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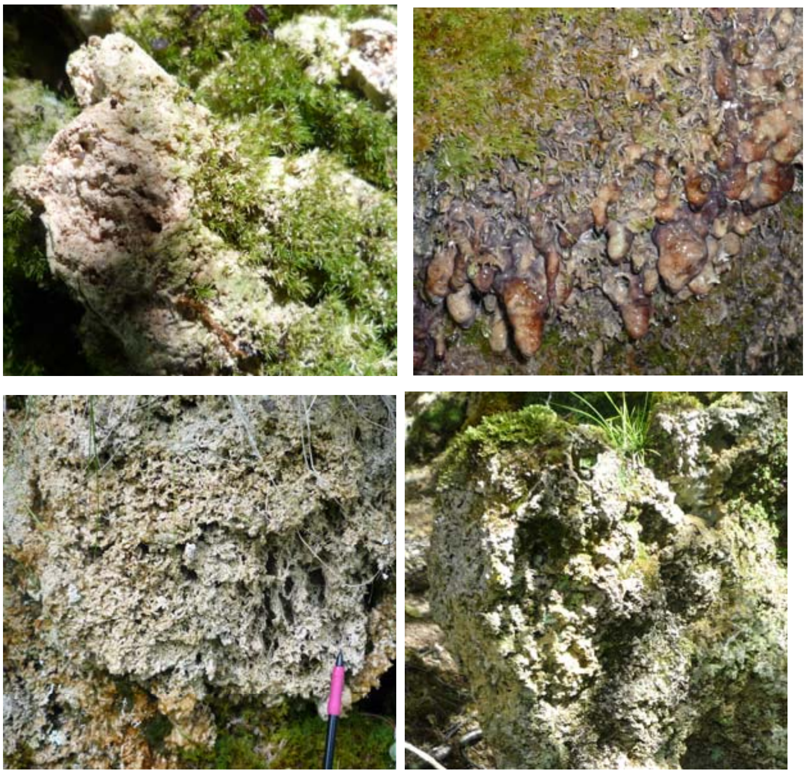
Creag nan Gamhainn Springs: a hydrogeological survey and interpretation of the groundwater system

Groundwater Science Programme

Commissioned Report CR/09/169C



BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

COMMISSIONED REPORT CR/09/169C

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Front cover

Tufa deposited by springs in the Creag nan Gamhainn SAC.

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B É Ó Dochartaigh

Keyworth, Nottingham British Geological Survey 2010

BRITISH GEOLOGICAL SURVEY

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) on behalf of the Moray Council.

The report contains geological map extracts taken from the BGS Digital Geological Map of Great Britain at the 1:50,000 scale (DiGMapGB-50). The geological layers – superficial and bedrock geology - are displayed separately as 10 by 10 cm extracts. Additional records consulted are held in the National Well Records Archive (part of the National Geoscience Data Centre NGDC).

More information on DigMapGB-50 and how the various rock layers are classified can be found on the BGS website (www.bgs.ac.uk), under the DiGMap and BGS Rock Classification Scheme areas. Further descriptions of the rocks listed in the map keys can also be obtained by searching against the Computer Code on the BGS Lexicon of named Rock Units, which is also on the BGS Website at by following the 'GeoData' link. The computer codes are labelled on the maps to try and help in their interpretation (with a dot at the bottom left hand corner of each label). However, please treat this with caution in areas of complex geology, where some of the labels may overlap several geological formations. If in doubt, please contact BGS enquiries. The geological formations are listed broadly in order of age in the map keys (youngest first) but only to the formation level (a formation is a package of related rocks). Within formations, please be aware that individual members may not be ordered by age.

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Summary

- A survey of the springs within the Creag nan Gamhainn Special Area of Conservation (SAC) has revealed new information about the hydrogeological and hydrochemical controls on the springs and their associated features, including tufa development.
- The bedrock geology underlying the Creag nan Gamhainn SAC comprises the Inchrory Limestone Formation, an ancient calcareous metamorphic rock. This is typically a blue-grey, medium to coarsely crystalline, thin- to medium-bedded metamorphosed limestone, with occasional thin interbeds of schist (metamorphosed mudstone). Calcareous rocks such as these are rare in Scotland.
- Eight distinct springs were observed as flowing or seeping at the time of the survey, in July 2009. A further two were identified as possible ephemeral seeps that were dry at the time of survey. All but one of the observed springs emerges on the steepest slopes on the north/east side of the River Avon, within the SAC. Many emerge from near-vertical rock faces. The locations of the identified springs are given in Appendix 1.
- Most of the observed springs have small flows, often better described as seeps. At some of the springs a number of small flows apparently emerge close to each other over an area of rock face approximately 2 to 5 m square. Most of the springs flow from rock faces covered by vegetation, particularly moss. The largest observed discrete flow from a single source was approximately 0.03 litres/second.
- The chemistry of groundwater flowing from the springs is distinctive, being significantly more mineralised than the average for other groundwaters in the region, even those from the rare examples of other calcareous rocks in the Highlands. Groundwater samples from the springs are slightly alkaline, oxygenated, and saturated with respect to calcite, with total dissolved solids between 500 and 650 mg/l, calcium concentrations between 100 and 150 mg/l and bicarbonate concentrations between 350 and 400 mg/l.
- The catchment area for the springs is relatively small – probably less than 3 km^2 (Figure 12), but groundwater is likely to remain in the aquifer for at least 10 to 20 years before discharging at the springs.
- Most of the springs, both larger flows and smaller seeps, are associated with chemical precipitates at the point where they discharge at the ground surface. This is tufa, or carbonate deposits. The tufa development is characteristic of the springs within the Creag nan Gamhainn SAC, but is rare at other springs across the UK. The available evidence indicates that tufa formation at the springs is slow, on the order of decades.
- The tufa development is largely controlled by the chemistry of the groundwater that discharges from the springs, which is in turn controlled by the type and chemistry of the limestone aquifer through which the groundwater flows. The high concentrations of calcium and bicarbonate in the groundwater are derived from dissolution of calcite in the limestone as the groundwater flows through the aquifer. As the groundwater discharges at the springs, chemical changes lead to the precipitation of tufa. This precipitation is likely to be mediated by microbes, probably in the form of a biofilm, but the predominant control is the super-saturated alkaline groundwater chemistry.
- The groundwater chemistry also shows signs of the impacts of agriculture within the catchment area, in the form of elevated nitrate concentrations.

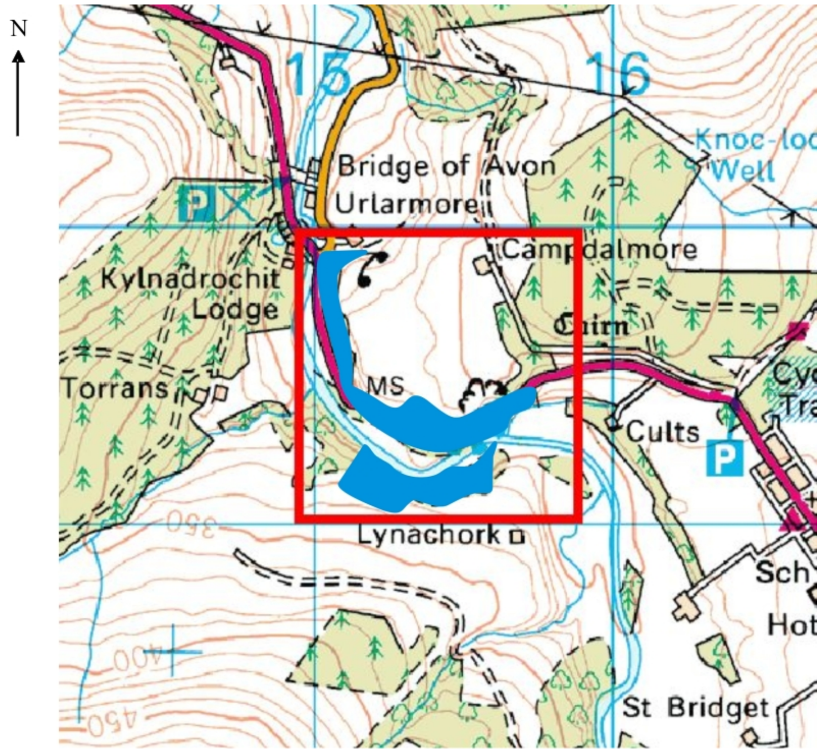
- Any changes to the slope angle at and around the springs in the SAC, and any changes to groundwater drainage in this area, is likely to result in changes to the location, flow rate and tufa development of the springs.

1 Introduction

The Creag nan Gamhainn Special Area of Conservation (SAC) / Site of Special Scientific Interest (SSSI) (in this report known as the Creag nan Gamhainn SAC) lies to the west of Tomintoul in the Highlands. Creag nan Gamhainn is designated as a SAC under the EC Directive 92/42/EEC on the Conservation of Natural Habitats and of Wild Flora and Fauna (the ‘Habitats Directive’) on the basis of the presence of hard-water springs depositing lime, also known as tufa springs, which is a priority habitat under the Directive.

The approximate National Grid Reference (NGR) for the centre of the Creag nan Gamhainn SAC is NJ 152 194. The A939 Bridge of Avon to Tomintoul road runs through the site (Figure 1).

The Moray Council employed the British Geological Survey (BGS) to carry out a hydrogeological survey of the springs at Creag nan Gamhainn SAC. This report describes the survey and provides an interpretation of the groundwater system related to the springs.



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SITE LOCATION

Information on the extent of the SAC / SSSI provided by Scottish Natural Heritage.

Figure 1 The general area of Creag nan Gamhainn, showing the approximate extent of the SAC / SSSI (shaded in blue)

2 Investigations

2.1 BACKGROUND

The first part of the survey involved a desk study of the available geological and hydrogeological information. Geological maps of the region and the local area were examined and a search of records of water boreholes and other springs in the area was carried out.

The overview geology of the region surrounding the Craig nan Gamhainn SAC, at 1:625,000 scale, is illustrated in Figure 2. More detailed maps of the geology of the SAC are provided in Section 3, below.

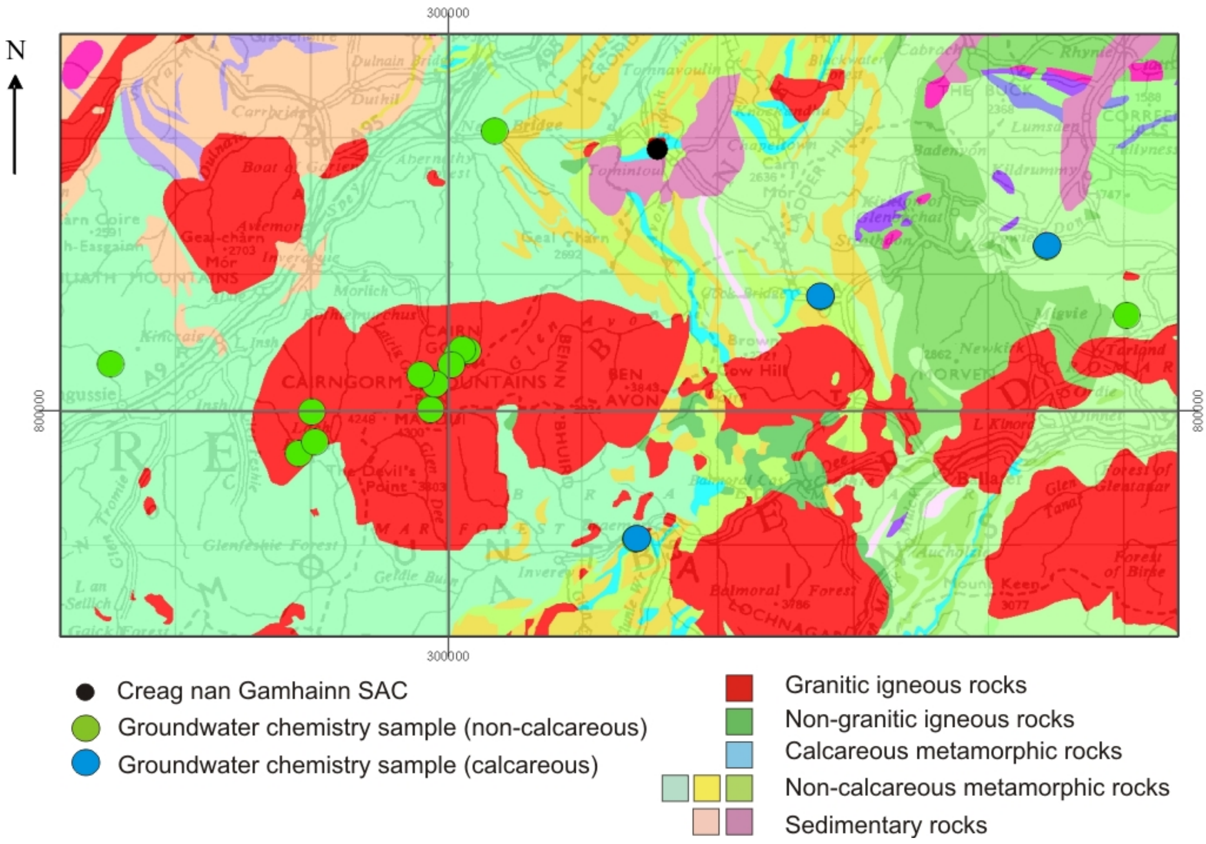


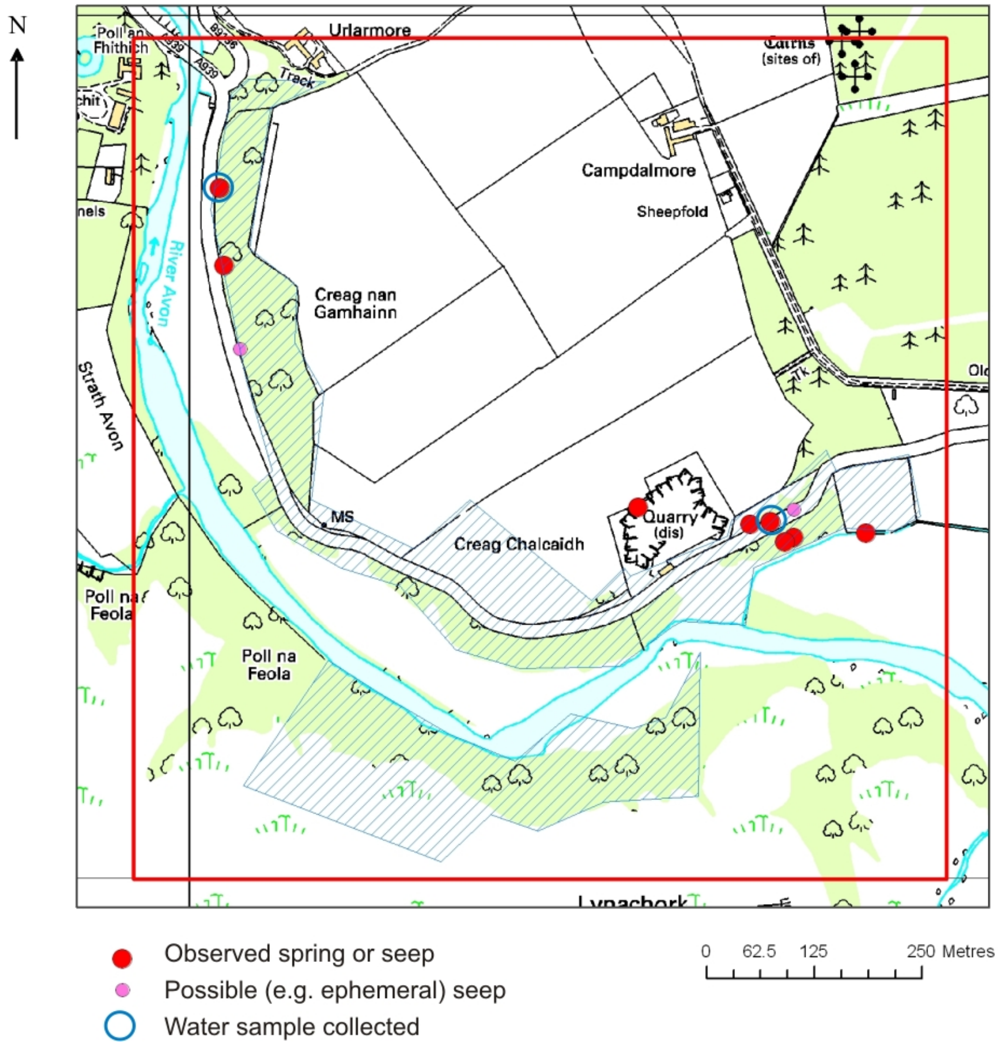
Figure 2 Overview geology (at 1:625,000 scale) of the region around Creag nan Gamhainn, also showing locations of known groundwater chemistry analyses (all from springs**)**

There are few current groundwater abstractions in this region. The British Geological Survey (BGS) has records of less than 20 currently and/or formerly used groundwater abstraction points – both boreholes and springs – within 20 km of the Craig nan Gamhainn SAC. There is, however, limited information on the chemistry of groundwater in this region, provided by a number of analyses of groundwater chemistry, also held by BGS. Sixteen records of detailed chemical analyses of groundwater – all from springs – are available from the 50 km region around Creag nan Gamhainn (Figure 2). Ten of these samples were collected from springs in granite rocks in the Cairngorms. At least two, and possibly three, of the others were collected from springs in calcareous metamorphic rocks – metalimestones or calcareous psammites – that are likely to be similar to the bedrock at Creag nan Gamhainn (see Section 3.2). The remaining samples were from springs flowing from non-calcareous metamorphic rocks.

2.2 FIELD SURVEY

A BGS hydrogeologist visited the Creag nan Gamhainn SAC and carried out a field survey on 29 and 30 July 2009. The weather at the time of the investigation was dry. The field survey incorporated the following activities:

- A walkover survey of the SAC/SSSI and surrounding probable spring catchment area.
- The accurate location, using GPS, of all observed springs/seeps, and of possible ephemeral springs/seeps that aren't currently flowing (Figure 3). The locations of the identified springs are given in Appendix 1.
- Assessment of hydrogeological characteristics of the observed springs, including, where relevant and/or possible, the flow rate and selected physico-chemical measurements of spring water (in particular, temperature and specific electrical conductivity or SEC).
- Collection of water samples for laboratory analysis from the two largest observed springs, including residence time samples from one of these.



The approximate extent of the SAC is highlighted by blue hatching

The locations of the springs and seeps shown are given in Appendix 2.

Figure 3 Location of springs and/or seeps identified during site survey at Creag nan Gamainn SAC

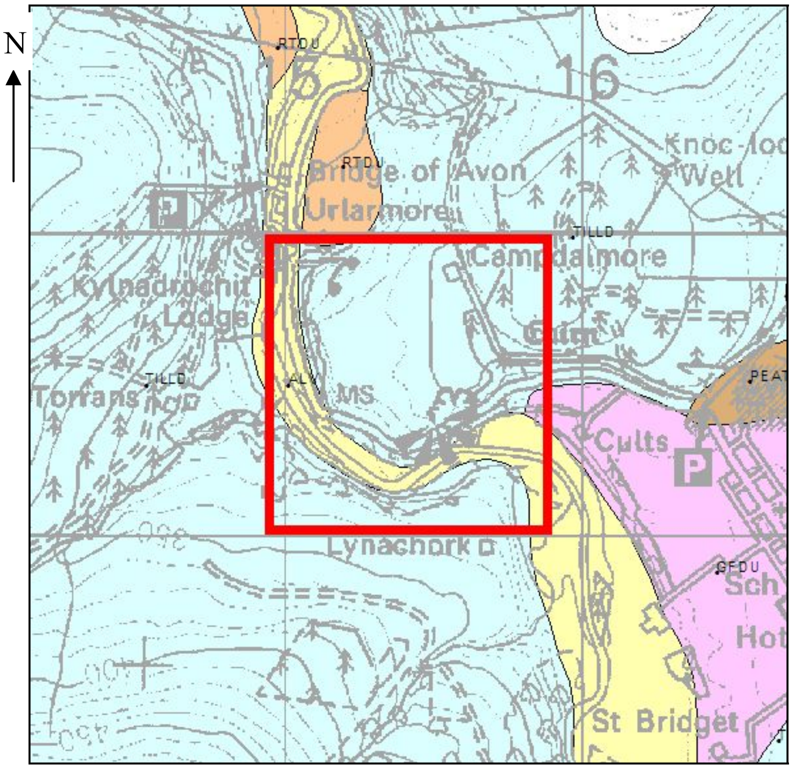
3 Local hydrogeology and the spring system

3.1 SUPERFICIAL GEOLOGY

Superficial deposits include recent, unconsolidated geological deposits, such as alluvial sands and gravels or glacial deposits, which overlie the bedrock in many areas.

Within and surrounding the area of the SAC, the dominant superficial deposit is glacial till (Figures 4 and 5). Field observations and limited borehole evidence indicate that the till comprises a mixed, poorly sorted deposit that ranges from a silty sand with small to large stones (e.g. Figure 5), to largely sand and gravel deposit. The till is likely to be no more than 1 to 3 m thick across most of the area.

Along the base of the River Avon valley, alluvium has been laid down by the river. Local boreholes show that the alluvium typically comprises sand and gravel, with occasional thin (~0.2 m thick) silty sand layers. Boreholes at and a few hundred metres to the north of the new Bridge of Avon (NGR NJ 149 199) show that the thickness of the alluvium here ranges from 1.4 m to 6.7 m. Observations along the river within the area of the SAC show that in many places the thickness of alluvium thins to zero, and bedrock is sometimes exposed at the ground surface (Figure 6).



Scale: 1:25000 (1cm = 250m)

SITE LOCATION

Key to superficial deposits:

Map colour	Computer Code	Rock name	Rock type
	ALV	ALLUVIUM	CLAY, SILT, SAND AND GRAVEL
	TILLD	TILL, DEVENSIAN	DIAMICTON
	GFDU	GLACIOFLUVIAL DEPOSITS	GRAVEL, SAND AND SILT
	PEAT	PEAT	PEAT
	RTDU	RIVER TERRACE DEPOSITS (UNDIFFERENTIATED)	GRAVEL, SAND, SILT AND CLAY

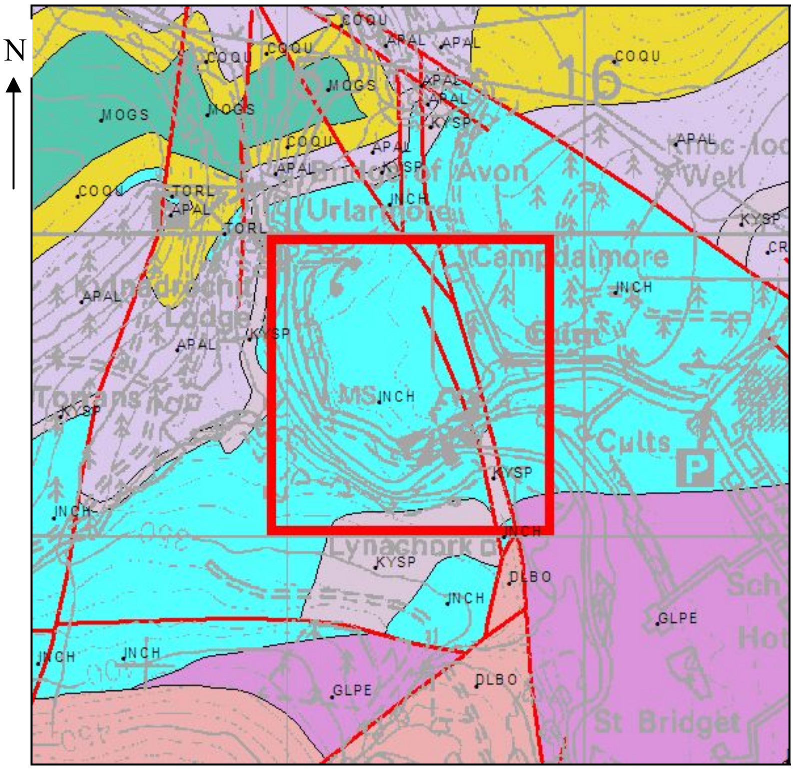
Figure 4 Map of superficial geology in the area of the Creag nan Gamhainn SAC

Figure 5 Exposure of glacial till on the higher slopes above the river bank, within the SAC

3.2 BEDROCK GEOLOGY

The SAC area is entirely underlain by metalimestone – calcareous metamorphic rocks – of the Inchrory Limestone Formation, typically a blue-grey coloured, medium to coarsely crystalline, thin- to medium-bedded limestone (Figures 6 and 8). It has occasional thin interbeds of graphitic to calcareous pelite and semipelite (metamorphosed mudstone, also called schist) and occasional chert nodules. The formation is part of the Appin Group, which itself is part of the Dalradian Supergroup, which includes most of the bedrock across this region of the Highlands.

The bedrock in this area has been extensively deformed by ancient folding and faulting, so that today the various rock units have a complex outcrop, with different formations juxtaposed against each other by bounding faults (Figure 6). The Inchrory Limestone Formation is surrounded by a variety of different rock types. It is bounded to the north, west and east largely by calcareous schists (semipelite, pelite and psammite – metamorphosed sandstone) of the Ailnack Phyllite and Limestone Formation and the Kylnadrochit Semipelite Member. These are also metamorphic rocks with some carbonate, but are much less calcareous (carbonate-rich) than the Inchrory Limestone Formation. To the southeast, the Inchrory Limestone Formation is bounded by non-calcareous schists of the Glenfiddich Pelite Formation; and to the southwest by younger sedimentary rocks – conglomerate and sandstone – of the Delbabo Conglomerate Formation.



Scale: 1:25000 (1cm = 250m)

SITE LOCATION

Fault. **Note: Faults are shown for illustration and to aid interpretation of the map. Not all faults are shown and their absence on the map face does not necessarily mean that none are present.**

Key to bedrock geology:

Map colour	**Computer Code**	**Rock name**	**Rock type**
	DLBO	DELNABO CONGLOMERATE FORMATION	CONGLOMERATE AND [SUBEQUAL /SUBORDINATE] SANDSTONE, INTERBEDDED
	APAL	AILNACK PHYLLITE AND LIMESTONE FORMATION	SEMIPELITE, PELITE AND PSAMMITE
	COQU	CORRYHABBIE QUARTZITE FORMATION	QUARTZITE
	CRSP	CLASHNOIR SEMIPELITE FORMATION	SEMIPELITE, PELITE AND PSAMMITE
	GLPE	GLENFIDDICH PELITE FORMATION	PHYLLITIC-GRAPHITIC PELITE AND PHYLLITIC-GRAPHITIC SEMIPELITE
	INCH	INCHRORY LIMESTONE FORMATION	METALIMESTONE
	KYSP	KYLNADROCHIT SEMIPELITE MEMBER	CALCAREOUS SEMIPELITE
	MOGS	MORTLACH GRAPHITIC SCHIST FORMATION	GRAPHITIC PELITE
	TORL	TORULIAN LIMESTONE MEMBER	METALIMESTONE

Figure 6 Map of bedrock geology in the area of the Creag nan Gamhainn SAC

Figure 7 Inchrory Limestone Formation exposed within and near the SAC: (left) exposed in the river bank; (right) showing the blocky, fractured nature of the exposed rock

3.3 DESCRIPTION OF THE SPRINGS

Eight distinct springs were identified during the current survey as currently flowing or seeping; another two sites were identified as possible ephemeral seeps which were dry at the time of the survey, but had evidence of groundwater flow, such as rock discolouration (Figures 3 and 9). All were on the north/east side of the River Avon. This is fewer than the number of flows or seeps that have been previously identified by Scottish Natural Heritage (SNH). Some of the additional springs identified by SNH may flow only in the winter or during particularly wet summers. There may also be other springs (permanent or ephemeral) in areas of very steep or thickly vegetated ground that aren't easily accessible. However, it is likely that the springs identified during the current survey include the largest and most significant springs in the SAC.

Most of the springs emerge on the steepest ground in the SAC, particularly from near-vertical rock faces. The only exception observed during the current survey was near the eastern end of the SAC, at approximate NGR NJ 158 194, where the exact spring source wasn't identified but appeared to rise in a gently sloping field.

Most of the springs observed have small flows, usually better described as seeps (e.g. Figure 9), but some of the most significant have a number of small flows over an area of rock face of approximately 2 to 5 m. Many of the springs flow from rock faces that are covered by vegetation, particularly moss, so that the individual outflows from the rock aren't visible (Figure 8). The total flow from these seeps over the wet area could be relatively large, but it is difficult to measure such diffuse flow accurately. The largest observed discrete flow from a single source (fracture) was St Jessie's Well, with a flow of approximately 0.03 l/s (Figure 10).

Figure 8 Multiple small spring flows (seeps) over areas of rock face, covered with vegetation

Figure 9 Groundwater seepage from discrete fracture in quarry face

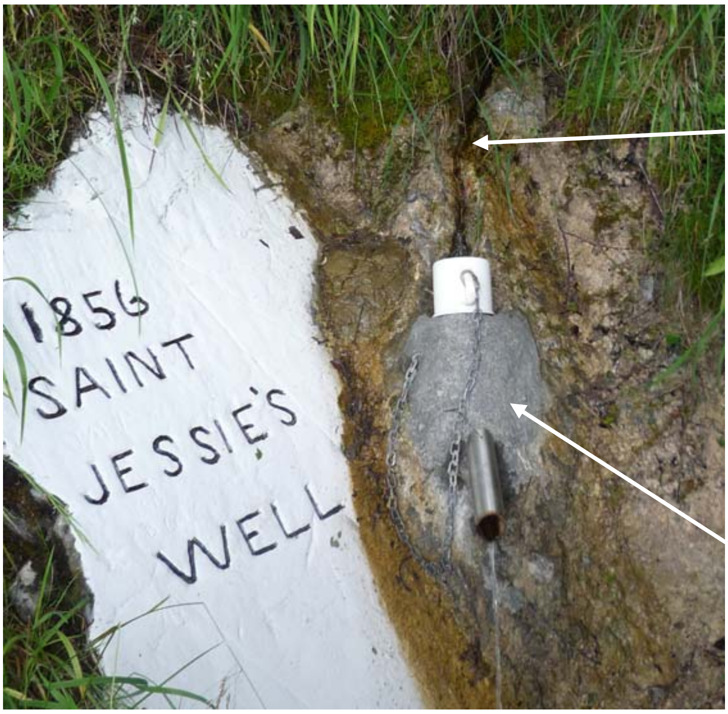


Figure 10 Spring flowing from discrete fracture in rock outcrop

Most of the springs, both larger flows and smaller seeps, are associated with chemical precipitates at the point where they discharge at the ground surface. This is tufa, or carbonate deposits. Tufa is formed from supersaturated alkaline groundwaters, which when they discharge at a spring, precipitate carbonate minerals. More detail on tufa development is given in Section 3.5. It takes various forms, from soft, often reddish-coloured algal-like coatings on vegetation, particularly on moss; to smooth, stalactite-like features growing downwards or apparent coatings on branches and rocks; to rough-textured, porous masses that appear to grow upwards (Figure 11). Much of this appears to be quite fragile, particularly when still soft, and easily damaged.

Not all of the springs show tufa to the same degree. At the fastest flowing of the springs observed during this survey, known as St Jessie's Well (NGR NJ 15673 19413), there is evidence of some tufa formation in the form of soft, reddish and brownish, mud-like precipitate, but little hardened or developed tufa as at other springs (Figure 10). This may be because this spring has apparently been relatively well known for a long time, according to the sign painted at the spring, and therefore is likely to be regularly visited, which may have caused incipient tufa to be damaged, preventing its development.

At a separate seep, from a rock wall in the disused quarry towards the east of the SAC (NGR NJ 1552 1943), there is discolouration of the rock over which the discharging spring water is flowing, some of which is likely to be caused by incipient precipitation of tufa. Access directly to the rock face at the seep wasn't possible for safety reasons, but from a distance the discolouration appears similar to the soft, algal-like coatings seen on vegetation and rock faces at other springs within the SAC. There is no evidence of more developed, harder tufa here (Figure 9).

Figure 11 Examples of tufa formation at springs within the Creag nan Gamhainn SAC

The length of time needed for tufa development is unknown. No observations of tufa growth at the springs at Creag nan Gamhainn are known of. The lack of developed tufa at the seep in the disused quarry – which is likely to be only a few decades old (the exact age of the quarry is unknown) – indicates that it may take decades for tufa to develop. As many factors, such as groundwater chemistry, flow rate and biological activity (see also Section 3.5), can affect the degree and rate of tufa development, this can't be taken as conclusive evidence of the rate of tufa development in the SAC.

3.4 HYDROGEOLOGY

3.4.1 Regional

The ancient metamorphic rocks of the Highlands generally form low productivity aquifers. The very hard, crystalline nature of these metamorphosed rocks means that they have almost negligible intergranular porosity and permeability. Intergranular porosity is thought to be invariably less than 1% in all geological units (Robins 1990). Weathering in the near-surface zone – perhaps to a few metres depth, and often most pronounced in areas of most intensive fracturing – can lead to the development of shallow zones of enhanced intergranular (matrix) permeability, but in general groundwater storage and flow is entirely within fractures (Ball 1999). These fractures are often more common in the near surface, sometimes enhanced by weathering, and become less common with depth. The fractures are often only millimetres wide, but their lateral extent (length) can vary considerably, from millimetres to many hundreds of metres. Water bearing fractures at depths of more than 80 m do occur, but are less common. Often a single fracture, or at most three or four fractures, provides all of the groundwater inflow to a borehole. Individual fracture flows can be as high as approximately 0.3 litres/second (l/s), although are typically lower than this. Records of borehole yields from these metamorphic aquifers are usually between 0.1 and 0.5 l/s, and the few available records of specific capacity are less than 2 m^3/day/m. The only recorded transmissivity value for a Dalradian metamorphic aquifer (the age of the rocks at Creag nan Gamhainn) in the Highlands is low, at 1.4 m^2/day.

3.4.2 Creag nan Gamhainn

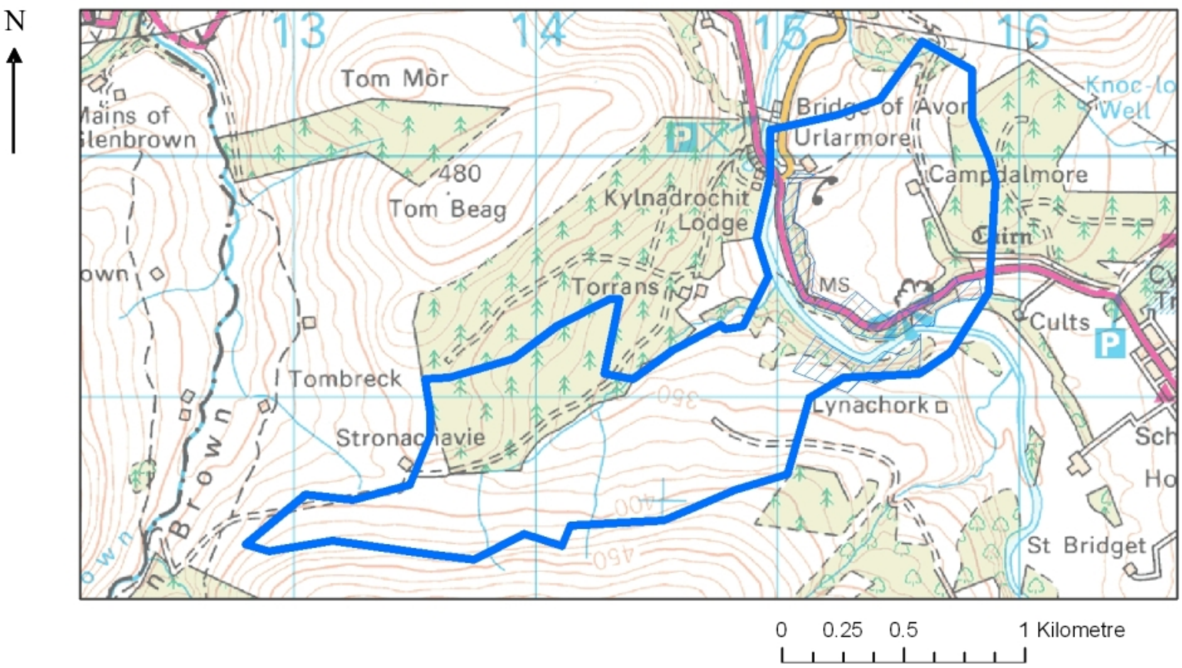
The Inchrory Limestone Formation, the aquifer feeding the springs at Creag nan Gamhainn, is likely to be slightly more productive, with a slightly higher permeability, than most of the surrounding rock formations in the area, and than most of the other metamorphic rocks in the Highlands. This is due to the probable dissolution of the calcareous rock, and the consequent enlargement of fractures. As with other metamorphic rocks in the region, all effective groundwater storage and flow occurs through these fractures, with virtually no intergranular groundwater storage and flow.

Inflow of groundwater to the Inchrory Limestone Formation from surrounding rock formations almost certainly occurs, but this is likely to be less significant than recharge from rainfall directly to the limestone.

Evidence of groundwater flow along discrete fractures at Creag nan Gamhainn can be seen at a number of locations where groundwater seepages and flows directly from the rock can be observed. One of the most obvious examples is within the disused quarry, where water seeping out of a fracture feeds a large pool of water on the quarry floor, and has left permanent discolouration on the rock (Figure 9). Another example is the largest of the observed springs, St Jessie's Well, where a flow of approximately 0.03 litres/second (l/s) emanates from a discrete fracture in the rock (Figure 10). Where the rock is exposed and there are no discrete flows, it is generally dry with no evidence of intergranular groundwater flow (e.g. Figure 8, right).

The catchment for the springs within the Creag nan Gamhainn SAC is likely to be defined both by the surface water catchment (i.e., the highest ground that forms the surface watershed) and by the outcrop of the Inchrory Limestone Formation, which is the main aquifer feeding the springs. Although it is impossible to draw detailed and accurate catchment boundaries for the springs without much more detailed investigations, such as tracer tests, the approximate zone from which most of the water discharging at the springs is likely to be drawn is shown in Figure 12. Note that the River Avon divides this area into two. Any springs to the south and west of the river will be fed from the western part of this zone. The springs to the north and east side of the river, including all of the ones identified in the current survey, will be fed from the northern part of this zone. This is a relatively small area, of only approximately 1 km square.

The base level for drainage within the catchment is likely to be the River Avon. Most groundwater within the catchment is likely to discharge either directly to the river, or to discharge as springs which feed streams, which in turn drain to the river. A small proportion of the groundwater, however, may be flowing at depths below the level of the River Avon, and this is likely to continue flowing within the bedrock, through the neighbouring rock formations, to ultimately discharge further downgradient, probably to the River Avon further downstream.



The approximate extent of the SAC is highlighted by blue hatching

Figure 12 The approximate catchment area from which spring water discharging within the Creag nan Gamhainn is likely to be drawn

3.5 HYDROCHEMISTRY

3.5.1 Regional

The available groundwater chemistry data for the surrounding region indicate clear differences between springs flowing from calcareous rocks, such as those of the Inchrory Limestone Formation from which the Creag nan Gamhainn springs flow, and those flowing from non-calcareous rocks. Overall, groundwaters from calcareous rocks in the region have noticeably higher calcium and bicarbonate concentrations (an average of 41 mg/l calcium and 96 mg/l bicarbonate) compared to the averages for non-calcareous rocks (7 mg/l calcium and 28 mg/l bicarbonate). The average pH of groundwaters from calcareous rocks across the region (7.9) also tends to be higher – more alkaline – than that of groundwaters from non-calcareous rocks (7.0).

3.5.2 Creag nan Gamhainn

The two spring water samples taken at Creag nan Gamhainn, both discharging from the Inchrory Limestone Formation, have broadly similar chemistry to each other, although slight differences occur in individual element concentrations. The samples are field-coded CnG1 (from Saint Jessie's Well) and CnG2 (from a tufa forming spring in the west of the SAC). The locations of the samples are highlighted in Figure 3, and National Grid References are given in Table 1, along with full results of the chemical analysis.

The groundwater samples from the springs are more mineralised than the average for other groundwaters in the region, even those from calcareous rocks, with total dissolved solids of 622 and 522 mg/l. They are oxygenated, with dissolved oxygen greater than 9 mg/l and redox (Eh) values greater than 266 mV. They are slightly alkaline, with pH values of 7.34 and 7.68. Both are strongly calcium-bicarbonate type waters (as illustrated in the Piper plot in Figure 13). The calcium (118 and 145 mg/l) and bicarbonate (350 and 395 mg/l) concentrations are significantly higher than any other groundwater samples recorded from this region – they are 3 to 3.5 times higher than the average for other calcareous rocks in the region. Both the samples are saturated with respect to calcite, with sample CnG2 showing the highest saturation index at 0.37, compared to a calcite saturation index of 0.17 for CnG1.

Concentrations of the other major ions (magnesium, sodium, potassium, chloride and sulphate) are relatively low. Concentrations of the most significant minor ions – iron and manganese – are also relatively low, as would be expected given the alkaline, oxygenated nature of the groundwater.

Nitrate concentrations are relatively high in both samples, at 31.7 and 38.8 mg/l (as NO_3). This is significantly higher than would be expected from rainfall inputs alone, and nitrate is not derived from rocks. Natural background nitrate concentrations in Scotland, in areas unaffected by intensive agriculture, are generally thought to be less than 5 mg/l as NO_3 (MacDonald et al 2003). The upper limit for drinking waters in Scotland is 50 mg/l as NO_3. The main source of nitrate in the spring waters in Creag nan Gamhainn is likely to be agricultural activity within the catchment area. The effect of nitrate on tufa deposition, if any, is unknown.

Trace gases – residence time indicators

Analysis of CFC and SF_6 gas concentrations in groundwaters can give an indication of their relative age – the length of time since groundwater fell as rain and infiltrated the aquifer. There are very rigorous sampling procedures for trace gases in groundwater, and it was only possible to collect samples from one of the springs (CnG1: Saint Jessie's Well). The results indicate that the spring water is a mixture of groundwater flowing along different flow paths through the aquifer. Because these flow paths are of different lengths, the groundwater flowing along them is of different ages (some taking longer to flow from recharge to spring discharge point than others). This supports the field evidence that groundwater flow through the limestone aquifer is dominantly through fractures, which as they branch through the rock can create quite intricate and variable flow paths. However, the CFC and SF_6 data indicate that in the mix of water discharging at the spring, older water (at least 10 to 20 years since it fell as rain) dominates over younger water (representing rainfall from weeks or months before). In other words, much of the spring water is likely to be decades old.

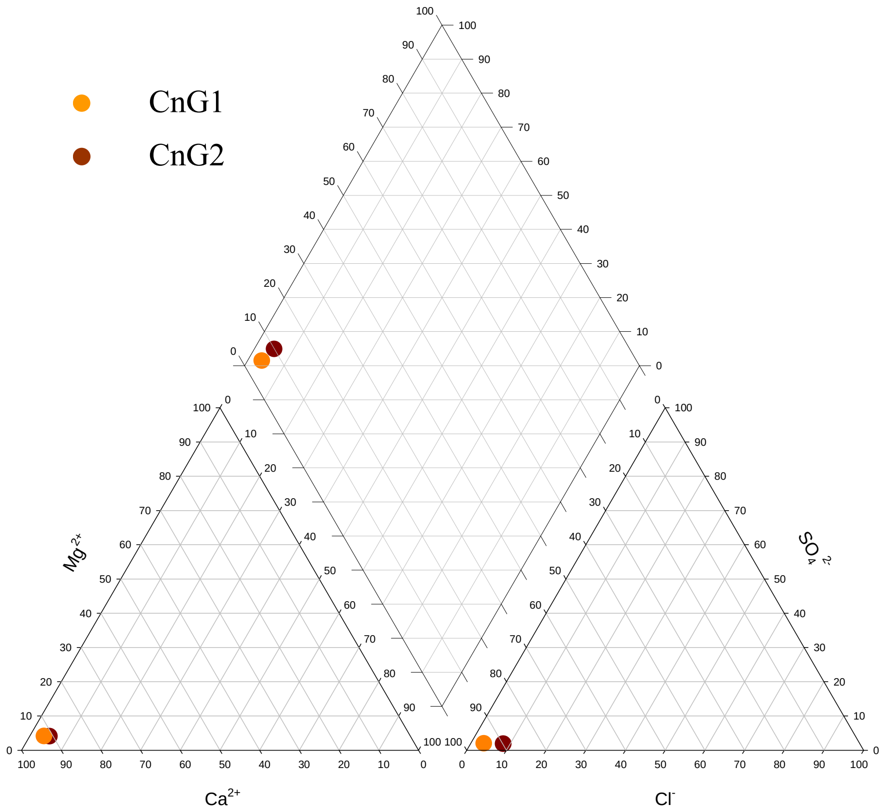


Figure 13 Piper diagram illustrating the major ion composition of the two spring samples from Creag nan Gamhainn.

Stable isotopes

Analysis of stable isotopes of oxygen (δ18O) and hydrogen (δ2H) has helped to confirm the conceptual model of groundwater recharge and the spring catchment area. The isotope evidence shows that δ18O and δ2H concentrations in the spring waters are consistent with what would be expected from groundwater recharged at altitudes slightly higher than the spring outflows, equal to the altitude of the hillslopes above the springs. There is no evidence for groundwater that has been recharged at much higher altitudes, which supports the interpretation that a relatively small catchment area feeds the springs.

Tufa

Tufa is formed from supersaturated alkaline waters, which have raised pCO_2 (partial pressure of carbon dioxide). When groundwater emerges at a spring, it degasses CO_2 due to the lower pCO_2 in the atmosphere compared to the pCO_2 in the aquifer, which causes an increase in pH (increased alkalinity) in the groundwater. Carbonate solubility decreases as pH increases, and so precipitation of carbonate minerals is induced. Although no mineral analysis of the tufa at the Creag nan Gamhainn springs is known to have been done, calcite is the dominant mineral found in other tufa deposits, with aragonite also found. It is now thought that tufa precipitation only occurs in the presence of microbes, e.g. in the form of a biofilm, and that physico-chemical conditions alone aren't enough to induce precipitation.

Table 1 Results of chemical analysis of groundwater samples from Creag nan Gamhainn springs

PARAMETER	UNITS	CNG1	CNG2
BGS Laboratory ID		12205-0001	12205-0002
Location		Saint Jessie's Well	Creag nan Gamhainn Spring
Easting		315673	315035
Northing		819413	819800
Sample Date		29/07/2009	30/07/2009
Sample Condition		Clear	Clear
Field parameters			
Temperature	°C	8.7	8.6
Redox (Eh)	mV	266	436
pH	-	7.34	7.68
HCO_3^-	mg/L	395	350
Specific Electrical Conductivity	µS/cm	763	589
DO	mg/L	9.08	9.34
TDS	mg/L	622	522
Dissolved gases			
CFC-11	pmol/L	6.25	
CFC-12	pmol/L	2.46	
SF6	fmol/L	0.879	
Stable isotopes			
δ18O	‰VSMOW	-9.47	-9.88
δ2H	‰VSMOW	-63.90	-72.80
δ13C	‰VSMOW	-15.59	-15.28
Major ions			
Ca	mg/L	145	118
Mg	mg/L	3.77	3.07
Na	mg/L	7.5	5.0
K	mg/L	3.5	1.0
Cl^-	mg/L	21.9	7.84
SO_4^{2-}	mg/L	5.96	5.32
NO_3^-	mg/L	38.8	31.7
Ionic Balance	%	0.79	-1.54
Calcite saturation index	-	0.17	0.37
Dissolved Organic Carbon	mg/L	1.95	0.958
Total P	mg/L	<0.01	<0.01
Total S	mg/L	3	3
Si	mg/L	3.88	4.10
SiO_2	mg/L	8.30	8.77

PARAMETER	UNITS	CNG1	CNG2
Trace ions			
Ag	µg/L	<0.005	<0.005
Al	µg/L	4.1	0.6
As	µg/L	0.12	<0.05
B	µg/L	<10	<10
Ba	µg/L	69	28
Be	µg/L	<0.005	<0.005
Cd	µg/L	<0.01	<0.01
Ce	µg/L	0.02	<0.01
Co	µg/L	0.07	0.02
Cr	µg/L	0.07	0.11
Cs	µg/L	0.05	0.04
Cu	µg/L	1.3	<0.5
Dy	µg/L	0.006	<0.005
Er	µg/L	0.005	<0.005
Eu	µg/L	0.010	<0.005
Fe	µg/L	14	1
Ga	µg/L	<0.05	<0.05
Gd	µg/L	0.007	<0.005
Hf	µg/L	<0.05	<0.05
Ho	µg/L	<0.005	<0.005
I	µg/L	3.86	0.69
La	µg/L	0.084	<0.005
Li	µg/L	<1	<1
Lu	µg/L	<0.005	<0.005
Mn	µg/L	1.0	0.1
Mo	µg/L	<0.2	<0.2
Nb	µg/L	<0.05	<0.05
Nd	µg/L	0.054	<0.005
Ni	µg/L	0.57	0.42
Pb	µg/L	<0.1	<0.1
Pr	µg/L	0.013	<0.005
Rb	µg/L	2.13	3.03
Sb	µg/L	0.042	0.016
Se	µg/L	0.09	0.20
Sn	µg/L	0.9	<0.1
Sm	µg/L	0.009	<0.005
Sr	µg/L	812	632

PARAMETER	UNITS	CNG1	CNG2
Ta	µg/L	<0.5	<0.5
Tb	µg/L	<0.005	<0.005
Th	µg/L	<0.05	<0.05
Ti	µg/L	<0.1	<0.1
Tl	µg/L	<0.1	<0.1
Tm	µg/L	<0.005	<0.005
U	µg/L	0.299	0.244
V	µg/L	<0.02	<0.02
W	µg/L	<0.5	<0.5
Y	µg/L	0.08	0.01
Yb	µg/L	0.005	<0.005
Zn	µg/L	1.6	<0.5
Zr	µg/L	0.04	<0.03

3.6 SUMMARY OF THE GROUNDWATER SYSTEM OF THE CREAG NAN GAMHAINN SPRINGS

The Creag nan Gamhainn springs occur over a relatively small area, mainly along steeper slopes of the valley side to the north of the River Avon (Figure 1). Most of the springs are small, sometimes only seeps. At two sites at least, a number of small seeps combine to produce significant wet areas across a few square metres of near-vertical rock face. These appear from the state of the vegetation to be semi-permanent if not permanent features, likely to flow for much or all of the year. The springs are fed by a limestone aquifer in which fracture flow dominates. The catchment area for the springs is relatively small – probably less than 3 km^2 (Figure 12), but groundwater is likely to remain in the aquifer for at least 10 to 20 years before discharging at the springs.

The most notable feature of the springs is the development of tufa features, to varying extents at different springs. At the springs with the largest surface area of flow – those with a number of small seeps combining across a rock face, which appear to be semi-permanent – tufa development is particularly significant. At springs which emerge over smaller areas (even if they have larger flows), and at those which appear to be more ephemeral, tufa is much less well developed. The variability in tufa development is likely to be partly due to local variations in groundwater chemistry, and partly to the complex and as yet poorly understood role of microbes in mediating tufa precipitation. The effect of differences in groundwater chemistry, even if minor, are illustrated by the higher calcite saturation index of the spring water at the sample site with the most significant tufa development, compared to the water flowing from Saint Jessie's well, which has little tufa.

4 Discussion

The springs in the Creag nan Gamhainn SAC flow from a limestone aquifer and are likely to have a relatively small catchment area. All of the springs observed in this survey are likely to be fed by groundwater from a catchment area of less than 1 km^2. Groundwater flow through the aquifer is virtually entirely through fractures in the rock.

The chemistry of the spring water is distinct from most other groundwaters in the Highlands, and indeed across Scotland. This chemistry is controlled by the interaction of the groundwater with the aquifer rock. This rock is a carbonate rich rock (limestone) that is also relatively depleted in magnesium and sulphate. As groundwater flows through the rock, dissolution of the rock minerals occurs and the groundwater becomes correspondingly more enriched in these minerals. The groundwater is subsequently harder (with significantly higher bicarbonate concentrations), and has higher calcium concentrations, than most other groundwaters from the Highlands and even the rest of Scotland.

This distinct groundwater chemistry has led to the formation of tufa features at the spring heads. Such features are rare in the UK and particularly in Scotland, although occasional large tufa deposits are known, associated with springs flowing from limestone rocks. The tufa features are likely to develop over many years, possibly even decades. Tufa development is likely to be mediated by local conditions at the spring heads, such as vegetation and the presence of biofilms or other microbial activity. These may in turn be partly controlled by the groundwater chemistry.

The groundwater has been affected by anthropogenic contamination, in the form of elevated nitrate concentrations. The nitrate is almost certainly derived from agricultural activity – such as slurry spreading or other fertilisation on silage fields – within the springs' catchment area.

Most of the observed springs are close to the A939 road that runs through the centre of the SAC. Any excavation along the road edges that intercepted tufa-forming springs is likely to damage and probably destroy tufa formations at those springs. If any springs continued to flow in the same locations after excavation ceased, it is possible that tufa would begin to regenerate. However, this may depend at least partly on other factors, such as vegetation conditions. Much of the observed tufa in the SAC is associated with vegetation, particularly mosses, and it is very likely that vegetation conditions, and possibly associated microbial activity, play a critical role, in combination with groundwater chemistry, in promoting tufa formation. In addition, the available evidence suggests that tufa may take decades to form, even where chemical and biological conditions support it.

Additionally, it is likely that excavation and/or associated work at and around the road in the general area within which the springs flow would have the effect of lowering the local water table. This could decrease or even halt the flow of existing springs, depending on their location and the location of works. For example, artificial drainage of any new road cutting is likely to reduce or halt the flow of water to springs immediately adjacent to, and at similar elevation to, the road.

Depending on the design of such new artificial drainage, it is possible that additional groundwater flow from the northeastern part of the spring catchment would be diverted through the limestone aquifer beneath the road, flowing in the direction of the River Avon. Such flow exists at present, as is evident from springs observed on the slopes between the road and the River Avon, which discharge below the elevation of the road. It is possible that increased groundwater flow through the aquifer below the road would increase the flow to springs in this area, which could, for example, increase the flow of perennial springs, or cause ephemeral springs to flow for longer. Higher flow rates could increase the rate of tufa development at these springs, but this is uncertain given the complex hydrogeological, chemical and biological controls on tufa development.

5 Conclusions

- A survey of the springs within the Creag nan Gamhainn Special Area of Conservation (SAC) has revealed new information about the hydrogeological and hydrochemical controls on the springs and their associated features, including tufa development.
- The bedrock geology underlying the Creag nan Gamhainn SAC comprises the Inchrory Limestone Formation, an ancient calcareous metamorphic rock. This is typically a blue-grey, medium to coarsely crystalline, thin- to medium-bedded metamorphosed limestone, with occasional thin interbeds of schist (metamorphosed mudstone). Calcareous rocks such as these are rare in Scotland.
- Eight distinct springs were observed as flowing or seeping at the time of the survey, in July 2009. A further two were identified as possible ephemeral seeps that were dry at the time of survey. All but one of the observed springs emerges on the steepest slopes on the north/east side of the River Avon, within the SAC. Many emerge from near-vertical rock faces.
- Most of the observed springs within the Creag nan Gamhainn SAC have small flows, often better described as seeps. At some of the springs a number of small flows apparently emerge close to each other over an area of rock face approximately 2 to 5 m square. Most of the springs flow from rock faces covered by vegetation, particularly moss. The largest observed discrete flow from a single source was approximately 0.03 litres/second.
- The chemistry of groundwater flowing from the springs is distinctive, being significantly more mineralised than the average for other groundwaters in the region, even those from the rare examples of other calcareous rocks in the Highlands. Groundwater samples collected from the springs are slightly alkaline, oxygenated, and saturated with respect to calcite, with total dissolved solids between 500 and 650 mg/l, calcium concentrations between 100 and 150 mg/l and bicarbonate concentrations between 350 and 400 mg/l.
- The catchment area for the springs is relatively small – probably less than 3 km^2 (Figure 12), but groundwater is likely to remain in the aquifer for at least 10 to 20 years before discharging at the springs.
- Most of the springs, both larger flows and smaller seeps, are associated with chemical precipitates at the point where they discharge at the ground surface. This is tufa, or carbonate deposits. The tufa development is characteristic of the springs within the Creag nan Gamhainn SAC, but is rare at other springs across the UK. The available evidence indicates that tufa formation at the springs is slow, on the order of decades.
- The tufa development is largely controlled by the chemistry of the groundwater that discharges from the springs, which is in turn controlled by the type and chemistry of the limestone aquifer through which the groundwater flows. The high concentrations of calcium and bicarbonate in the groundwater are derived from dissolution of calcite in the limestone as the groundwater flows through the aquifer. As the groundwater

discharges at the springs, chemical changes lead to the precipitation of tufa. This precipitation is likely to be mediated by microbes, probably in the form of a biofilm, but the predominant control is the super-saturated alkaline groundwater chemistry.

- The groundwater chemistry also shows signs of the impacts of agriculture within the catchment area, in the form of elevated nitrate concentrations.
- Any changes to the slope angle at and around the springs in the SAC, and any changes to groundwater drainage in this area, is likely to result in changes to the location, flow rate and tufa development of the springs.

References

Ball D F. 1999. An overview of groundwater in Scotland. British Geological Survey Technical Report WD/99/44.

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Appendix 1 Location of springs identified during the survey

SITE	EASTING	NORTHING	TYPE	DETAILS
1	315520	819430	Seep	Flowing from fracture; rock discolouration but no tufa.
2	315035	819800	Spring	Diffuse, fast drops from near-vertical, moss covered rockface. Extensive tufa features.
3	315040	819710	Spring	Diffuse, fast drops from near-vertical rock face. Extensive calcareous deposits on moss, but less tufa.
5	315673	819413	Spring	Saint Jessie's Well: discrete spring flowing from cleft in rock. Soft, possibly calcareous muddy deposits around spring but no obvious tufa.
6	315700	819427	Possible ephemeral seep	Very slight evidence of tufa in the form of possibly calcarous muddy deposit. Although this could have formed from rain wash-off, it could also have been formed by an ephemeral seep of groundwater.
8	315784	819400	Seep	Exact source not obvious but probably within field above this grid reference. Water appears at base of field above stream.
9	315700	819395	Seep	Flowing from groove in steep rocky slope. Tufa features. Also evidence of more tufa slightly further downslope, on currently dry rock, which could be an ephemeral seep.
10	315690	819390	Seep	Very small seeps.
13	315650	819410	Seep	Small seeps from rock face. Some tufa formation.
19	315058	819613	Possible ephemeral seep	Very faint & small evidence for calcareous tufa deposits on rock face.

Eastings and northings are given in British National Grid coordinates.

Appendix 2 GENERAL CONDITIONS FOR THE SUPPLY OF SERVICES BY THE NATURAL ENVIRONMENT RESEARCH COUNCIL AS REPRESENTED BY THE BRITISH GEOLOGICAL SURVEY (HEREINAFTER REFERRED TO AS “The Council”)

1. Performance of the Work

1.1 The Council will use reasonable endeavours to perform the Work in accordance with Schedule 1, but the Council does not undertake that the Work will lead to any particular result, and does not guarantee a successful outcome.

1.2 The Council will provide suitably qualified personnel to carry out the Work and will carry out the work using reasonable skill and care and in accordance with accepted professional standards.

1.3 The Work will be managed by the Council. In particular the Council will be solely responsible for:

1.3.1 Determining how the Work is to be carried out, including where and by whom the Work is to be done and whether personnel are employed or engaged as sub-contractors;

1.3.2 Issuing all instructions to all personnel engaged in performing the Work; and

1.3.3 Removing any personnel from the Work;

but will consult with the Customer where appropriate.

1.4 If the Customer requests a variation to the Work, the Council is not obliged to effect the variation unless and until the parties have agreed the scope of the variation and the associated additional cost (if any). The parties will record that agreement in writing and when they have done so this Agreement will be amended accordingly.

1.5 The Council will use all reasonable endeavours to provide the Customer with a report of the Work at the completion of the Work and, if set out in Schedule 1, with reports summarising the progress of the Work at the intervals set out in Schedule 1.

1.6 The Customer will provide or assist in the provision of all information, data, reports and maps necessary for the carrying out of the Work, and will take all steps necessary to enable the Council to perform its obligations under this Agreement without interruption.

1.7 All equipment purchased or constructed using funds provided by the Customer will be the property of the Customer. The Council is not obliged to insure any property of the Customer used in the performance of the Work.

2. Fees and payment

2.1 All amounts payable to the Council under this Agreement are exclusive of VAT or any similar sales tax which will be paid by the Customer at the rate and in the manner from time to time prescribed by law.

2.2 The Customer will pay each invoice within 30 days after the date of the invoice. If the Customer fails to make any payment due to the Council under this Agreement then, without prejudice to the Council’s other rights and remedies, the Council may charge interest (both before and after any judgment) on the amount outstanding, on a daily basis at the rate of four per cent per year above the base rate from time to time in force of any London clearing bank which the Council may nominate. That interest will be calculated from the date or last date for payment to the actual date of payment, both dates inclusive, and will be compounded quarterly. The Customer will pay that interest to the Council on demand.

3. Ownership and publication of results

3.1 The Customer will own all intellectual property rights in all maps, reports and data created by the Council in the performance of the Work (“Results”).

3.2 The Council and each employee, student, visiting researcher and agent of the Council have the irrevocable, royalty-free right to use the Results for academic research purposes, including in research projects that are sponsored by third parties provided that the use of the Results in those projects does not involve the disclosure of any Confidential Information (as defined below) to the third parties.

3.3 The personnel engaged to perform the Work are, subject to this clause, entitled to make publications of the Results in accordance with normal academic practice. The Council will use all reasonable endeavours to submit Results intended for publication to the Customer in writing not less than 60 days in advance of the publication. If the Council receives no objection from the Customer within 30 days, it may proceed with the proposed Publication.

3.4 The Council will use all reasonable endeavours not to disclose to any third party any information, techniques and know-how (in any form or stored on any medium) which are disclosed by the Customer to the Council for use in the Work and identified as confidential at the time of disclosure ("Confidential Information"); or constitute Results. The Council will not breach this obligation to the extent that the Confidential Information which is disclosed is or becomes publicly known without the fault of the Council, or is published in accordance with clause 3.3 or 3.5.

3.5 The Council is subject to the Freedom of Information Act 2000 and regulations made under it, which require the Council to make certain information (which may include Results) available to members of the public on request. Wherever possible, and in accordance with any applicable Code of Practice issued with the legislation, the Council will consult with the Customer before making any disclosure of Results pursuant to the legislation.

4. Limitation of liability

4.1 The Council makes no representation or warranty that advice or information given by any of its employees or any personnel engaged in performing the Work, or the content or use of any materials or information provided in connection with the Work, will not constitute or result in infringement of third-party rights.

4.2 The Council accepts no responsibility for any use which may be made of any Results, nor for any reliance which may be placed on Results, nor for advice or information given in connection with Results.

4.3 The Customer agrees to indemnify the Council, and every employee of the Council, and all personnel engaged to perform the Work ("the Indemnified Parties"), and keep them fully and effectively indemnified, against any claim made against any of the Indemnified Parties as a result of the Customer's use of Results or any materials, works or information received from them pursuant to the terms of this Agreement.

4.4 The liability of the Council for any breach of this Agreement, or arising in any other way out of the subject-matter of this Agreement, will not extend to any incidental or consequential damages or losses or any loss of profits, loss of data, loss of contracts or opportunity, even if the Customer has advised the Council of the possibility of those losses or if they were within the Council's contemplation.

4.5 In any event, the maximum liability of the Council to the Customer under or otherwise in connection with this Agreement or its subject-matter is equal to the total of the sums payable by the Customer under this Agreement.

4.6 Nothing in this Agreement is intended to exclude or restrict any liability of the Council in respect of death or personal injury caused by its negligence.

5 Force majeure

If the Council's performance of the Work is delayed or prevented by circumstances beyond its reasonable control, then the Council will use all reasonable endeavours to resume performance as soon as possible, but will not be in breach of this Agreement because of any delay in performance. However, if the delay in performance exceeds six months, the Customer may terminate this Agreement with immediate effect by giving notice to the Council.

6. Termination

6.1 Either party may terminate this Agreement with immediate effect by giving notice to the other party if:

6.1.1 the other party is in breach of any provision of this Agreement and (if it is capable of remedy) the breach has not been remedied within 30 days after the first party's notice specifying the breach and requiring its remedy; or

6.1.2 if the other party becomes insolvent, or if an order is made or a resolution is passed for the winding up of the other party (other than voluntarily for the purpose of solvent amalgamation or reconstruction), or if an administrator, administrative receiver or receiver is appointed over the whole or any part of the other party's assets, or if the other party makes any arrangement with its creditors.

6.2 If the Customer terminates this Agreement pursuant to clause 5, or the Council terminates this Agreement pursuant to clause 6.1.1, the Customer will immediately pay any unpaid sums in respect of Work completed before the date of termination, and any costs of the Council incurred as a result of the termination including (but not limited to) the cost of any materials or goods reasonably ordered by the Council for use in the performance of the Work which the Council has paid for or is liable to pay for.

6.3 Clauses 2, 3, 4, 6.2, 6.3 and 7 will survive the completion of the Work or termination of this Agreement for any reason.

7. General

7.1 Notices. Any notice to be given under this Agreement must be in writing and addressed to the party's representative as set out on the front page of this Agreement. It may be served as follows:

Method of service	Deemed day of receipt
By hand	The day of delivery
By pre-paid national business post	The second day after posting
By international courier	The seventh day after posting
By fax	The next day after sending

7.2 Headings. The headings in this Agreement are for ease of reference only and do not affect the interpretation of this Agreement.

7.3 Assignment etc. No party may assign or otherwise transfer this Agreement or any of its rights or obligations under it, whether in whole or in part.

7.4 Illegal/unenforceable provisions. If the whole or any part of any provision of this Agreement is void or unenforceable in any jurisdiction, the other provisions of this Agreement, and the rest of the void or unenforceable provision, will continue in force in that jurisdiction, and the validity and enforceability of that provision in any other jurisdiction will not be affected.

7.5 No agency etc Nothing in this Agreement is intended to create, imply or evidence any partnership or joint venture between the parties or the relationship between any of them of principal and agent. No party has any authority to make any representation or commitment or incur any liability on behalf of any of the others.

7.6 Entire agreement. This Agreement and any Schedule or Schedules (which are incorporated into and made a part of this Agreement) constitute the entire agreement between the parties relating to its subject-matter. Each party acknowledges that it has not entered into this Agreement on the basis of any warranty, representation, statement, agreement or undertaking except those expressly set out in this Agreement. Each party waives any claim for breach of, or any right to rescind this Agreement in respect of, any representation which is not an express provision of this Agreement. However, this clause does not exclude any liability which any party may have to any other (or any right which any party may have to rescind this Agreement) in respect of any fraudulent misrepresentation or fraudulent concealment prior to the execution of this Agreement.

7.7 Variations. No variation of this Agreement will be effective unless it is made in writing and signed by each party or its authorised representative.

7.8 Any other terms and conditions of contract which may be printed on any correspondence, including purchase orders shall not be applicable or supersede those included in this quote

7.9 Governing law, etc. This Agreement will be governed by and construed in accordance with English law. The English Courts will have exclusive jurisdiction to deal with any dispute which has arisen or may arise out of or in connection with this Agreement, except that any party may bring proceedings for an injunction in any jurisdiction.