0.2 g/m^2/day [13]. Subsequent results from Shetland and all results from Thurso and Stornoway were below all limit values.

Table 4. Results from Frisbee dust deposition gauges (note: sampling period varied by site for operational reasons).

Location	Deployment period	Deposition rate (g/m^2/day)
Shetland (South Mainland)	23/05/11 20:00 to 24/05/11 18:00	2.06
Shetland (South Mainland)	24/05/11 18:00 to 30/05/11 09:40	0.01
Thurso	24/05/11 15:20 to 26/05/11 12:15	0.08
Thurso	26/05/11 12:15 to 30/05/11 11:30	0.04
Thurso	30/05/11 11:30 to 01/06/11 14:20	0.02
Stornoway	24/05/11 18:00 to 30/05/11 10:15	0.04

Dust deposition tiles coated with Vaseline were deployed in Stornoway and subsequently analysed by optical microscopy. However, it was not possible to accurately assess dust deposition using this method due to the difficulties in distinguishing between air bubbles and dust particles in the samples.

Sticky pad results were obtained from Thurso and Shetland (Table 5). The percentage effective area coverage per day (%EAC/day) value for Shetland on 26/05/11 (8%EAC/day) exceeded the 'serious complaints' thresholds for dust (5%EAC/day) [14]. It is difficult to assess whether these results were due to volcanic ash deposition or whether they reflect background dust levels from the surrounding area, particularly given the very severe weather conditions that prevailed during this period (chemical assessment of the dusts is not possible for this type of sample).

Table 5. Results from sticky pads measuring dust deposition from Thurso and Shetland

Site	Exposure period (hours)	Collection date	Percentage effective area coverage per day (%EAC/day)
Thurso	24	26/05/11	3.0
Shetland	24	26/05/11	8.0
Shetland	24	27/05/11	3.0
Shetland	24	28/05/11	2.3
Shetland	24	29/05/11	3.3
Shetland	24	30/05/11	3.3

The Scottish Air Quality Database [4] showed a notable increase in PM_{10} concentrations overnight on 23-24 May 2011 at monitoring stations in Aberdeen to the extent that two stations reported a moderate classification for PM_{10} concentrations on 24 May 2011. A moderate classification states that "mild effects, unlikely to require action, may be noticed amongst sensitive individuals" [4]. Values quickly declined back to more typical levels during 24 May 2011.

Conclusions

Analysis of rainwater, airborne particulates and deposited dust has allowed us to assess the environmental and human health implications of the Grímsvötn volcanic eruption for Scotland. The evidence indicates that the risks posed by this eruption were negligible.

This second recent Icelandic volcano eruption substantiated our ability to respond quickly and, should a more serious event occur in future, then we will again provide appropriate sampling, analysis and interpretation.

The continued commitment and engagement of the public in supporting our rainfall monitoring network is invaluable. During this event it helped us to provide good spatial and temporal coverage in our monitoring. Collaboration between government, agency departments and academic groups continues to enhance our capability, capacity and resilience to respond to future events.

References

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Appendices

Appendix 1: Precipitation (rainwater) monitoring locations and analytical results

Table 6. Location of precipitation monitoring sites.

Location code	Location description	Easting	Northing
14916	River South Esk flow gauging station at Gella Bridge	337000	765000
15066	Meikle Tombane Storage rain gauge	295000	740000
15078	Montrose SWT Storage rain gauge	370000	757000
15098	South Drumdowie No. 2 Storage rain gauge	286000	714000
15105	Hallmanor House Storage rain gauge	321000	635000
15113	Selkirk (Toft House) Storage rain gauge	347000	628000
15131	Harelaw, Chirnside Storage rain gauge	388000	658000
15143	Tulliallan (Kincardine) Storage rain gauge	293000	689000
15146	Carnbo Storage rain gauge	306000	703000
115204	Blairdaff, Rainfall Gauge, Don	370000	818000
115207	Bogmuchals, Rainfall Gauge, Banff Coastal	354000	858000
115237	Netherley, Rainfall Gauge, Kincardine and Angus	386000	793000
115248	Tullynessle, Rainfall Gauge, Don	356000	819000
115319	Coille Mhorgil, Rainfall Gauge, Ness	210000	801000
115326	Dalarossie, Rainfall Gauge, Findhorn	277000	824000
115353	Inchnadamph No 2, Rainfall Gauge, Inver	225000	922000
115369	Loch Of Hundland, Rainfall Gauge, Orkney Coastal	330000	1026000
115370	Lochcarron, Rainfall Gauge, Sounds Coastal	190000	840000
115385	Old Town Ardgay, Rainfall Gauge, Dornoch Coastal	260000	890000
115387	Quidnish, Rainfall Gauge, Lewis and Harris Coastal	109000	887000
115406	Urquhart, Rainfall Gauge, Cromarty Coastal	258000	859000
115409	West Sandwick Yell, Rainfall Gauge, Yell Coastal	445000	1190000
115501	Amod Farm, Rainfall Gauge, Kintyre Coastal	164000	613000

Location code	Location description	Easting	Northing
115512	Barwhillanty, Rainfall Gauge, Dee (Solway)	272000	571000
115562	Eliock, Rainfall Gauge, Nith	280000	607000
115588	Inveruglas, Rainfall Gauge, Leven (Loch Lomond)	232000	709000
115600	Lagafater Lodge, Rainfall Gauge, Water of Luce	214000	576000
115621	Mugdock Country Park, Rainfall Gauge, Kelvin	255000	678000
115645	Saughall, Rainfall Gauge, Irvine	260000	636000
115655	Torhouse Mill, Rainfall Gauge, Bladnoch	240000	555000
335803	Nether Borlum rain gauge, 1 Nether Borlum, Knockando	320000	842000
335980	Dunvegan Suardal Raingauge, Dunvegan, Skye	124000	851000
336228	Cunningsburgh - North Raingauge	444000	1128000
337079	Toldrie rain gauge	358000	708000
337108	Shielsknowe rain gauge	371000	611000
341344	Dall Rannoch rain gauge (No2)	259000	756000
411987	Bettyhill, Galdonagh Rain Gauge	271000	961000
462422	Met Office Rain Gauge Station at Gruline House, Mull	155000	739000
132460	SEPA Ayr Office	234000	621000
-	SEPA Dingwall Office	254000	860000
-	SEPA East Kilbride Office	261000	655000
-	SEPA Edinburgh Office	318000	670000
-	SEPA Elgin Office	323000	862000
-	SEPA Kirkwall Office, Orkney	344000	1012000
-	Shetland (South mainland)	438000	1116000
212006	Melbost STW Isle of Lewis	147000	932000
464804	SEPA Thurso Office	310000	969000

Table 7. Rainwater chemical analysis.

SEPA location code	Full station name	Sample collection end date	pH (pH units)	Fluoride (mg/l)	Total iron (mg/l)	Total manganese (mg/l)
336228	Cunningsburgh - North Raingauge	23/05/2011 12:00	6.2	<0.03	-	-
464804	SEPA Thurso Office	24/05/2011 08:00	6.4	0.01	2.51	0.0456
-	Shetland South Mainland	24/05/2011 08:00	6.4	<0.03	0.0943	0.005
-	SEPA Edinburgh Office	24/05/2011 10:30	5.9	2.96	0.217	0.34
336228	Cunningsburgh - North Raingauge	24/05/2011 12:00	6.3	<0.03	-	-
132460	SEPA Ayr Office	24/05/2011 14:15	6.2	<0.03	0.775	0.0256
212006	Melbost STW Isle of Lewis	24/05/2011 15:00	6.4	0.15	1.86	0.0846
-	SEPA Elgin Office	24/05/2011 15:00	6.6	<0.03	5.78	0.359
-	SEPA Edinburgh Office	24/05/2011 17:00	5.9	1.86	0.175	0.052
464804	SEPA Thurso Office	25/05/2011 08:00	Insufficient Sample Volume	0.05	Insufficient Sample Volume	Insufficient Sample Volume
-	Shetland South Mainland	25/05/2011 08:00	-	<0.03	6.2	0.117
14916	River South Esk flow gauging station at Gella Bridge	25/05/2011 09:00	5.2	<0.03	-	-
115512	Barwhillanty, Rainfall Gauge, Dee (Solway)	25/05/2011 09:30	6.3	<0.03	-	-
115645	Saughall, Rainfall Gauge, Irvine	25/05/2011 10:00	6.3	<0.03	-	-
115369	Loch Of Hundland, Rainfall Gauge, Orkney Coastal	25/05/2011 10:00	6.4	0.03	-	-
132460	SEPA Ayr Office	25/05/2011 12:00	5.9	0.06	0.59	0.0397
-	SEPA Dingwall Office	25/05/2011 12:00	6.1	0.09	3.85	0.073
-	SEPA Kirkwall Office, Orkney	25/05/2011 14:00	Insufficient Sample Volume	<0.03	Insufficient Sample Volume	Insufficient Sample Volume
335803	Nether Borlum rain gauge, 1 Nether Borlum, Knockando	25/05/2011 15:00	6.9	<0.03	-	-
212006	Melbost STW Isle of Lewis	25/05/2011 15:00	6.4	0.06	0.144	0.0138
411987	Bettyhill, Galdonagh Rain Gauge	26/05/2011 08:00	Insufficient Sample Volume	<0.03	-	-
464804	SEPA Thurso Office	26/05/2011 08:00	Insufficient Sample Volume	0.1	Insufficient Sample Volume	Insufficient Sample Volume

SEPA location code	Full station name	Sample collection end date	pH (pH units)	Fluoride (mg/l)	Total iron (mg/l)	Total manganese (mg/l)
115406	Urquhart, Rainfall Gauge, Cromarty Coastal	26/05/2011 08:15	5.9	<0.03	-	-
462422	Met Office Rain Gauge Station at Gruline House, Mull	26/05/2011 09:00	6.3	<0.03	-	-
115588	Inveruglas, Rainfall Gauge, Leven (Loch Lomond)	26/05/2011 09:00	6.4	<0.03	-	-
115207	Bogmuchals, Rainfall Gauge, Banff Coastal	26/05/2011 09:00	6.4	<0.03	-	-
115353	Inchnadamph No 2, Rainfall Gauge, Inver	26/05/2011 09:00	5	<0.03	-	-
115562	Eliock, Rainfall Gauge, Nith	26/05/2011 09:00	6.2	<0.03	-	-
115370	Lochcarron, Rainfall Gauge, Sounds Coastal	26/05/2011 09:00	6.5	<0.03	-	-
-	Shetland South Mainland	26/05/2011 09:20	-	<0.03	0.128	0.0037
115501	Amod Farm, Rainfall Gauge, Kintyre Coastal	26/05/2011 09:30	6.5	<0.03	-	-
-	SEPA Edinburgh Office	26/05/2011 10:00	6.3	0.51	Insufficient Sample Volume	Insufficient Sample Volume
115369	Loch Of Hundland, Rainfall Gauge, Orkney Coastal	26/05/2011 10:00	6.4	0.2	-	-
337079	Toldrie rain gauge	26/05/2011 10:00	7.5	<0.03	-	-
115237	Netherley, Rainfall Gauge, Kincardine and Angus	26/05/2011 10:00	Insufficient Sample Volume	<0.03	-	-
335980	Dunvegan Suardal Raingauge, Dunvegan, Skye	26/05/2011 12:00	9.1	0.2	-	-
-	SEPA East Kilbride Office	26/05/2011 12:00	7.1	0.03	0.0575	0.0117
115385	Old Town Ardgay, Rainfall Gauge, Dornoch Coastal	26/05/2011 12:00	6.7	<0.03	-	-
212006	Melbost STW Isle of Lewis	26/05/2011 15:00	6.2	0.12	-	-
-	SEPA Elgin Office	26/05/2011 15:00	7	<0.03	0.612	0.0373
-	SEPA Kirkwall Office, Orkney	26/05/2011 15:00	6.3	<0.03	1.96	0.0772
-	Shetland South Mainland	27/05/2011 06:45	-	<0.03	0.443	0.0087
115387	Quidnish, Rainfall Gauge, Lewis and Harris Coastal	27/05/2011 09:00	Insufficient Sample Volume	<0.03	-	-
115326	Dalarossie, Rainfall Gauge, Findhorn	27/05/2011 09:00	5.3	<0.03	-	-

SEPA location code	Full station name	Sample collection end date	pH (pH units)	Fluoride (mg/l)	Total iron (mg/l)	Total manganese (mg/l)
212006	Melbost STW Isle of Lewis	27/05/2011 15:00	6.5	<0.03	-	-
-	SEPA Dingwall Office	27/05/2011 15:00	6.4	<0.03	3.6	0.243
115655	Torhouse Mill, Rainfall Gauge, Bladnoch	28/05/2011 08:00	-	<0.03	-	-
341344	Dall Rannoch rain gauge (No2)	28/05/2011 09:00	6.6	<0.03	-	-
15143	Tulliallan (Kincardine) Storage rain gauge	28/05/2011 09:00	6.4	<0.03	-	-
115204	Blairdaff, Rainfall Gauge, Don	28/05/2011 09:00	7.1	<0.03	-	-
115409	West Sandwick Yell, Rainfall Gauge, Yell Coastal	28/05/2011 09:20	5.2	<0.03	-	-
-	Shetland South Mainland	28/05/2011 10:00	-	<0.03	0.268	0.0056
15105	Hallmanor House Storage rain gauge	29/05/2011 09:30	6.3	<0.03	-	-
115319	Coille Mhorgil, Rainfall Gauge, Ness	29/05/2011 10:00	6.2	<0.03	-	-
-	Shetland South Mainland	29/05/2011 10:30	-	<0.03	0.393	0.0078
115406	Urquhart, Rainfall Gauge, Cromarty Coastal	30/05/2011 08:20	5.8	<0.03	-	-
336228	Cunningsburgh - North Raingauge	30/05/2011 09:00	-	<0.03	-	-
-	Shetland South Mainland	30/05/2011 10:30	-	<0.03	0.197	0.0048
337108	Shielsknowe rain gauge	31/05/2011 08:45	6.7	<0.03	-	-
15146	Carnbo Storage rain gauge	31/05/2011 12:00	6.6	<0.03	-	-
115588	Inveruglas, Rainfall Gauge, Leven (Loch Lomond)	01/06/2011 09:00	6.4	<0.03	-	-
15098	South Drumdowie No. 2 Storage rain gauge	01/06/2011 09:00	6.5	<0.03	-	-
115621	Mugdock Country Park, Rainfall Gauge, Kelvin	01/06/2011 09:45	6.6	<0.03	-	-
115369	Loch Of Hundland, Rainfall Gauge, Orkney Coastal	01/06/2011 10:00	6.2	<0.03	-	-
115387	Quidnish, Rainfall Gauge, Lewis and Harris Coastal	02/06/2011 09:00	6.2	<0.03	-	-
115353	Inchnadamph No 2, Rainfall Gauge, Inver	04/06/2011 09:00	-	<0.03	-	-
341344	Dall Rannoch rain gauge (No2)	05/06/2011 09:00	6.6	<0.03	-	-
15131	Harelaw, Chirnside Storage rain gauge	05/06/2011 09:00	6.8	<0.03	-	-
411987	Bettyhill, Galdonagh Rain Gauge	06/06/2011 07:00	6.2	<0.03	-	-

SEPA location code	Full station name	Sample collection end date	pH (pH units)	Fluoride (mg/l)	Total iron (mg/l)	Total manganese (mg/l)
462422	Met Office Rain Gauge Station at Gruline House, Mull	06/06/2011 09:00	6.5	<0.03	-	-
15143	Tulliallan (Kincardine) Storage rain gauge	06/06/2011 09:00	6.6	<0.03	-	-
337108	Shielsknowe rain gauge	06/06/2011 09:00	6.3	<0.03	-	-
335803	Nether Borlum rain gauge, 1 Nether Borlum, Knockando	06/06/2011 09:30	-	<0.03	-	-
115501	Amod Farm, Rainfall Gauge, Kintyre Coastal	06/06/2011 09:30	6.2	<0.03	-	-
335980	Dunvegan Suardal Raingauge, Dunvegan, Skye	07/06/2011 09:00	6.2	<0.03	-	-
115645	Saughall, Rainfall Gauge, Irvine	07/06/2011 09:00	6.5	0.069	-	-
115370	Lochcarron, Rainfall Gauge, Sounds Coastal	07/06/2011 09:00	6.6	<0.03	-	-
115319	Coille Mhorgil, Rainfall Gauge, Ness	07/06/2011 10:00	6.4	<0.03	-	-
115326	Dalarossie, Rainfall Gauge, Findhorn	07/06/2011 10:00	5.5	<0.03	-	-
115655	Torhouse Mill, Rainfall Gauge, Bladnoch	08/06/2011 08:00	6.8	<0.03	-	-
15113	Selkirk (Toft House) Storage rain gauge	08/06/2011 09:00	6.5	<0.03	-	-
115248	Tullynessle, Rainfall Gauge, Don	08/06/2011 09:00	6.4	<0.03	-	-
15105	Hallmanor House Storage rain gauge	08/06/2011 09:00	6.8	<0.03	-	-

Appendix 2: Air monitoring locations and results

Table 8. Location of airborne particulate monitoring sites.

Location name	Type of equipment	Easting	Northing
Stornoway	Tiles/Vaseline layer	146000	932000
Stornoway	Dust from car	143000	933000
Stornoway	Frisbee deposition gauge	140000	933000
Stornoway	Osiris units	140000	933000
Shetland	Sticky pads	438000	1116000
Shetland	Dust from car	442000	1125000
Shetland	Frisbee deposition gauge	438000	1116000
Thurso	Sticky pads	310000	969000
Thurso	Frisbee deposition gauge	310000	969000
Thurso	Osiris units	310000	969000
Orkney	Dust from car	344000	1012000
Orkney	Dust from car	344000	1012000
Orkney	Dust from car	344000	1012000
Orkney	Osiris units	346000	1011000
Lanarkshire	Osiris units	272000	647000
Edinburgh	Osiris units	318000	670000
East Lothian	Osiris units	360000	670000
Chapelcross	Ambient radioactive substances monitoring network	322000	569000
Dounreay	Ambient radioactive substances monitoring network	298000	967000
Hunterston	Ambient radioactive substances monitoring network	218000	651000
Torness	Ambient radioactive substances monitoring network	375000	675000

Table 9. Results of airborne particulate monitoring for 24 May 2011

	PM_{10}		$PM_{2.5}$	
Monitoring location	**24 hour mean ($\mu g/m^3$)**	**Max 15 minute mean ($\mu g/m^3$)**	**24 hour mean ($\mu g/m^3$)**	**Max 15 minute mean ($\mu g/m^3$)**
Lanarkshire (14:34-23:49)	16.9	31.4	8.5	12.1
Stornoway (18:19-23:49)	8.2	13.8	5.1	7.0
Thurso (17:11-23:56)	61.6	143.2	19.3	35.6
Edinburgh (00:05-23:56) (5 minute mean)	16.4	49.0	4.1	6.7

Table 10. Results of airborne particulate matter analysis for the period 25 May to 29 May 2011.

		PM_{10}				$PM_{2.5}$		
Monitoring location	**Date (24 hours monitoring unless otherwise stipulated)**	**24 hour mean ($\mu g/m^3$)**	**Max 15 minute mean ($\mu g/m^3$)**	**PM_{10} Objective 24 hour mean**	**PM_{10} Pollution band**	**24 hour mean ($\mu g/m^3$)**	**Max 15 minute mean ($\mu g/m^3$)**	**$PM_{2.5}$ Objective annual mean (Scotland only)**
Lanarkshire	25-May-11	17.6	31.4	50 $\mu g/m^3$	Low	8.6	12.2	12 $\mu g/m^3$
Edinburgh	25-May-11	18.5	23.0	50 $\mu g/m^3$	Low	5.3	6.9	12 $\mu g/m^3$
Stornoway	25-May-11	25.9	52.5	50 $\mu g/m^3$	Low	5.4	7.9	12 $\mu g/m^3$
Thurso	25-May-11	19.8	31.6	50 $\mu g/m^3$	Low	9.0	16.4	12 $\mu g/m^3$
East Lothian	25-May-11 (13:59-23:59)	10.1	13.3	50 $\mu g/m^3$	Low	5.8	7.4	12 $\mu g/m^3$
Lanarkshire	26-May-11	6.7	16.6	50 $\mu g/m^3$	Low	3.8	12	12 $\mu g/m^3$
Edinburgh	26-May-11	6.7	30.2	50 $\mu g/m^3$	Low	2.0	6.3	12 $\mu g/m^3$
Stornoway	26-May-11	16.0	37.7	50 $\mu g/m^3$	Low	5.4	8.7	12 $\mu g/m^3$
Thurso	26-May-11	20.3	75.6	50 $\mu g/m^3$	Low	7.8	17	12 $\mu g/m^3$
East Lothian	26-May-11	10.5	26.7	50 $\mu g/m^3$	Low	6.3	18.6	12 $\mu g/m^3$
Lanarkshire	27-May-11	7.3	20.1	50 $\mu g/m^3$	Low	3.3	9.0	12 $\mu g/m^3$
Edinburgh	27-May-11	6.7	19.5	50 $\mu g/m^3$	Low	1.5	3.2	12 $\mu g/m^3$
Stornoway	27-May-11	12.6	60.3	50 $\mu g/m^3$	Low	3.1	7.8	12 $\mu g/m^3$
Thurso	27-May-11	10.9	22.0	50 $\mu g/m^3$	Low	4.4	9.8	12 $\mu g/m^3$
Orkney	27-May-11	11.1	17.4	50 $\mu g/m^3$	Low	3.7	6.3	12 $\mu g/m^3$
East Lothian	27-May-11	No data	No data	50 $\mu g/m^3$	No data	No data	No data	12 $\mu g/m^3$
Lanarkshire	28-May-11	10.8	24.3	50 $\mu g/m^3$	Low	4.8	10.5	12 $\mu g/m^3$
Edinburgh	28-May-11	10.5	21.3	50 $\mu g/m^3$	Low	3.5	7.9	12 $\mu g/m^3$
Stornoway	28-May-11	9.0	21.8	50 $\mu g/m^3$	Low	5.5	12.0	12 $\mu g/m^3$
Thurso	28-May-11	9.8	21.5	50 $\mu g/m^3$	Low	4.5	9.0	12 $\mu g/m^3$

Orkney	28-May-11	16.6	37.4	50 µg/m^3	Low	6.7	12.9	12 µg/m^3
East Lothian	28-May-11	No data	No data	50 µg/m^3	No data	No data	No data	12 µg/m^3
Lanarkshire	29-May-11	15.0	26.4	50 µg/m^3	Low	8.2	19.3	12 µg/m^3
Edinburgh	29-May-11	13.6	34.7	50 µg/m^3	Low	4.7	11.1	12 µg/m^3
Stornoway	29-May-11	8.6	28.7	50 µg/m^3	Low	3.3	8	12 µg/m^3
Thurso	29-May-11	9.8	27.5	50 µg/m^3	Low	4.2	10.4	12 µg/m^3
Orkney	29-May-11	15.8	38.3	50 µg/m^3	Low	6.6	16.1	12 µg/m^3
East Lothian	29-May-11	No data	No data	50 µg/m^3	No data	No data	No data	12 µg/m^3

Appendix 3: Herbage and soil monitoring (volcanic ash) decision support models

Acknowledgement

These decision support models were based on the initial concepts put forward by Mark Aitken (SEPA Operations team)

Based on the decision models below, soil and herbage monitoring are not warranted at this time (May 27, 2011). The highest level of ash total deposition predicted from the Met Office was 1 g/m^2, which does not exceed the trigger values derived in the decision models.

1. Herbage decision model (sampling trigger)

If ash F concentration < 100 mg F/kg ash, herbage sampling is not warranted.

If ash F concentration > 200 mg F/kg ash and *cumulative* deposition is > 10 g/m^2 (0.2 t/ha), commence herbage sampling.

Use the decision matrix table (Table 11) for fine-checking other ash F concentration and deposition mass scenarios.

Table 11. Decision matrix table for herbage monitoring: table entries show herbage concentration of F (mg F/kg dry mass) for stated ash F concentration and cumulative deposition amount.

Ash F mg/kg	Ash deposition (g/m^2)					
	1	2	5	10	20	30
100	16	17	19	23	32	40
200	17	18	23	32	48	65
300	18	20	28	40	65	90
400	18	22	32	48	82	115
500	19	23	36	57	98	140
600	20	25	40	65	115	165
700	21	27	44	73	132	190
800	22	28	48	82	148	215
900	23	30	53	90	165	240

Entries in red indicate potential exceedance of a 40 mg F/kg herbage limit.

2. Soil decision model (sampling trigger)
Soil sampling should be triggered if *cumulative* ash fall exceeds 48 t/ha (4800 g/m^2) or a deposition thickness of 3.2 mm.

Underlying data for decision models
Common reference point: to prevent fluorosis in stock, the annual average fluoride (F) content of forage should not exceed 40 mg/kg dry wt.

1. Herbage trigger values
If ash F concentration is less than 100 mg F/kg ash, an ash deposition in excess of 30 g/m^2 (or 0.3 t/ha) would have to occur before herbage approached a surface concentration of 40 mg/kg, i.e. the toxic threshold level for livestock (this assumes a standard herbage density of 1200 kg dm/ha and a natural F level in herbage of 15 mg/kg). Moreover, this would have to occur during a dry period where no loss of F (i.e. no loss from leaching/washing from rain) would occur.

2. Soil trigger values

2.1 If animals ingest ~10% soil per unit herbage consumed, a soil concentration of 400 mg/kg would equal the 40 mg/kg dry wt intake (ignoring herbage).

2.2 An estimate of background soil F is 61 mg/kg. Therefore added F would need to exceed 339 mg/kg soil to exceed the threshold and create a toxicity risk.

2.3 If 1 cm depth of surface soil is considered, 1 ha soil (100x100m) has a soil mass of 120 t (assuming soil bulk density 1.2 g/cm^3).

2.4 This means 40.7 kg F/ha is needed to raise soil F to 339 mg/kg (i.e. 40.7kg F /120 t soil = 339 mg F/kg soil).

2.5 If ash is 850 mg F/kg (equalling 0.85kg F/t), amount of ash needed/ha is 40.7t/0.850 = 48 t.

2.6 Considering a dry bulk density of ash = 1.5, 48 t ash/ha equates to a depth of 3.2 mm.

Caveats

Some assumptions were necessary to generate a guideline number for soil. These should be borne in mind for context.

- Soil ingestion can vary above the 10% by mass amount (depending on season and herbage status).
- The F background level of soil can vary – the 61 mg/kg value adopted is from the sludge amended soil database (mean F level for soils in that data base).
- F content of ash can vary, 850 mg F/kg was a peak level from 2010.
- The deposition should be considered over the duration of the volcanic activity (i.e. it is cumulative).