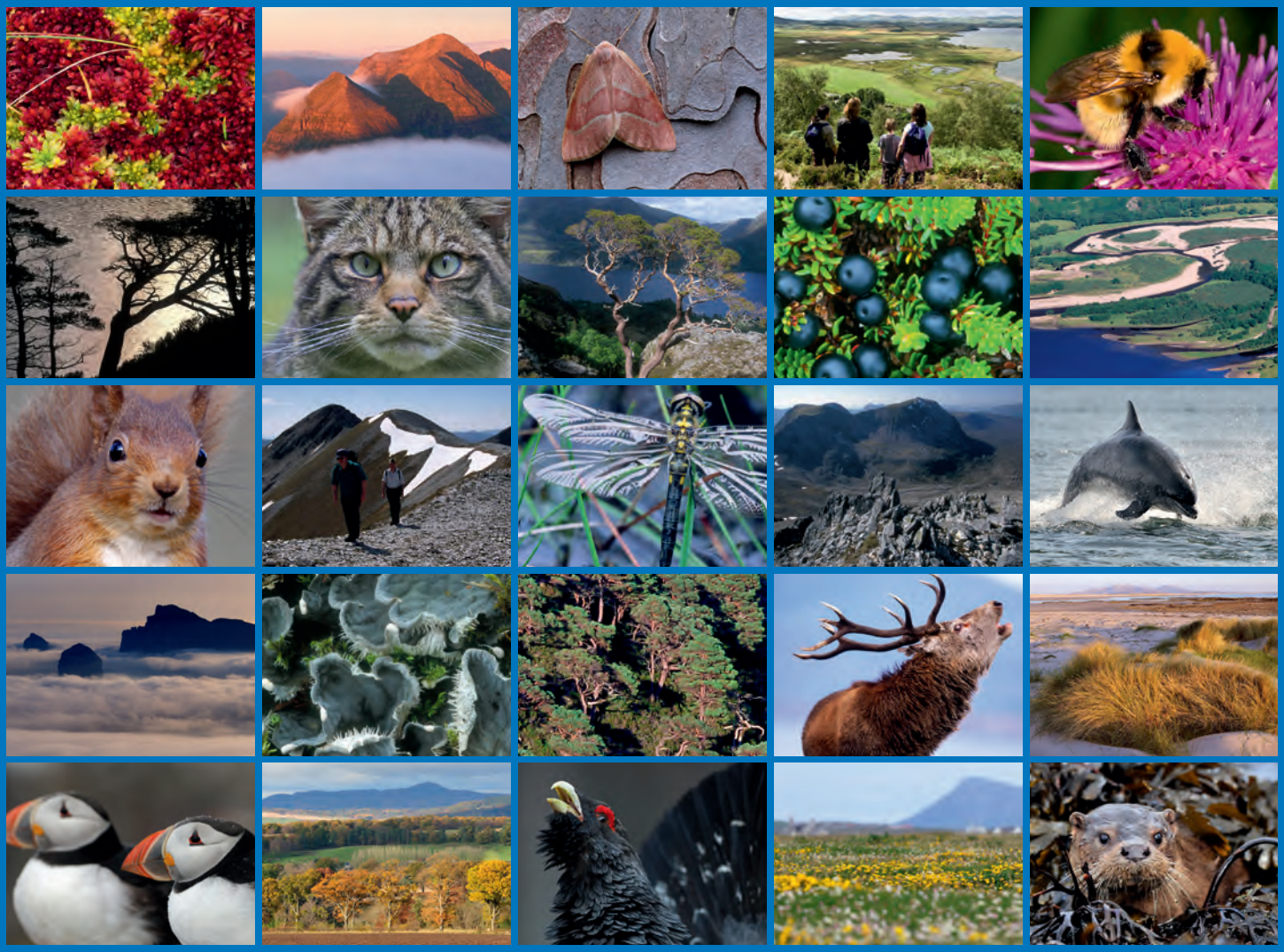
Scottish Natural Heritage
Research Report No. 1014

A climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland including all Earth science features in Sites of Special Scientific Interest (SSSI)



Scottish Natural Heritage
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RESEARCH REPORT

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A climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland including all Earth science features in Sites of Special Scientific Interest (SSSI)

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COMMISSIONED REPORT

Summary

A climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland including all Earth science features in Sites of Special Scientific Interest (SSSI)

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Keywords

geosites; climate change; risk assessment; geoheritage; geoconservation; geodiversity

Background

Climate change is a significant concern for nature conservation in the 21st century. One of SNH's duties within the Scottish Climate Change Adaptation Programme (2014) is to identify the consequences of climate change for protected areas and to put in place adaptation or mitigation measures. This assessment, which forms part of the SNH contribution to a wider ClimateXChange project (Brooker *et al*., 2014), has developed a risk-based approach to assessing future impacts of climate change on groups of similar geoheritage features (Site Categories) in Scotland. The assessment uses a systematic approach that involves a combination of current understanding of how climate change will affect the features, and knowledge of the characteristics of geosites in Scotland. The following changes were considered: coastal, river, freeze-thaw processes, rainfall patterns and vegetation growth.

Main Findings

Although currently 97% of protected geoheritage features are recorded as being in favourable condition with respect to their conservation status; this assessment rates 11 Site Categories as being at 'high' risk from anticipated climate change. These include active soft-sediment coastal and river features, periglacial features, sites with palaeoenvironmental records, and spatially-finite Quaternary sediments and landforms, rock exposure, fossil and mineral features. They include 66 notified SSSI features, 9.9% of the total number of notified Earth Science features in Scotland. Conversely 73.2% of Earth Science features were considered to be more resilient to climate change (i.e. 'medium' to 'low' risk), with 16.9% at moderate (medium-high) risk.

This risk-assessment approach and the development of indicative geoheritage climate change actions as recommended in this report will form a sound basis from which to incorporate climate change planning for geoheritage sites into local and regional climate change action plans within Scotland. This detailed site-level approach builds on and advances the development of higher-level actions and general principles.

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Table of Contents **Page**

Acknowledgements

This work was developed as part of a wider ClimateXChange project on climate change impact risk to all notified natural heritage features in Scotland (http://www.climatexchange.org.uk/adapting-to-climate-change/assessing-climate-risk-to-notified-features/). The expert opinions used in the analysis are those of the listed authors: Rachel M.L. Wignall (SNH), John E. Gordon (University of St Andrews), Vanessa Brazier Kirkbride (SNH), Colin C.J. MacFadyen (SNH), Nick S. Everett (SNH). The authors would like to thank the other members of the ClimateXChange Earth Science project team, Rob Brooker (James Hutton Institute), Clare Bond (University of Aberdeen), John Rowan (University of Dundee) and Alistair Rennie (SNH), for useful discussion and feedback during development of this work; and additional thanks to Rob for number crunching the data. Many thanks also to SNH for supporting the work and especially to the staff members who held the post of 'Climate change officer' during the period, Christina Bell and Julia Quin, for their role in coordination.

1. INTRODUCTION

The world's climate has always fluctuated due to a range of geological, biological, atmospheric, oceanographic and astronomic factors. However, there is now scientific consensus that climate variations over the last ~150 years can only be explained by the impacts of human activities acting in conjunction with natural factors (Stocker *et al*., 2013). The pace of change is not even across the world, with some places more affected than others. Left unchecked these changes will accelerate (Defra, 2009; Jenkins *et al*., 2009; http://ukclimateprojections.metoffice.gov.uk/), with significant consequences for nature and society. In contrast to biodiversity, the impacts of climate change on geosites and geoheritage have received comparatively little attention, particularly from the perspective of risk assessment, mitigation and adaptation (Prosser *et al*., 2010; Sharples, 2011; Brazier *et al*., 2012; E.J. Brown *et al*., 2012; Crofts & Gordon, 2015).

In Scotland, climate change is likely to result in extensive landscape modification (Land Use Consultants, 2011), with the greatest changes expected in coastal areas, along river corridors and in the uplands (Werritty *et al*., 2002; Werritty & Chatterton, 2004; Orr *et al*., 2008; Brazier *et al*., 2012; I. Brown *et al*., 2012; HR Wallingford *et al*., 2012; Ramsbottom *et al.*, 2012; Werritty & Sugden, 2012; Hansom *et al.*, 2017). The potential impacts of climate change in the UK on both biodiversity (Walmsley *et al.*, 2007) and geodiversity (Prosser *et al*., 2010) have been reviewed, and their impacts on all aspects of the natural heritage in Scotland are now widely recognised (Scottish Natural Heritage, 2016). As a result, Scottish parliamentary actions on climate change include measures for the natural heritage, which address the management of protected areas for biodiversity and geodiversity.

The 'Climate Ready Scotland' Scottish Climate Change Adaptation Programme (Scottish Government, 2014) sets out Scottish Ministers' objectives, policies and proposals to tackle the climate change impacts identified for Scotland in the UK Climate Change Risk Assessment (ASC, 2016), as required by section 53 of the Climate Change (Scotland) Act 2009 (Scottish Government, 2009). Objective N2 of this programme is to 'Support a healthy and diverse natural environment with capacity to adapt', and as one of the actions to fulfil this Objective, Scottish Natural Heritage (SNH), as the Scottish Government's adviser on all aspects of nature and landscape, was tasked to 'Identify the consequences of climate change for protected places and the Natura network and put in place adaptive measures'. As part of this process, Scottish Natural Heritage (SNH) contributed to a ClimateXChange project on climate change impact risk to all notified natural heritage features in Scotland (http://www.climatexchange.org.uk/adapting-to-climate-change/assessing-climate-risk-to-notified-features/). A significant part of the SNH contribution, which is detailed fully in this report, was the development of a risk-based assessment methodology to identify the relative level of risk, from the impacts of climate change, to nationally and internationally important geological and geomorphological sites in Scotland. This included all notified Earth Science features in Sites of Special Scientific Interest (SSSI) which are protected under the Nature Conservation (Scotland) Act (2004) (Scottish Government, 2004).

Nationally and internationally important geoheritage features within the SSSI network in Great Britain (also known as 'Earth Science' features) are underpinned by the Geological Conservation Review (GCR). Undertaken by the Nature Conservancy Council (NCC) between 1977 and 1990, and subsequently managed by the Joint Nature Conservation Committee (JNCC), the GCR was a major initiative to identify and describe those sites of national and international importance that together show all the key scientific elements of the geoheritage of Britain (Ellis *et al*., 1996; Ellis, 2011). These sites have attributes that range from sequences of contemporary sediments and geomorphological processes to ancient rocks, together with fossils, minerals and features of the landscape that make a special contribution to our understanding and appreciation of Earth science and the geological history of Britain. Scotland has over 900 GCR sites, selected for around 100 categories

(known as ‘GCR Blocks') encompassing the range of geological and geomorphological features of Britain. Each GCR site is selected to demonstrate a single geological or geomorphological topic, and many of these have been subsequently incorporated as protected features in approximately 500 designated SSSIs. GCR sites for different topics may coincide or overlap and it is possible for multiple GCR sites, representing different Earth science topics, to be protected within a single SSSI. Therefore, to assess the climate change risk to geoheritage features in SSSIs, the process developed must assess the risk to ~900 GCR sites.

Currently 97% of protected geological and geomorphological features in SSSIs in Scotland are assessed as being in favourable condition or favourable conservation status, and only at one site, Tinto Hills SSSI in South Lanarkshire, has climate change been noted specifically as a currently active negative pressure on the feature. Future climate change is likely to have a wide range of impacts on geohertiage features (Prosser *et al*., 2010), however, these figures suggest that in Scotland there may still be time to plan and implement effective climate change adaptation and mitigation measures to ensure the future of nationally and internationally important geoheritage features.

The aim of this study was to develop and apply a systematic risk assessment using expert judgement to inform climate change adaptation management for geoheritage features in SSSIs. Primarily the risk assessment is needed as a tool for deciding which sites to prioritise for development of geoheritage climate change actions. First, we outline the relevant aspects of climate change considered most likely to impact geoheritage features. We then group the ~900 GCR sites in Scotland into Climate Change Risk Categories, with features in each Category likely to respond to climate change in a similar way. Each Category is then evaluated for the likelihood of any given aspect of climate change affecting it and for the risk of detrimental impact from climate change, to give an overall qualitative risk assessment. We then discuss the results and the geoconservation management options and provide examples of indicative geoheritage climate change actions for sites assessed to be at high risk. The main focus of the paper is on the direct impacts of climate change, but indirect impacts that may also arise from human responses (e.g. the erection or extension of sea-defences to mitigate coastal erosion) were also considered (Prosser *et al*., 2010).

2. METHODOLOGY

The latest climate projections for the UK, UKCP09 (Defra, 2009; Jenkins et al., 2009; http://ukclimateprojections.metoffice.gov.uk/), are based on strong and credible climate science and form the basis for assessing the impacts of climate change on geoheritage sites. They show how various aspects of climate could change, under three different greenhouse gas emission scenarios, by the middle and end of the 21st century, including changes in average summer and winter temperatures, changes in rainfall patterns and sea-level rise. These will, in turn, have likely consequences, such as drier ground in summer, decreased freeze-thaw activity in winter, increased river flooding and erosion, increased coastal erosion and inundation or changes in vegetation cover, all of which may affect geoheritage features. The effects of any given aspect of climate change on a specific geoheritage feature will depend on the nature of the interest and the characteristics of the site where it is present (Prosser *et al*., 2010); for example, whether it is an exposure of a very restricted fossil resource or of an extensive sedimentary sequence, whether it is an active river channel or a relict glacial moraine, whether it is close to or distant from the coast or a river, or whether it is a hard rock sea cliff or a soft sandy coast.

Individually assessing all ~900 GCR sites in a robust and systematic way would be a lengthy task. Equally the number of sites under consideration means that a purely intuitive approach, for example experts listing those sites they considered most at risk in their own field of knowledge, could result in sites being overlooked or inconsistent levels of risk being assigned across different fields of expertise. The premise of the methodology adopted here (Figure 1), is that if the sites and the geoheritage features they contain can be grouped into site categories that are likely to respond in similar ways to the various aspects of climate change, then the task becomes both more manageable, and easier to moderate in terms in aligning the input of different experts and making a consistent assessment across a wide variety of sites. The approach taken in this study resulted in a single level of assessed risk for each group of several features (comprising one Site Category) rather than, for example, a ranked list of features or sites. This Site Category approach involves a degree of generalisation that must be borne in mind when assessing and applying the results. The Site Categories selected here also include only the range of GCR sites present in Scotland.

The following sections deal with the aspects of climate change considered likely to affect geoheritage feature in Scotland, the selection and definition of Site Categories, and the methods used to score the risk-based assessment.

2.1 Selecting relevant aspects of climate change

The first step in the risk assessment process (Figure 1) was to identify those aspects of climate change considered to be most likely to affect geoheritage sites in Scotland, based on current understanding of the direct impacts of climate change (e.g. Harrison *et al*., 2001; Prosser *et al*., 2010; Gordon *et al*., 2008; Brazier *et al*., 2012). The likely major changes in Scotland, under all the emission scenarios, are warmer and wetter winters, hotter and drier summers and rising sea levels (Table 1). There are also likely to be more extreme weather events such as storms, floods and gales.

Indirect impacts of climate change that may arise from human response (Prosser *et al*., 2010), such as the installation or extension of coastal defences or flood embankments, were specifically excluded from the risk assessment rating, although in most cases it will be important to take these into account in the development of any climate change actions (section 5). However, for the risk assessment rating, where existing man-made structures, such as roads or bridges, are likely to be defended from the direct impacts of climate change, these were treated as immovable objects (section 2.2) that may, for example, restrict the evolution of an active geomorphological system.

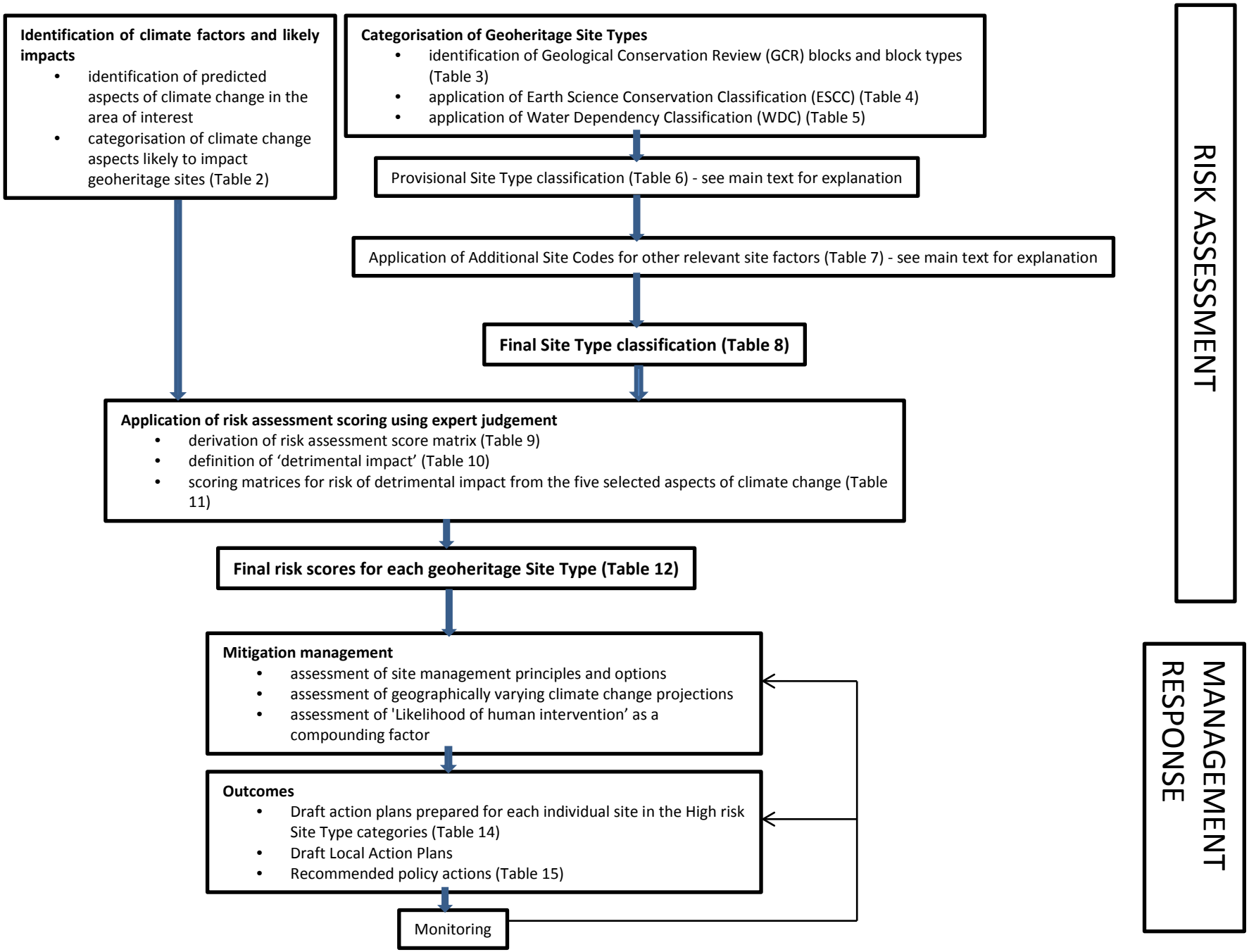

Figure 1. Methodology and steps in the risk-based assessment procedure and its implementation.

Table 1. Scottish UKCP09 projections for the end of the 21st century (2080s for temperature and precipitation, 2095 for sea-level rise) relative to the 1961-1990 mean, based on the 'medium emissions' scenario.

Variable	Projected changes
Winter mean temperature	All areas of Scotland will get warmer, but less so in the far north. Central estimates of temperature rise are between 2.2˚C and 2.6˚C across Scotland dependent on location. They are very unlikely to be less than 0.9˚C-1.4˚C and very unlikely to be more than 3.6˚C-4.0˚C.
Summer mean temperature	All areas of Scotland will get warmer, but less so in the far north. Central estimates of temperature rise are between 3.0˚C and 3.5˚C across Scotland dependent on location. They are very unlikely to be less than 1.5˚C-1.8˚C and very unlikely to be more than 4.9˚C-5.7˚C.
Winter mean precipitation	Winter precipitation is likely to increase across Scotland, more so in the west. Central estimates of precipitation change are between +12% and +21% dependent on location. They are very unlikely to be less than +1% to +6% and very unlikely to be more than +25% to + 42%,.
Summer mean precipitation	Summer precipitation is likely to decrease across Scotland, less so in the north. Central estimates of precipitation change are between -12% and -17% dependent on location. They are very unlikely to be less than -29% to -33% and very unlikely to be more than +1% to + 4%.
Sea-level rise	Sea-level rise ranging from a minimum of around 25cm in parts of Argyll to a maximum of around 50cm in Shetland.

The likely direct impacts of climate change on geoheritage sites are relatively varied (Prosser *et al*., 2010), and not all will apply in Scotland. Extreme events are likely to have the greatest impact. However, impacts will depend on the robustness or sensitivity of the features, whether tipping points are triggered and the role of cumulative effects. For example, slopes may fail during intense rainstorms or after prolonged saturation by lower intensity rainfall (Brazier *et al*., 2012). Hence, assessing how a GCR site might respond to changes in different climate variables, some of which may combine to cause a significant impact and some of which will have little or no immediate effect, is complex. Therefore, for the purposes of this assessment, the likely impacts on geoheritage features were grouped into four 'aspects of climate change', each with similar contributing climate variables (Table 2). These aspect groups were derived to facilitate the identification of the impacts on specific geoheritage Site Categories during the risk assessment process, the caveat being that all likely climate change impacts on Scottish GCR sites should be covered. Therefore, the aspects of climate change groups are descriptive to the extent thought to be helpful and are not formulaic. For example, coastal sites will be affected primarily by rising sea levels, though increase in extreme events, or possible changes in storminess, may also impact rates of coastal erosion; these aspects were combined under 'Coastal change: rising sea level, changes in storminess and patterns and intensity of coastal erosion and deposition'. In contrast, the 'Changes in vegetation cover' group, does not list the climate variables but it is relatively easy to consider how 'changes in vegetation' might affect a feature. Aspects could be defined differently for different purposes, for example 'Summer drought', 'Oversaturation of ground' and 'Longer growing season' could replace 'Changes in rainfall patterns' and 'Changes in vegetation cover'. However, the climate aspects selected were considered most appropriate for the current risk-based assessment of Scottish GCR sites. Although these climate aspects are specific to geoheritage sites in Scotland, the assessment method is flexible and pragmatic, and could be adapted to incorporate other or different aspects of climate change if required.

Table 2. Selected aspects of climate change used to assess risk to geoheritage sites.

	Selected aspects of climate change likely to impact geoheritage sites	Comment
1	Coastal change: rising sea level, changes in storminess and patterns and intensity of coastal erosion and deposition	Coastal sites will be affected primarily by rising sea levels, although increase in extreme events, or possible changes in storminess, are also likely to have an impact on rates of coastal erosion. On cliff coastlines, increased mass movement activity may arise from elevated pore water pressure or enhanced undercutting by marine erosion.
2	Rivers: increased flooding and changes in patterns of erosion and deposition	Changes in rainfall, but probably more so increases in extreme events, are likely to be the main causes of impacts on sites near or including rivers features.
3	Decrease in freeze-thaw processes (due to warmer winters)	Increased winter temperatures are a very specific change that is likely to impact features dependent on freeze-thaw processes, such as patterned ground.
4	Changes in rainfall patterns (drier summers/wetter winters)	Summer droughts are most likely to affect sites such as peat bogs, leading to drying out of organic deposits and permanent loss of some environmental records. Increased winter rainfall may trigger slope instabilities and enhance mass movement on vulnerable sites.
5	Changes in vegetation cover/increased vegetation growth	Changes in vegetation cover, though likely to affect many sites, will be dependent on a complex mix of factors: summer drought may result in reduced vegetation cover and increased erosion, or an increased growing season may result in increased vegetation cover and declining visibility of geoheritage features. Increased frequency or intensity of storms may produce more bare ground through enhanced erosion, and less recovery time for vegetation between storms may enhance slope vulnerability to erosion. Shallow, finite, soft sediment sites may be damaged by windthrow of trees during storms and the uprooting of large root plates. Increased penetration by deep roots may also damage shallow, finite, soft sediment sites.

2.2 Defining Site Categories for the risk-based assessment of geoheritage sites

The selection and definition of geoheritage Site Categories was based on a number of factors (Figure 1). The starting point was the division of GCR sites into GCR blocks and the broad groupings of these known as ‘block types’ (Table 3). These divisions can be used to distinguish groupings such as coastal geomorphology sites, fluvial geomorphology sites, caves and karst, from sites that are primarily rock exposure, such as mineral or structural geology sites, and that will clearly respond differently to climate change. Similarly there will be differences in responses between hard rock sites and soft sediment Quaternary sites. The GCR divisions also reflect the different areas of expertise of Earth Science specialists and facilitated expert input to the assessment, which was an important part of the process.

Table 3. GCR blocks with sites occurring in Scotland listed under the sub-headings of their relevant GCR block types.

GCR blocks		
Stratigraphy blocks		
Cenomanian-Maastrichtian	Hettangian, Sinemurian, Pleinsbachian	Caradoc-Ashgill
Oxfordian	Permian-Triassic (red Beds)	Llandeilo
Kimmeridgian	Westphalian	Arenig-Llanvirn
Bathonian	Dinantian of Scotland	Tremadoc-Arenig
Callovian	Non-Marine Devonian	Tremadoc
Aalenian-Bajorcian	Wenlock	Cambrian
Toarcian	Llandovery	Cambrian-Tremadoc
Structural and Metamorphic Geology blocks		
Moine	Torridonian	Lewisian
Dalradian	Caledonian Structures of the Southern Uplands	Caledonian Structures of Shetland[1]
Igneous Petrology blocks		
Tertiary Igneous	Old Red Sandstone Igneous	Caledonian Igneous
Carboniferous-Permian Igneous	Ordovician Igneous	
Mineralogy blocks		
Mineralogy of Scotland		
Palaeontology blocks		
Jurassic-Cretaceous Reptilia	Pleistocene Vertebrata	Permian/Carboniferous Fish/Amphibia
Permian-Triassic Reptilia	Palaeoentomology	Tertiary Palaeobotany
Tertiary Mammalia	Arthropoda (excluding insects, ostracods, trilobites and Quaternary arthropods)	Mesozoic Palaeobotany
Mesozoic Mammalia	Silurian-Devonian Chordata	Palaeozoic Palaeobotany
Quaternary Geology and Geomorphology blocks		
Quaternary of Scotland	Tufa	
Geomorphology blocks		
Caves	Coastal Geomorphology of Scotland	Fluvial Geomorphology of Scotland
Karst	Saltmarsh morphology	Mass Movement

[1] This is a recently added block (http://jncc.defra.gov.uk/page-4171) not listed in Ellis *et al.* 1996.

Prosser *et al*. (2010) discussed the effects of climate change on geosites with reference to the Earth Science Conservation Classification (ESCC) (Table 4). The ESCC divides geosites into 3 broad classes: (1) Exposure or extensive sites containing geological features that are relatively extensive beneath the surface, (2) Finite sites containing geological features of limited extent, and (3) Integrity sites that require holistic management to conserve the feature, including both active process and relict/static (inactive) geomorphological features. Prosser *et al*. (2010) concluded that the greatest differences in response to climate change are likely to be between the active process sites within the Integrity Sites type, and all other sites. However, there will also be differences between the impacts of climate change on sites within the Exposure or Extensive, Finite, and non-active Integrity types depending on their nature and location. The composition of a geoheritage feature, for example whether it is composed of hard rock or soft sediment will affect the specific impacts of climate change. However there are also many water-related influences on how sites may be affected by

climate change. Proximity of coasts or rivers, and more specifically the influence of coastal and river processes, will strongly affect how climate change impacts on geoheritage sites. Changes in ground and surface water levels, influenced by seasonal rainfall patterns, will also affect certain geosites such as peat bogs with palaeoenvironmental records, karst and caves. For active process sites, in addition to changes in coastal and river processes, changes in periglacial processes will alter some Quaternary sites with patterned ground formed by frost-related processes. Changes in rainfall amounts and intensity are also likely to impact sites affected by mass movement processes. Therefore, the Site Categories selected for the risk assessment also need to be groupings of sites with the same dependencies and proximities to water, and water-related processes.

Table 4. The Earth Science Conservation Classification (ESCC) (after Prosser et al., 2006).

Earth Science Conservation Classification	**Site Code**
Exposure or extensive sites	
Active quarries and pits	EA
Disused quarries and pits	ED
Coastal cliffs and foreshore	EC
River and stream sections	EW
Inland outcrops	EO
Exposure underground mines and tunnels	EU
Extensive buried interest	EB
Road, rail and canal cuttings	ER
Integrity sites	
Static (fossil) geomorphological	IS
Active process geomorphological	IA
Caves	IC
Karst	IK
Finite sites	
Finite mineral, fossil or other geological	FM
Mine dumps	FD
Finite underground mines and tunnels	FU
Finite buried interest	FB

ESCC codes have been assigned to all GCR sites in Scotland (Appendix 1). Some larger or more complex sites often having multiple ESCC codes, for example EC, EW and EO where a site contains coastal, river and inland outcrops. Features with some specific characteristics such as coastal cliff and foreshore, or stream section outcrops, and specific features with unique water dependencies such as caves and karst, can be identified using the ESCC classification. For sites with multiple ESCC codes, this can still be done, for example all sites with coastal outcrop will contain EC as part of their coding; however in any cases where multiple codes might put sites into two separate categories (e.g.' IA, IS' for a geomorphological site with both active and static elements), the site was ultimately placed in the category considered most at risk from climate change (i.e. the most vulnerable elements of the feature were given primacy). Combining the ESCC with the GCR blocks can also distinguish, for example, active coastal geomorphology features from active fluvial geomorphology features. However, a separate index of water dependence was also employed in combination with the ESCC and the GCR blocks to distinguish groups of sites such as bog sites with palaeoenvironmental records and periglacial process sites. This Water Dependency Classification (WDC) (Table 5) was first developed by the current authors in 2005 as part of the SNH response to the EU Water Framework Directive (European Commission, 2000). All GCR sites are assigned to one of the four categories in the classification (Appendix 1). If a site is complex, then the most significant relevant water dependence is assigned (usually the lowest numerical value).

Table 5. Water Dependency Classification (WDC).

WDC code	Summary description	WDC description of water dependency
1	Features formed directly by water or water-related processes	Features for which the most significant dependency on water is direct formation of all or part of the feature by water or water-related processes (e.g. river features with an active component, coastal features where wave- or tide-dependent processes are of prime interest, some karst, some caves, lake sediment sites with palaeoenvironmental records).
2	Features dependent on water saturation	Features for which the most significant dependency on water is saturation of all or part of the feature by surface or groundwater (e.g. peat/bog sites with palaeoenvironmental records, some caves, aeolian dune systems).
3	Features exposed through the action of water	Features for which the most significant dependency on water is for the visibility of all or part of the feature. (e.g. sites with foreshore, river or loch side outcrop exposed by the action of water).
9	No dependence on water	No water dependency

Combining the four codes of GCR block type, GCR block, ESCC and WDC allows a considerable number of Provisional Site Categories to be defined (Table 6). However, some key factors have not been taken into account. These include whether coastal, fluvial and landform features are composed of hard rocks or soft sediments, whether landform and palaeoenvironmental record sites are close to the coast, and whether sites are susceptible to slope failure either as part of their scientific interest or as a damaging factor. Additionally two issues were identified with coastally exposed features. These are whether water-exposed coastal features are at foreshore or cliff-top level, and the size and extent of finite sites at the coast. This latter is particularly relevant for coastal-located mineralogical and palaeontological sites, where relatively extensive features are often coded as 'FM, EC' or 'EC, FM' (i.e. finite with coastal exposure). This is in contrast to similar sites along river banks which are usually coded to include EO ('Inland Outcrop') if they extend beyond the immediate river bank. A final factor that it was considered important to include in the categorisation of sites was whether any site is effectively restricted in size by artificial constraints. These artificial constraints may include coastal roads or other structures, the defence of which against erosion will restrict adjacent active coastal process sites and coastal exposure sites from their natural migration inland under conditions of coastal erosion and sea-level rise.

These additional key factors, considered relevant to how geoheritage features will be affected by climate change were taken into account by adding further coding, collectively referred to here as 'Additional Sites Codes' (Table 7) for GCR sites affected by these factors(Appendix 1), and by modifying the Site Categories accordingly (Table 8). Relevant information for some coding was available in published GCR site literature (e.g. May & Hansom, 2003) and from study of site maps (e.g. proximity to coast or of man-made structures that might restrict the site); but in some cases the process required the input of Earth Science experts. In total, for this part of the process, around 70 sites had to be considered individually by experts.

Table 6. Initial classification and definition of Provisional Site Categories using GCR block type, GCR block, ESCC code and WDC code only. GCR = GCR block name (Table 3), GCRBT = GCR Block Type (Table 3), ESCC = Earth Science Conservation Classification (Table 4), WDC = Water Dependency Classification (Table 5).

Provisional Site Category Code	Description	Definition codes
Coastal Geomorphology of Scotland		
1a	Finite active coastal features	• GCR = 'Coastal Geomorphology of Scotland' or 'Coastal Geomorphology of Scotland (saltmarsh morphology)', • ESCC includes FM
2a	Non-finite active coastal features	• GCR = 'Coastal Geomorphology of Scotland' or 'Coastal Geomorphology of Scotland (saltmarsh morphology)', • ESCC does not include FM
Active Fluvial Geomorphology of Scotland		
1b	Active rivers features	• GCR = 'Fluvial Geomorphology of Scotland', • ESCC = IA
Caves and Karst		
1c	Karst features	• GCR = Karst
2c	Cave features	• GCR = 'Caves'
Quaternary of Scotland, Mass Movement, passive Fluvial Geomorphology of Scotland		
1d	Finite coastal-exposed Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC = EC,FM or EC,IS,FM or IS,EC,FM
2d	Part coastal, part non-water exposed Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC includes EC but does not include FM.
3d	Finite river/lake exposed Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC = EW,FM or EW,IS,FM or IS,EW,FM
4d	Extensive river/lake exposed Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC = EW, EW,IS or IS,EW.
5d	Part river/lake, part non-water exposed Quaternary features	• GCR = 'Quaternary of Scotland', • WDC = 3, • ESCC includes EW but ≠ EW or EW,IS or IS,EW
6d	Inland exposure and buried Quaternary features away from rivers	• GCR = 'Quaternary of Scotland', • WDC = 9, • ESCC does not include IS or IA
7d	Relict landform only features with no water-exposed sediment element	• GCR = 'Quaternary of Scotland' or 'Fluvial Geomorphology of Scotland' or 'Mass Movement', • ESCC includes IS, does not include EC or EW or IA
8d	Active freeze-thaw features	• WDC = 9, ESCC includes IA
Palaeoenvironmental archive sites		
1e	Lake-only palaeoenvironmental records	• WDC = 1, • GCR = 'Quaternary of Scotland', • ESCC is not IA
2e	Peat/bog palaeoenvironmental	• WDC = 2,

	records	• GCR = ‘Quaternary of Scotland’
3e	Tufa features	• GCR = ‘Quaternary of Scotland’, • WDC = 1, ESCC = 1A
Palaeontology and Mineralogy		
1f	Finite area coastal-only water-exposed fossil and mineral features	• GCRBT = ‘Mineralogy’ or ‘Palaeontology’, • ESCC = EC or FM,EC
2f	Fossil and mineral features partly coastal-water-exposed but extending inland.	• GCRBT = ‘Mineralogy’ or ‘Palaeontology’, • ESCC includes EC but is not EC or FM,EC
3f	River-only water-exposed fossil and mineral features	• GCRBT = ‘Mineralogy’ or ‘Palaeontology’, • ESCC = EW or FM,EW
4f	Fossil and mineral features partly river-water-exposed and partly non-water-exposed	• GCRBT = ‘Mineralogy’ or ‘Palaeontology’, • ESCC includes EW but is not EW or FM,EW
5f	Non-water dependent fossil and mineral features	• WDC = 9, • GCRBT = ‘Palaeontology’ or ‘Mineralogy’
Stratigraphy, Structural and Metamorphic Geology, Igneous Petrology		
1g	Finite area coastal-only igneous, metamorphic and stratigraphy water-exposed features	• GCRBT = ‘Stratigraphy’ or ‘Structural and Metamorphic Geology’ or ‘Igneous Petrology’, • ESCC = FM,EC
2g	Extensive coastal-only (and mostly coastal with some river) igneous, metamorphic and stratigraphy water-exposed features	• GCRBT = ‘Stratigraphy’ or ‘Structural and Metamorphic Geology’ or ‘Igneous Petrology’, • ESCC = EC or FM,EC or EC,EW
3g	Finite area river-only, igneous, metamorphic and stratigraphy water-exposed features	• GCRBT = ‘Stratigraphy’ or ‘Structural and Metamorphic Geology’ or ‘Igneous Petrology’, • ESCC = FM,EW
4g	Extensive river-only (and mostly river with some coastal), igneous, metamorphic and stratigraphy water-exposed features	• WDC = 3, • GCRBT = ‘Stratigraphy’ or ‘Structural and Metamorphic Geology’ or ‘Igneous Petrology’, • ESCC = EW or EW,EC
5g	Partly water-exposed and partly non-water-exposed igneous, metamorphic and stratigraphy features.	• WDC = 3, • GCRBT = ‘Stratigraphy’ or ‘Structural and Metamorphic Geology’ or ‘Igneous Petrology’, • ESCC is not FM,EC or EC or EC,EW, or FM,EW or EW or EW,EC,
6g	Non-water dependent igneous, metamorphic and stratigraphy features.	• WDC = 9, • GCRBT = ‘Stratigraphy’ or ‘Structural and Metamorphic Geology’ or ‘Igneous Petrology’

Table 7. Site factors requiring Additional Site Codes for this assessment, and details of the coding used.

Code is required for	Relevant Provisional Site Categories	Additional Site Codes	Comment
Distinguishing soft sediment from hard rock active coastal sites	1a, 2a	'3. Hard-rock cliffs, 6. Gravel and 'shingle' beaches, 7. Sandy beaches and dunes, 8. Sand spits and tombolos, 9. Machair, 10. Saltmarsh, 11. Coastal assemblages.	These are the coastal type categories within the Coastal Geomorphology of Great Britain GCR volume (May & Hansom, 2003). All codes except 3 are considered 'soft sediment'.
Distinguishing soft sediment from hard rock fluvial and landform sites	1b, 7d	'soft sediment' or 'hard-rock'	New coding applied from literature review supported by by expert judgement.
Identifying landform and environmental archive sites close to the coast.	7d, 1e, 2e	'coastal' where site at or very near the coast.	New coding applied from map analysis supported by expert judgement. N.B. there are no lake-only environmental archive sites (1e) near the coast in Scotland.
Highlighting sites prone to slope failure and distinguishing whether failures are damaging to the feature or not.	7d	'slope failure' or 'slope failure aspect of feature' (where slope failure not considered damaging to the feature).	New coding applied from literature review supported by expert judgement.
Identifying cliff top features which, while coastal, are unlikely to be affected by changes in coastal processes.	1f, 2f, 1g, 2g	'coastal cliff top' where feature well above normal high tide level in hard-rock cliffs	New coding applied from literature review supported by expert judgement. N.B. there are no cliff top 1g or 2g sites in Scotland.
Identifying coastal sites coded as 'finite' but extending beyond the area affected by coastal processes.	1f, 2f	'extensive' for any feature known or believed to extend inland further than likely effects of coastal erosion and sea-level rise.	New coding applied from literature review and map analysis supported by expert judgement. Many fossil and mineral resources are of finite extent (coded FM) but they extend inland further than any likely effects of coastal erosion and sea-level rise.
Identifying sites which are physically restricted in area by man-made structures	1a, 2a, 1b, 1d, 3d, 4d, 1f, 2f, 1g, 2g	'restricted' where current or likely future defence of any man-made structure will restrict natural evolution of the site under conditions of climate change	New coding applied from map analysis supported by expert judgement.

The final list of Site Categories, with their descriptions and the coding that defines them (Table 8), is designed to encompass the range of GCR sites in Scotland. A similar list of geoheritage Climate Change Risk-based Assessment Site Categories could be developed for other areas, though this would undoubtedly require a similar level of expert input and most likely the application of more or different codes.

Table 8. Final geoheritage Site Categories and definitions as used in this assessment. GCR = GCR block name, GCRBT = GCR Block Type (Table 3), ESCC = Earth Science Conservation Classification (Table 4), WDC = Water Dependency Classification (Table 5).

Site Category Code	Description	Definition codes
Coastal Geomorphology of Scotland[1]		
a_1	Finite or restricted[2] soft sediment active coastal features	• GCR = 'Coastal Geomorphology of Scotland' or 'Coastal Geomorphology of Scotland (saltmarsh morphology)', • ESCC includes FM or Type includes 'restricted'
a_2	Unrestricted, non-finite soft sediment active coastal features	• GCR = 'Coastal Geomorphology of Scotland' or 'Coastal Geomorphology of Scotland (saltmarsh morphology)', • ESCC does not include FM, • Type is 6, 7, 8, 9, 10 or 11 and does not include 'restricted'.
a_3	Hard rock active coastal features	• GCR = 'Coastal Geomorphology of Scotland', • Type = 3. Hard rock cliffs
Active Fluvial Geomorphology of Scotland		
b_1	Active hard rock rivers features	• GCR = 'Fluvial Geomorphology of Scotland', • ESCC = 1A, • Type = 'hard rock'
b_2	Non/lightly-restricted, active soft sediment river features	• GCR = 'Fluvial Geomorphology of Scotland', • ESCC = 1A, • Type includes 'soft sediment' but does not include 'restricted'
b_3	Restricted, active soft sediment river features	• GCR = 'Fluvial Geomorphology of Scotland', • ESCC = 1A, • Type = 'restricted soft sediment'
Caves and Karst		
c_1	Karst features	• GCR = Karst
c_2	Cave features	• GCR = Caves
Quaternary of Scotland, Mass Movement, inactive Fluvial Geomorphology of Scotland		
d_1	Finite coastal-exposed Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC = EC,FM or EC,IS,FM or IS,EC,FM; or • ESCC = EC, or EC,IS or IS, EC and Type includes 'restricted'
d_2	Part coastal, part non-water exposed Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC includes EC but does not include FM, and • ESCC is not EC or EC,IS or IS,EC if • Type includes 'restricted'.
d_3	Finite or restricted river/lake exposed Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC = EW,FM or EW,IS,FM or IS,EW,FM; or • ESCC = EW or EW,IS or IS,EW and Type includes 'restricted'

d_4	Non-restricted or extensive river/lake exposed soft sediment Quaternary features	• GCR = 'Quaternary of Scotland', • ESCC = EW, EW,IS or IS,EW, • Type does not include 'hard rock', or 'restricted'.
d_5	Part river/lake, part non-water exposed Quaternary features	• GCR = 'Quaternary of Scotland', • WDC = 3, • ESCC includes EW but is not EW or EW,IS or IS,EW
d_6	Inland exposure and buried Quaternary features away from rivers	• GCR = 'Quaternary of Scotland', • WDC = 9, • ESCC does not include IS or IA
Landform only sites		
d_7	Soft sediment landforms at the coast (with no water-exposed sediment element)	• GCR = 'Quaternary of Scotland' or 'Fluvial Geomorphology of Scotland' or 'Mass Movement', • ESCC includes IS, does not include EC or EW or IA, • Type = 'coastal soft sediment'
d_8	Hard rock coastal landforms with no water-exposed sediment element	• GCR = 'Quaternary of Scotland' or 'Fluvial Geomorphology of Scotland' or 'Mass Movement', • ESCC includes IS, does not include EC or EW or IA, • Type = 'coastal hard rock'
d_9	Inland soft-sediment landform sites prone to damaging slope failure	• GCR = 'Quaternary of Scotland', or 'Fluvial Geomorphology of Scotland' or 'Mass Movement', • Type includes 'slope failure' but not 'slope failure aspect of feature'.
d_{10}	Non-coastal landforms with no water-exposed sediment element and not prone to slope failure or river erosion.	• GCR = 'Quaternary of Scotland' or 'Fluvial Geomorphology of Scotland' or 'Mass Movement', • WDC is not 2, • ESCC includes IS, but does not include EC, IA or EW, except IS,EW if Type = 'hard rock'. • Type does not include 'coastal' or 'slope failure'
d_{11}	Active freeze-thaw features	• WDC = 9, • ESCC includes IA
Palaeoenvironmental archive sites		
e_1	Lake-only palaeoenvironmental record features	• WDC = 1, • GCR = 'Quaternary of Scotland', • ESCC is not IA
e_2	Peat/bog palaeoenvironmental records away from the coast	• WDC = 2, • GCR = 'Quaternary of Scotland', • Type does not include 'coastal'
e_3	Peat/bog palaeoenvironmental records near the coast	• WDC = 2, • GCR = 'Quaternary of Scotland', • Type includes 'coastal'
e_4	Tufa features	• GCR = 'Quaternary of Scotland', • WDC = 1, • ESCC = 1A

Palaeontology and Mineralogy

f_1	Finite area or restricted coastal-only water-exposed fossil and mineral features	• GCRBT = 'Mineralogy' or 'Palaeontology', • ESCC = EC or FM,EC, • Type is not 'coastal cliff top' or include 'extensive'
f_2	Fossil and mineral features partly coastal-water-exposed but extending inland.	• GCRBT = 'Mineralogy' or 'Palaeontology', • ESCC includes EC but • ESCC is not EC or FM,EC unless Type = 'coastal cliff top' or 'extensive'
f_3	River-only water-exposed fossil and mineral features	• GCRBT = 'Mineralogy' or 'Palaeontology', • ESCC = EW or FM,EW
f_4	Fossil and mineral features partly river-water-exposed and partly non-water-exposed	• GCRBT = 'Mineralogy' or 'Palaeontology', • ESCC includes EW but is not EW or FM,EW
f_5	Non-water dependent fossil and mineral features	• WDC = 9, • GCRBT = 'Palaeontology' or 'Mineralogy'
Stratigraphy, Structural and Metamorphic Geology, Igneous Petrology		
g_1	Finite area or restricted, coastal-only igneous, metamorphic and stratigraphy water-exposed features	• GCRBT = 'Stratigraphy' or 'Structural and Metamorphic Geology' or 'Igneous Petrology', • ESCC = FM,EC or EC • Type = 'restricted'
g_2	Extensive, non-restricted coastal-only (and mostly coastal with some river) igneous, metamorphic and stratigraphy water-exposed features.	• GCRBT = 'Stratigraphy' or 'Structural and Metamorphic Geology' or 'Igneous Petrology', • ESCC = EC or FM,EC or EC,EW • Type is not 'restricted'
g_3	Finite area river-only, igneous, metamorphic and stratigraphy water-exposed features.	• GCRBT = 'Stratigraphy' or 'Structural and Metamorphic Geology' or 'Igneous Petrology', • ESCC = FM,EW
g_4	Extensive, non-restricted, river-only (and mostly river with some coastal), igneous, metamorphic and stratigraphy water-exposed features.	• WDC = 3, • GCRBT = 'Stratigraphy' or 'Structural and Metamorphic Geology' or 'Igneous Petrology', • ESCC = EW or EW,EC
g_5	Restricted, partly water-exposed and partly non-water-exposed igneous, metamorphic and stratigraphy features.	• WDC = 3, GCRBT = 'Stratigraphy' or 'Structural and Metamorphic Geology' or 'Igneous Petrology', • ESCC is not FM,EC or EC or EC,EW, or FM,EW or EW or EW,EC, • Type includes 'restricted'
$\mathbf{g_6}$	Non-restricted, partly water-exposed and partly non-water-exposed igneous, metamorphic and stratigraphy features.	• WDC = 3, GCRBT = 'Stratigraphy' or 'Structural and Metamorphic Geology' or 'Igneous Petrology', • ESCC is not FM,EC or EC or EC,EW, or FM,EW or EW or EW,EC, • Type does not include 'restricted'.
$\mathbf{g_7}$	Non-water dependent igneous, metamorphic and stratigraphy features.	• WDC = 9, • GCRBT = 'Stratigraphy' or 'Structural and Metamorphic Geology' or 'Igneous Petrology'

[1] Inactive coastal features are mixed with active ones on all sites, whereas a few fluvial sites include only relict features (e.g. terraces and palaeochannels).
[2] Physically or spatially restricted features (see section 2.2 for detail)

Despite careful use of Additional Site Codes, it is foreseen that there may be anomalous sites or sites incorrectly assigned to Site Categories. This is primarily because the original ESCC coding was not designed with applications to climate change risk-assessment in mind. Therefore, for example, extent of features is not coded as 'extensive' or 'finite' with respect to likely climate change processes. Similarly, coding for inland outcrop in largely coastal or river and stream section sites, and river and stream section coding in largely coastal sites, though taken to imply that the feature extends inland, do not necessarily mean that the inland extent of the feature is significant with respect to likely coastal/river erosion and sea-level rise. The relatively extensive nature of some 'finite' fossil and mineral sites was taken into account with Additional Site Coding of fossil/mineral sites and some other issues by revising individual ESCC codes. However, if such anomalies come to light, some limited re-coding may need to be done in future on an individual site basis.

2.3 Risk-based assessment method

Two factors were considered to obtain a qualitative risk rating for each geoheritage Site Category against each climate change aspect: 'likelihood of this aspect of climate change affecting a feature' and 'predicted severity of detrimental impact if the feature affected'. This means that the rating is a risk of specifically *detrimental* impacts. Positive impacts were not considered. The factors were rated on a qualitative 'none-low-medium-high' scale using expert judgement. Ratings for the two factors were then combined. Initially risk-rating matrix was used that gave overall ratings of 'no risk', 'low', 'medium' or 'high' for each climate change aspect. But this did not produce results that matched known expert opinion on many sites. Therefore a more complex matrix was developed (Table 9) to give a risk score for each Site Category of 'no risk', 'low', 'medium-low', 'medium', 'medium-high', or 'high' for each climate change aspect. The highest of these ratings for each Site Category was taken as the overall risk rating. Therefore, the final overall risk rating for each Site Category is a measure of maximum assessed risk of detrimental impact to that Site Category from all aspects of climate change.

Table 9. The matrix used for combining scores for 'likelihood of this aspect of climate change affecting feature' ('Likelihood' columns) and 'predicted severity of detrimental impact if feature affected' ('Impact' rows) to give an overall climate change risk-based assessment risk score. For explanation of risk scores (no risk to high risk) see main text.

		Likelihood of aspect of climate change affecting a feature			
		None	**Low**	**Medium**	**High**
Predicted severity of impact	**None**	no risk	no risk	no risk	no risk
	Low	no risk	low	medium-low	medium
	Medium	no risk	medium-low	medium	medium-high
	High	no risk	medium	medium-high	high

Assessment of the likelihood of any given aspect of climate change affecting a given Site Category was informed by the location of the sites in that category (e.g. coastal or not coastal) and/or the nature of the features in the category (e.g. whether they are easily eroded or not). A 'likelihood' rating of 'none' was given where it was considered that the feature would not be impacted by that aspect of climate change; and a score of 'high' likelihood was given where some impact was considered certain or highly likely. For example an inland exposure of Quaternary deposits away from any rivers (Site Category d_6) has a likelihood rating of 'none' for coastal changes, while coastal geomorphology sites (Site Categories a_1-a_3) will definitely be impacted so are scored 'high'. 'Low' and 'medium' ratings were given for appropriate levels of likelihood between 'none' and 'high'. For example coastal stratigraphic geology sites (Site Category g_2) have a low likelihood of being affected directly by changes in rainfall pattern but for example it is possible, if unlikely in most cases, that increased winter rainfall may cause increased in erosion of the feature if there are areas of exposed soft shale near the cliff top; so likelihood is rated 'low'. However, lakes with

palaeoenvironmental records in lake bed sediments (Site Category e_1) are more likely to be affected due to the possibility of the lake edge sediment drying out in hotter, drier summers, so are scored ‘medium’.

Assessing the likely severity of detrimental impact on features of any given Site Category likely to be affected by climate change required a clear definition of ‘detrimental impact’. For this assessment, detrimental impact was defined as anything that would cause the feature to be classed as Unfavourable, Partially Destroyed or Totally Destroyed under SNH’s Site Condition Monitoring (SCM) programme. The latter was developed for assessing the condition of features notified in SSSIs (Ellis, 2004; Scottish Natural Heritage, 2015). The SCM programme methodology for assessment of Earth Science (geoheritage) features uses the most appropriate of two approaches: (1) whether the current state of the feature is sufficient to support the description of the feature in the legal documentation (citation) that protects the site, or (2) comparison of the current site condition with that of a photographically recorded ‘favourable condition baseline’ which records a condition sufficient to support the description of the feature in the legal documentation. The latter approach is used in preference to allow non-specialists to undertake the SCM assessment. Although not all GCR sites in Scotland are protected as notified features in SSSIs, the same principles can be used to assess all GCR sites, with the GCR statement of scientific interest (Ellis, 1996), or its description in a published GCR volume (e.g. May & Hansom, 2003) being used in place of the citation text.

For both Site Condition Monitoring (SCM) approaches, the assessment is made by considering either two or three condition assessment Attributes of the feature depending on the nature of the site (Ellis, 2004): for all sites the Physical Attributes of the feature, and the Visibility of the feature; and, for active process sites only, the Process Dynamics of the feature (Table 10). Physical Attributes includes the extent, structure and composition of the feature, and also its morphology in the case of geomorphological features. Visibility covers the ability to study the feature appropriately; so includes the ability to physically get to and view the feature from appropriate distances including distant and close up views. For buried features, it includes the ability to see the feature location and get to it to excavate it as appropriate. Process Dynamics covers the ability of an active system to evolve naturally; so the most likely cause for targets for this attribute to fail are construction of man-made structure such as coastal and river defences. Generic targets for these attributes are shown in Table 10.

The targets for each feature attribute must be met for the feature to be assessed as in ‘Favourable’ condition. If one or more of the targets is not met, the feature is assessed as being in 'Unfavourable' condition if the damage is reversible (e.g. vegetation growth); or, if the damage is irreversible (e.g. removal of rock outcrop), the feature is assessed as 'Partially Destroyed' or 'Totally Destroyed' depending on the severity of the damage. A Partially Destroyed assessment is given where the remainder of the feature is still sufficient to support the citation.

The same principles were used to assess the severity of detrimental impacts of climate change on the Site Category features (Table 10). A ‘low’ impact was considered to be one that was unlikely to cause the feature to be in Unfavourable, Partially Destroyed, or Totally Destroyed Condition. A ‘medium’ impact was considered to be one that might cause the feature to be in Unfavourable condition. A ‘high’ impact rating was assigned where the impact was considered likely to cause the site to be assessed as Partially Destroyed or Totally Destroyed.

Table 10. Definition of 'severity of detrimental impact if a feature affected', based on site condition assessment attributes for geoheritage features in the SNH Site Condition Monitoring programme.

GCR block	Attribute	Target for favourable condition	Severity of detrimental impact if feature affected		
			Low (Favourable condition)	**Medium (Unfavourable condition)**	**High (Partially/Totally destroyed)**
All	Physical Attributes	If NO baseline available: The essential physical manifestations of the feature, on which the citation is based, continue to be present and intact. If appropriate baseline available: No part of the feature has been damaged, moved or removed (except by natural processes on a temporary basis, or by consented activities) since the time of the baseline.	Changes are unlikely to be damaging to the feature.	Any damage is likely to be reversible through appropriate management.	All or part of the feature is likely to be permanently damaged or destroyed.
All	Visibility	If NO baseline available: The essential physical manifestations of the feature on which the citation is based are visible in close and distant views as appropriate (for research and study). If appropriate baseline available: No part of the feature has been partially or wholly covered or otherwise been made inaccessible for viewing (except by natural processes on a temporary basis, or by consented activities) since the time of the baseline.	Changes are unlikely to cause any decrease in visibility of the feature.	Any loss of visibility is likely to be reversible through appropriate management.	The visibility of all or part of the feature is likely to be permanently lost.
Coastal Geomorphology of Scotland; most Fluvial Geomorphology of Scotland; Karst; Caves[1]	Process Dynamics	If NO baseline available: The essential natural processes on which the citation is based, and/or the natural processes forming the essential active process indicators on which the citation is based continue to operate without constraint. If appropriate baseline available: The essential natural processes on which the citation is based, and/or the natural processes forming the essential active process indicators on which the citation is based are not further constrained (except by consented activities) than they were at the time of the baseline.	Changes in the operation of natural processes are unlikely to affect key aspects of the feature.	Operation of key natural processes may be interrupted or become periodic, resulting in fluctuating favourable and unfavourable feature condition.	Operation of the key natural processes is likely to cease or be severely inhibited or permanently reduced.

[1] Mass Movement sites are not included here there are no active Mass Movement sites in Scotland.

Geographically varying climate change projections were not incorporated in the assessment because defining a single meaningful ‘strength of climate change’ or ‘exposure to climate change’ value for different or multiple aspects of climate changes (e.g. sea-level rise and decrease in freeze-thaw processes) was not possible. Different aspects of climate change will vary in different ways across the country and are not necessarily linked to one another. Sea-level rise, in particular, is difficult to incorporate into a generic dataset as it will have a relatively large, though varying, impact at the coast and none at all in inland areas. A dataset of predicted geographically varying magnitude of climate change across Scotland was developed for the assessment of terrestrial biodiversity features (Brooker *et al*., 2014), but this did not include projections of sea-level rise, so was considered not to be suitable for assessment of mixed coastal and non-coastal geoheritage features. Consequently, the overall risk ratings do not reflect any detail of geographically varying climate change projections. For example, a coastal feature at risk of inundation in an area of relatively large predicted sea-level rise would rate the same as a physically similar feature (same Site Category) in an area of lower predicted sea-level rise. This lack of geographical variation detail in the assessment should be borne in mind when using the risk rating results, and it is recommended that some spatial climate change data is considered during the production of indicative geoheritage climate change actions for high risk sites to address this issue.

Once overall risk rating had been obtained, it is recommended that the details of the individual GCR sites within each Site Category with a 'high' risk rating are scrutinised in order to recommend priority geoheritage climate change actions for each 'high' risk Site Category. Geographically based climate change projection data (http://ukclimateprojections.defra.gov.uk), such as geographically differing sea-level rise and increased winter temperature projections, can be used to select priority GCR sites recommended for actions such as monitoring or rescue and posterity recording (‘rescue and record’). Once priority actions for individual sites have been selected, these can be grouped by local SNH management area for use by the teams responsible for local site management. However, indicative geoheritage climate change actions developed as described here are specifically designed to highlight actions to mitigate and adapt to the impacts of climate change only on geoheritage features within sites. They are based on the best currently available information on both climate change and the nature of geoheritage sites in Scotland, but factors such as the interests and requirements of biodiversity features that overlap spatially, resource implications and other priorities have not been considered. Therefore these indicative geoheritage climate change actions should be taken into account and incorporated appropriately in wider integrated climate change action plans for the relevant sites or regions, but should not be pursued in isolation.

3. RESULTS

The completed risk-based assessments for the five selected aspects of climate change are presented in Table 11. The final risk ratings for each geoheritage Site Category are given in Table 12. The total number of geoheritage Site Categories and GCR sites with each final risk rating is given in Table 13. The full list of geoheritage sites in Scotland assessed as being at 'high' risk from climate change is given in Appendix 1. The distribution of these by GCR block type is given in Table 14.

Table 11. Scoring matrices for risk of detrimental impact from the five selected aspects of climate change (Table 1) on geoheritage Site Categories.

A. Coastal changes: rising sea level, changes in storminess and patterns and intensity of coastal erosion and deposition.

		Likelihood of aspect of climate change affecting a feature			
		None	**Low**	**Medium**	**High**
Predicted severity of impact	**None**	c_1, c_2, d_6, d_9, d_{10}, e_1, e_2, e_4	-	-	-
	Low	-	f_4, f_5, g_7	g_4, g_6	a_3
	Medium	-	b_1, b_2, d_3, d_4, d_5, f_3	g_5	a_2, d_2, d_8, f_2, g_2
	High	-	b_3, d_{11}, g_3	-	a_1, d_1, d_7, e_3, f_1, g_1

B. River changes: increased flooding and changes in patterns of erosion and deposition

		Likelihood of aspect of climate change affecting a feature			
		None	**Low**	**Medium**	**High**
Predicted severity of impact	**None**	c_1, d_6, d_9, g_7	-	-	-
	Low	-	a_2, a_3, d_1, d_2, d_8, d_{10}, e_1, f_2, f_5	b_1, e_2, e_3, g_2, g_6	f_4, g_4
	Medium	-	a_1, d_7, d_{11}, f_1, g_1	c_2, d_5, g_5	b_2, d_4, f_3, g_3
	High	-	-	e_4	b_3, d_3

C. Decrease in freeze-thaw processes (due to warmer winters)

		Likelihood of aspect of climate change affecting a feature			
		None	**Low**	**Medium**	**High**
Predicted severity of impact	**None**	a_1, a_2, c_2	-	-	-
	Low	-	a_3, b_2-b_3, d_1-d_8, d_{10}, e_1-e_3, f_1-f_5, g_1-g_7	b_1, c_1, d_9, e_4	-
	Medium	-	-	-	-
	High	-	-	-	d_{11}

D. Changes in rainfall patterns (drier summers/wetter winters)

		Likelihood of aspect of climate change affecting a feature			
		None	**Low**	**Medium**	**High**
Predicted severity of impact	**None**	f_5, g_7	-	-	-
	Low	-	a_1-a_3, d_6-d_8, d_{10}, f_1, f_2, g_1, g_2, g_5, g_6	b_1, b_2, e_1, f_3, f_4, g_3, g_4	-
	Medium	-	d_3-d_5,d_{11}	b_3, c_2, d_1, d_2, e_4	c_1
	High	-	-	-	d_9, e_2, e_3

E. Changes in vegetation cover/increased vegetation growth

		Likelihood of aspect of climate change affecting a feature			
		None	**Low**	**Medium**	**High**
Predicted severity of impact	**None**	a_3, b_1, c_2	-	-	-
	Low	-	a_2, b_2, b_3, d_1-d_5, d_7, d_8, d_{10}, f_1-f_4, g_1-g_7	d_9	-
	Medium	-	a_1, c_1, d_6, f_5	d_{11}, e_1	-
	High	-	e_4	e_2, e_3	-

3.1 Coastal change: rising sea level, changes in storminess and patterns and intensity of coastal erosion and deposition

Active coastal features (a_1-a_3, see Table 8 for detail) are clearly likely to be impacted by changes in sea-level, storminess and coastal erosion ('high' likelihood). In some cases, impacts on the feature may be severe (e.g. entire soft sediment features could be eroded away). However, in less sensitive Sites Categories, changes may be relatively small or may not be detrimental to the interest feature, so that a lower impact rating is assigned (Table 11A).

Other coastally-located features (d_1, d_2, d_7, d_8, e_3, f_1, f_2, g_1, g_2, g_5, g_6) will be affected by coastal changes. For small finite sites or sites that are highly restricted in area by physical barriers, the loss of even a small area is likely to be highly damaging to the feature, so a 'high' impact is assigned (Table 11A). In the worst-case scenario, features currently only found near low spring tide mark will become inaccessible if sea levels rise. Sites where the feature extends inland beyond the likely reach of coastal change are relatively less likely to be severely impacted.

3.2 Rivers: increased flooding and changes in patterns of erosion and deposition

Active river features (b_1-b_3, see Table 8 for details) will be impacted by the effects of changes in river flow such as flooding and erosion, but the likelihood of impacts such as changes in erosion is lower for hard rock reaches than for soft-sediment reaches. Therefore a 'high' likelihood is assigned for soft-sediment rivers features and a 'medium' likelihood for hard rock features (Table 11B). The greatest impacts are also likely to occur in soft-sediment rivers. Bedrock reaches (b_1) are likely to see little change, so a 'low' impact is assigned (Table 11B). Some changes in soft-sediment river reaches will be detrimental to the features. However many will not, unless the river system is highly restricted by physical barriers and unable to evolve naturally. Therefore a 'medium' impact rating is assigned except for systems considered to be 'restricted' where a 'high' impact rating is assigned.

Caves (c_2) will be affected by changes to rivers that flow through them and water percolating through them. However, not all cave areas will necessarily be affected; hence a 'medium' likelihood is assigned. Effects are also likely to be muted and not all changes may be damaging, so a 'medium' impact rating is also assigned (Table 11B).

River changes may or may not affect tufa (e_4) sites ('medium' likelihood). If they do, it could be highly damaging so a 'high' impact rating is assigned.

Features located adjacent to a river (d_3-d_5, f_3, f_4, g_3, g_4) will be affected by river changes; however those that extend away from a river are proportionately less likely to be affected. The effects on soft sediment, Quaternary sites, are likely to be greater than for hard rock sites. For small finite sites and restricted sites, the loss of even a small area is likely to be highly damaging to the feature. Therefore a 'high' impact is assigned for soft-sediment Quaternary sites that do not extend significantly beyond the riverbank/loch shore or are restricted by physical barriers (Table 11B). For hard rock sites (e.g. fossil or mineral features) the effects of river changes are likely to be relatively less, and sites where the feature extends beyond the immediate river area, are also relatively less likely to be severely impacted (Table 11B).

3.3 Decrease in freeze-thaw processes (due to warmer winters)

Active periglacial features (d_{11}) will clearly be affected by changes in freeze-thaw activity, so a 'high' likelihood rating is assigned (Table 11C). Current observations at Tinto Hill SSSI, South Lanarkshire (NS 952 344) recorded as part of SNH's SCM programme, suggest that the formation of active sorted stripes within the site is sensitive to changes in seasonal

freeze-thaw patterns (this is recorded under the category of 'natural event' in the SCM database http://www.environment.scotland.gov.uk/get-interactive/data/protected-nature-sites/), so a 'High' impact rating is also assigned (Table 11C).

3.4 Changes in rainfall patterns (drier summers/wetter winters)

Peat bogs are very likely to be affected by changes in rainfall, so a 'high' likelihood is assigned to Peat/bog palaeoenvironmental features (e_2, e_3). Drying out of a peat bog could destroy the palaeoenvironmental record particularly through oxidation in the surface layers, so a 'high' impact is also assigned (Table 11D). Lakes with palaeoenvironmental records (e_1) may be affected by rainfall changes as lake levels may vary ('medium' likelihood), leading to sediments at the margins drying out.However, palaeoenvironmental records in the majority of the lake bed will not be affected ('low' impact).

Formation of karst (c_1) features will be affected by changes in rainfall, so a 'high' likelihood is assigned. These changes could have a damaging effect on the karst (e.g. increased dissolution rates) or may not; so a 'medium' impact is assigned as a precautionary rating (Table 11D).

Caves (c_2) will be affected by changes to rainfall patterns and water percolating. However, not all cave areas will necessarily be affected; hence a 'medium' likelihood is assigned. Effects are also likely to be muted and not all changes may be damaging, so a 'medium' impact rating is also assigned (Table 11D).

Changes in rainfall patterns are likely to affect the stability of slopes in sites prone to slope failure (d_9) ('high' likelihood). The effects are likely to be detrimental for relict landform sites, as they may obscure features ('high' impact) (Table 11D). Rainfall may also affect some Quaternary exposure sites (d_1-d_5), increasing slumping of exposures. Soft coastal cliffs are also prone to increased mass movement and slumping under increased rainfall, so coastal Quaternary sites (d_1, d_2) that may contain soft cliffs are rated 'medium' likelihood (Table 11D). The impact is also rated as 'medium', with most likely scenario considered to be small slumps temporarily obscuring part of the feature. Note that there are no soft cliff Coastal Geomorphology GCR sites in Scotland.

3.5 Changes in vegetation cover/increased vegetation growth

Changes in vegetation cover could affect peat bog features (e_2, e_3), and the likelihood is considered 'medium' (Table 11E). Since certain changes (e.g. growth of tree cover following drying out of the bog surface) could damage the palaeoenvironmental record preserved in the bog, a 'high' impact is assigned.

Vegetation changes resulting from climate change may affect almost all types of geoheritage features, including non-water dependent features of all types (d_6, d_9, f_5, g_7), by changing the visibility of the feature. An increase in large trees with roots penetrating soft sediments could also be an issue, especially where windthrow might bring up large root plates that disrupt the feature. Although the likelihood of damaging vegetation changes occurring is probably not high, the most vulnerable sites are likely to be Quaternary sites (d_6), and fossil and mineral sites (f_5), which tend to be small and could easily be obscured or disrupted by penetration of roots (Table 11E). This is likely to be the biggest impact of climate change on these non-water dependent sites.

Table 12. Summary of the final risk scores assigned to each geoheritage Site Category.

Site Category	Description	Highest risk score	Climate change aspect giving this score	No. of GCR sites
Coastal Geomorphology of Scotland				
a_1	Finite or restricted soft sediment coastal features.	High	1. Coastal change	5
a_2	Unrestricted, non-finite soft sediment coastal features.	Medium-high	1. Coastal change	26
a_3	Bedrock coastal features.	Medium	1. Coastal change	12
Active Fluvial Geomorphology of Scotland				
b_1	Active bedrock rivers features	Medium-low	2. River flooding/erosion	5
b_2	Non- or lightly-restricted, active soft sediment river features.	Medium-high	2. River flooding/erosion	17
b_3	Restricted, active soft sediment river features.	High	2. River flooding/erosion	4
Caves and Karst				
c_1	Karst features.	Medium-high	4. Rainfall changes	1
c_2	Cave features.	Medium	2. River flooding/erosion 4. Rainfall changes	2
Quaternary of Scotland, Mass Movement, passive Fluvial Geomorphology of Scotland				
d_1	Finite coastal-exposed Quaternary features.	High	1. Coastal change	12
d_2	Part coastal, part non-water exposed Quaternary features.	Medium-high	1. Coastal change	6
d_3	Finite or restricted river/lake exposed Quaternary features.	High	2. River flooding/erosion	3
d_4	Non-restricted or extensive river/lake exposed soft sediment Quaternary features.	Medium-high	2. River flooding/erosion	14
d_5	Part river/lake, part non-water exposed Quaternary features	Medium	2. River flooding/erosion	10
d_6	Inland exposure and buried Quaternary features away from rivers	Medium-low	5. Vegetation changes	16
Landform only sites				
d_7	Soft sediment landforms at the coast (with no water-exposed sediment element).	High	1. Coastal change	6
d_8	Hard rock coastal landforms with no water-exposed sediment element.	Medium-high	1. Coastal change	3

d_9	Inland soft-sediment landform sites prone to damaging slope failure.	High	4. Rainfall changes	2
d_{10}	Non-coastal landforms with no water-exposed sediment element and not prone to slope failure or river erosion.	Low	2. River flooding/erosion 3. Decreased freeze-thaw 4. Rainfall changes 5. Vegetation changes	46
d_{11}	Active freeze-thaw features	High	3. Decreased freeze-thaw	8
Palaeoenvironmental archive sites				
e_1	Lake-only palaeoenvironmental record features.	Medium-low	4. Rainfall changes	14
e_2	Peat/bog palaeoenvironmental records away from the coast.	High	4. Rainfall changes	14
e_3	Peat/bog palaeoenvironmental records near the coast	High	1. Coastal change 4. Rainfall changes	3
e_4	Tufa features.	Medium-high	2. River flooding/erosion	1
<u>Palaeontology and Mineralogy</u>				
f_1	Finite area or restricted coastal-only water-exposed fossil and mineral features.	High	1. Coastal change	13
f_2	Fossil and mineral features partly coastal-water-exposed but extending inland.	Medium-high	1. Coastal change	29
f_3	River-only water-exposed fossil and mineral features.	Medium-high	2. River flooding/erosion	21
f_4	Fossil and mineral features partly river-water-exposed and partly non-water-exposed.	Medium	2. River flooding/erosion	9
f_5	Non-water dependent fossil and mineral features.	Medium-low	5. Vegetation changes	67
<u>Stratigraphy, Structural and Metamorphic Geology, Igneous Petrology</u>				
g_1	Finite area or restricted, coastal-only igneous, metamorphic and stratigraphy water-exposed features.	High	1. Coastal change	10
g_2	Extensive, non-restricted coastal-only (and mostly coastal with some river) igneous, metamorphic and stratigraphy water-exposed features.	Medium	1. Coastal change	141
g_3	Finite area river-only, igneous, metamorphic and stratigraphy water-exposed features.	Medium-high	2. River flooding/erosion	4
g_4	Extensive, non-restricted, river-only (and mostly river with some coastal), igneous, metamorphic	Medium	2. River flooding/erosion	41

	and stratigraphy water-exposed features.			
g_5	Restricted, partly water-exposed and partly non-water-exposed igneous, metamorphic and stratigraphy features.	Medium	1. Coastal change 2. River flooding/erosion	4
g_6	Non-restricted, partly water-exposed and partly non-water-exposed igneous, metamorphic and stratigraphy features.	Medium-low	1. Coastal change 2. River flooding/erosion	189
g_7	Non-water dependent igneous, metamorphic and stratigraphy features.	Low	1. Coastal change 2. River flooding/erosion 5. Vegetation changes	146

3.6 Summary

In summary, 11 Site Categories are rated as being at 'high' risk (Table 13). They comprise active soft-sediment coastal and fluvial features, finite coastal and river Quaternary sediment exposures and landforms, periglacial features, sites with palaeoenvironmental records, finite or restricted rock exposures and fossil and mineral features. These 'high' risk Site Categories contain 80 GCR sites, 8.8% of the total number in Scotland (Table 10), and include 66 notified SSSI features, which is 9.9% of the total number of notified Earth Science features in Scotland. At the lower end of the risk scale ('low' and 'medium-low') are bedrock river reaches and non-water-related features. Overall 77.7% of GCR sites, including 73.2% of Earth Science SSSI features, are assessed as being relatively resilient to climate change ('medium' to 'low' risk), with 13.5% of GCR sites (16.9 % Earth Science SSSI features) at moderate ('medium-high') risk.

Table 13. Summary statistics of final climate change risk-based assessment risk scores.

Final risk score	Low	Medium-low	Medium	Medium-high	High
No. of Site Categories	2	5	7	10	11
No. of GCR sites	192 (21.2%)	291 (32.2%)	219 (24.3%)	122 (13.5%)	80 (8.8%)
No SSSI features	122 (18.4%)	204 (30.7%)	160 (24.1%)	112 (16.9%)	66 (9.9%)

The full list of geoheritage sites in Scotland assessed as being at 'high' risk from climate change is given in Appendix 2. The distribution of these by GCR block type is given in Table 14.

Table 14. Summary statistics of GCR sites assessed as at 'high' risk from climate change by GCR block type (with 'Geomorphology' sub-divided into GCR blocks).

GCR block type GCR block	No. of GCR Sites at 'high' risk from climate change
Stratigraphy	8
Igneous Petrology	2
Palaeontology	13
Quaternary Geology and Geomorphology	47
Geomorphology	
Coastal Geomorphology of Scotland	5
Fluvial Geomorphology of Scotland	5

The majority of sites (47 out of 80) assessed as being at 'high' risk from climate change are Quaternary Geology and Geomorphology sites within the 'Quaternary of Scotland' GCR

block (Table 14). This is in part due to the wide physical variety of sites incorporated under ‘Quaternary Geology and Geomorphology’ and partly due to the relatively fragile and finite nature of many of these features, which can vary from small pockets of easily eroded sediment to climate-controlled active freeze-thaw features.

Geomorphology sites though often highly exposed to the consequences of climate change are also often inherently robust with respect to these where the geoheritage interest is primarily in the continuing active natural evolution of the site. Such sites will only be at ‘high’ risk where their natural evolution is in some way restricted, and this is reflected in the relatively low numbers (10 out of 80) of these features assessed as at ‘high risk compared to Quaternary Geology and Geomorphology features.

The lack of any Mineralogy sites in the final list of sites at ‘high’ risk from climate change is due solely to the fact that no small finite mineralogy sites in Scotland are located near to the coast. It should not be taken to mean that mineralogy sites are inherently less at risk from climate change than palaeontology sites.

4. MANAGEMENT RESPONSES

4.1 Site management principles and actions

Crofts & Gordon (2015) set out principles for geoconservation in protected areas and summarised the management objectives for different types of site in the ESCC, while Prosser *et al*. (2006) provided detailed guidance on management techniques. Many of these principles and techniques are applicable to implementing mitigation and adaptation responses to managing the impacts of climate change on geoheritage sites (Table 15). In some cases, it may be possible to prevent loss or mitigate the deterioration of the geoheritage interest. Mitigation measures might include proactive management such as reducing the pressures on the geoheritage feature, as advocated in SNH's climate-change Adaptation Principles (Scottish Natural Heritage, 2016). This could be through actions such as reducing grazing pressure vegetation clearance, or drain blocking as part of bog restoration at palaeoenvironmental record sites. Mitigation measures could also include the burial of some sites to protect highly vulnerable finite interests (Bridgland, 2013) or, exceptionally, the construction of hard defences to protect finite features. In the case of exposure sites, excavation of replacement sections may be feasible. However, in other cases it may be necessary to accept the deterioration or loss of some of the geoheritage interest and to implement adaptation measures. These may include detailed recording for posterity and, where appropriate, recovery or rescue of particular features ('rescue and record'), such as fossils, for curation in museum collections and archiving of photographic records or sediment logs. This is particularly important for finite sites, and those with important mineral or fossil records. Planning for change, and taking an adaptive approach in this way, also closely follows SNH's climate-change Adaptation Principles (Scottish Natural Heritage, 2016).

In the case of active geomorphological processes, and at the broader landscape scale the most appropriate (and cost effective) approach should be to allow these processes to adapt naturally to changing climate conditions (Sharples, 2011; Crofts & Gordon, 2015). This 'do nothing' approach should apply where there is space for active geomorphological processes to evolve naturally. In line with SNH's climate-change Adaptation Principle of making space for natural processes (Scottish Natural Heritage, 2016), the preferred response for geomorphological systems will be to allow natural processes to evolve undisturbed and to manage the consequences of change (e.g. adapt site boundaries) rather than attempt to stabilise and control the active system (Brazier *et al*., 2012). Where some form of protection is deemed essential to protect other interests (e.g. infrastructure), and where space allows or can be created, nature-base solutions or 'soft' forms of intervention (e.g. managed realignment or beach nourishment) should be the first option considered. This approach may mean accepting the loss or relocation of particular geomorphological features in active process systems where rates of change may be too fast to maintain existing assemblages of features (Orford & Pethick, 2006; Brazier *et al*., 2012). This is in line with SNH's climate-change Adaptation Principles of taking an adaptive approach to land and conservation management, and planning for change (Scottish Natural Heritage, 2016).

Monitoring of changes to sites and their features of interest is a fundamental part of the management process to help decide at what point intervention is required and to inform the type of intervention required. As for biodiversity, a key part of this process will be the development of decision triggers to support evidence-based responses (Addison *et al*., 2016). More general actions outside the scope of this report include communication with planning authorities and local communities to integrate geoconservation into wider climate change adaptation (Prosser *et al*., 2010; E.J. Brown *et al*., 2012).

Table 15. Management actions for geoheritage sites at risk from climate change, and the SNH climate-change Adaptation Principles to which they relate.

Measures	Description	SNH climate change Adaptation Principles
Site monitoring	Monitor sites at a frequency appropriate for their level of risk.	6 **Take an adaptive approach to land and conservation management** e.g. by changing objectives and management measures in response to new information.
Revision of protected area boundaries	Modify existing protected area boundaries where the location of the feature has changed (e.g. as a consequence of coastal retreat).	6 **Take an adaptive approach to land and conservation management**
Posterity recording and research	Research and record for posterity both soft-sediment and hard-rock features where the interest will be unavoidably lost, and rescue and archive material where appropriate.	7 **Plan for habitat change** where assessments indicate losses of habitats or species are inevitable, for example as a result of sea-level rise.
Replacement exposures	Establish the extent of high risk features in, and beyond, the current site boundary, so that options for replacement exposures can be assessed where appropriate.	6 **Take an adaptive approach to land and conservation management** 7 **Plan for habitat change**
Proactive management to mitigate impacts	Implement proactive mitigation such as pre-emptive tree felling, managed re-alignment, river restoration, slope stabilisation through woodland regeneration and reduction in grazing pressure, bog restoration, or installation of hard protection or burial in exceptional cases where finite sites are threatened and using research and monitoring data to refine conservation management.	1 **Reduce other pressures on ecosystems, habitats and species** – e.g. pollution, unsustainable use, grazing, habitat fragmentation and invasive non-native species. 6 **Take an adaptive approach to land and conservation management**
Liaison with other stakeholders	Liaise with planning authorities regarding features that climate change impacts will put at risk from planning-controlled activities (e.g. features squeezed between rising sea-level and coastal infrastructure) and assist in developing appropriate action plans. Liaise with the research community, museums and local geoconservation groups to undertake or assist monitoring, research, rescue or posterity recording where appropriate.	1 **Reduce other pressures on ecosystems, habitats and species** 2 **Make space for natural processes** including geomorphological, water and soil processes, and species interactions. 6 **Take an adaptive approach to land and conservation management** 7 **Plan for habitat change**
Awareness raising	Co-ordinate high-profile awareness raising of best practice e.g. 'leaving space for nature', avoidance of hard coastal and river defences, and the benefits of nature-based solutions including understanding the role of river and coastal processes in sediment transport and the maintenance of natural forms of protection (e.g. beaches, dunes and saltmarshes).	1 **Reduce other pressures on ecosystems, habitats and species** 2 **Make space for natural processes** 6 **Take an adaptive approach to land and conservation management**

4.2 Development of indicative geoheritage climate change actions

Using the risk assessment results developed in this study, preparation of indicative geoheritage climate change actions can be prioritised for sites assessed as being at 'high' risk. Indicative geoheritage climate change actions are designed to highlight what can be done to help mitigate and adapt to the impacts of climate change on Scotland's geoheritage; but they do not take into account other factors such as the requirements of biodiversity features on the same sites. The indicative geoheritage climate change actions also do not take into account resource implications, other limitations or local or national priorities that may influence what actions are appropriate on any given site. Therefore, indicative geoheritage climate change actions for the 'high' risk geoheritage features are not designed to be pursued in isolation. They are instead intended as the geoheritage input into wider climate change action plans for the relevant sites or regions.

For other sites assessed as being at 'medium-high' or 'medium' risk, SNH's SCM programme should help provide early alert of detrimental changes, as it includes recording of any activities or changes in the vicinity of the site that might affect the interest feature in the future, with a site visit every 6 to 7 years.

To ensure that actions for sites within each category are consistent, indicative geoheritage climate change actions for individual sites within each category, need to take into account the nature of the site and climate change projections for that site, in comparison to the nature and climate change projections for all other sites in the same Site Category. This is the stage where it is recommended that some geographically varying climate change data are taken into account. Climate change projections from UKCP09 (and updates) can be used to assess the magnitude of likely changes for sites at different geographical locations. Climate change projections likely to be relevant included: relative sea-level rise and extreme water-level projections for coastal sites; variations in both increases in minimum winter temperature and increases in mean winter temperature for periglacial (freeze-thaw dependent) features; increases in mean winter precipitation for landslide-prone sites; and increases in relative summer drought risk (decreased summer rainfall, increased summer temperature) and relative winter-drought risk (decreased winter rainfall, increased winter temperature) for peat bog palaeoenvironmental record sites. The sites with the greatest predicted changes within each Site Category should be prioritised for increased frequency of monitoring, and the assessment can also be used to identify potential sites for rescue/archiving and posterity recording.

Recommended actions for individual sites, other than increased monitoring frequency, are likely to be primarily based on individual site characteristics (e.g. whether a feature extends beyond the normal tidal zone or is only exposed at extreme low tide), combined with an assessment of the likelihood of human intervention in natural change. It is suggested that a 'Likelihood of human intervention' factor is initially rated on a qualitative 'high', 'medium' and 'low' basis. Its inclusion is supported by the conclusion of Land Use Consultants (2011) that 'mitigation and adaptation measures are likely to have a more significant influence on Scotland's landscapes and quality of life than the direct effects of climate change' (Scottish Natural Heritage, 2011).

Once indicative geoheritage climate change actions have been selected for the sites within each Site Category, the actions for individual sites should be grouped by local SNH management area for use by the teams responsible for local site management. However, as discussed earlier, these indicative geoheritage actions should not be pursued in isolation. They are not ready-to-implement actions for a climate change action plan. This is because they do not take into account factors such as the interests and requirements of spatially overlapping biodiversity features, resource implications or other priorities that may be of key importance. The appropriate implementation of indicative geoheritage climate change

actions derived as described above, is only through incorporated them appropriately in wider integrated climate change action plans for the relevant sites or regions.

Examples of indicative geoheritage climate change actions such as could be developed for all geoheritage features assessed as being at 'high' risk from climate change are given in Tables 16a & 16b.

Table 16a. Selected 'Finite or restricted soft sediment active coastal features' (a_1) Site Category GCR sites and their corresponding SSSIs with 'Likelihood of human intervention' score and some notes on the nature of the site included; and recommended indicative geoheritage climate change actions.

SSSI name	GCR site name	GCR block	Likelihood of human intervention	Notes on nature of site	Indicative geoheritage climate change actions and timescale
Dunnet Links	Dunnet Bay	Coastal Geomorphology of Scotland	High	Rapid frontal dune retreat likely to continue or accelerate. Sand-blow (and future erosion) will continue to impact on A836 road. Likely sea-level rise 35-40cm.	Immediate: Initiate discussion on future status and management of A-road with highway authority/local council and adoption of natural management solutions to coastal erosion.
Gruinart Flats	Loch Gruinart, Islay	Coastal Geomorphology of Scotland	Low	Risk of coastal squeeze of saltmarsh against flood embankment. Embankment upgrade would contribute to loss of GCR interest. Likely sea level rise ~30cm.	Immediate: Seek managed re-alignment of flood embankment. Work with landowner to appraise managed re-alignment options and timescale.
St Ninian's Tombolo	St Ninian's Tombolo	Coastal Geomorphology of Scotland	Low	Temporary breaches of tombolo by storm waves will become more frequent until it is largely an intertidal feature. Likely sea-level rise ~50cm.	Immediate: change 'finite' aspect of SSSI citation wording ('largest sandy tombolo currently active in Britain') to reflect dynamic nature of site (e.g. 'sandy landforms actively expressing wave activity from opposing directions and subject to change through submergence')
Tayport – Tentsmuir Coast	Tentsmuir	Coastal Geomorphology of Scotland	Low	Frontal dune retreat affecting significant sectors likely to continue, accelerate and expand. Erosion will increasingly intercept conifer plantation, arguably reducing naturalness of change. Likely sea-level rise 30-35cm.	Immediate: Seek 'pre-emptive' felling of trees to give space for beach and dunes to evolve as sea level rises.

Table 16b. Selected 'Bog pollen features away from the coast' (e2) Site Category GCR sites and their corresponding SSSIs with 'Likelihood of human intervention' score and some notes on the nature of the site included; and recommended indicative geoheritage climate change actions.

SSSI name	GCR site name	Feature name	Likelihood of human intervention	Notes on nature of site	Indicative geoheritage climate change actions and timescale
Abernethy Forest	Abernethy Forest	Quaternary of Scotland	Low	Likely one of the pollen features most exposed to winter drought but not to summer drought (UKCP09 data).	Immediate: Investigate options to monitor site for signs of drying out, more frequently than Site Condition Monitoring (e.g. every 3-5 years[1]). Future: Support bog restoration measures such as drain-blocking.
Ardmeanach	Gribun	Quaternary of Scotland	Low	This site has some agricultural impacts. Likely one of the pollen features least exposed to either summer or winter drought (UKCP09 data).	Immediate and future: Monitor for signs of drying out during Site Condition Monitoring and any other site visits.
Mollands	Mollands	Quaternary of Scotland	Low	Site likely to become surrounded by new houses. Key issue is management of drainage from housing, and how catchment changes affect hydrology of this site. Likely one of the pollen features most exposed to summer drought and also one of the more highly exposed to winter drought (UKCP09 data).	Immediate: Investigate options to monitor site for signs of drying out, more frequently than Site Condition Monitoring (e.g. every 3-5 years[1]). Support bog restoration measures such as drain-blocking.
St Kilda	Gleann Mor, Hirta	Quaternary of Scotland	Low	Likely one of the pollen features least exposed to either summer or winter drought (UKCP09 data).	Immediate and future: Monitor for signs of drying out during Site Condition Monitoring and any other site visits.
Tynaspirit	Tynaspirit	Quaternary of Scotland	Low	Likely one of the pollen features most exposed to summer drought and also one of the more highly exposed to winter drought (UKCP09 data).	Immediate: Investigate options to monitor site for signs of drying out, more frequently than Site Condition Monitoring (e.g. every 3-5 years[1]). Support bog restoration measures such as drain-blocking and removal of trees. Future: Consider designation of already documented replacement site nearby.

[1] Within SNH's current SCM programme, a full Site Condition Monitoring Assessment for these features would be undertaken every 18-21 years with less rigorous 'Site Checks' every 6-7 years.

5. DISCUSSION

5.1 Assessment of the methodology

Assessments of risk will always have a level of uncertainty; therefore any risk-based assessment should be viewed as a working tool that may be used with appropriate levels of caution, and with an understanding of any assumptions and generalisations that have been made. Although the results of this risk-based assessment were largely as expected on intuitive grounds in terms of confirming the Site Categories at 'high' risk, the methodology adopted in this study has the advantage of being systematic, detailed and thorough. The premise, namely of grouping geoheritage sites into Site Categories and then assessing the risks form climate change to the category as a whole, is that this process reduces the scale of the assessment task, and makes it easier both to ensure a consistent assessment across a wide variety of sites and to align the input of different experts.

Individually assessing all ~900 GCR sites would be a lengthy task as it would necessarily involve comparing assessments of each site with assessments from a number of other sites, if not every other site, to insure consistency. This comparison would need to be done initially by individual experts for particular groups of sites, and then between groups of sites assessed by different experts. The reasons for each risk assessment rating would need to be recorded in a consistent way to ensure that meaningful comparison of assessments was possible. This is likely to take as long as, or longer than, the Site Categories method used here. However, assessing individual sites may be worth trialling for smaller site networks, such as county inventories.

If using an intuitive approach, such as experts simply listing those sites they considered most at risk in their own field of knowledge, similar steps to ensure consistency between the assessments of each individual expert would also need to be employed. Additionally with an intuitive approach there is the risk of sites being overlooked.

Overall, it is likely to be very difficult to assess the risk to ~900 sites without grouping them in some way, either for assessment or for comparison to ensure consistency.

The current approach was developed progressively over 3 years as part of a wider project to assess the risk of climate change to all notified natural heritage features in Scotland (Brooker *et al*., 2014). Over this period, the methodology was revised a number of times. Initially 9 Site Categories were defined and a more basic risk-rating system was used that gave only ratings of 'low', 'medium' or 'high'. However, this did not produce results that matched known expert opinion on many sites; so a number of the original Site Categories were divided giving a total of 19 Site Categories (Table 6). The current risk-rating method was also introduced. This, however, still gave unsatisfactory results for some features. Therefore additional factors were taken into account as described in section 2.2, and the number of Site Categories increased to the final 35. The final methodology largely used existing data. Expert input was only required to assess the risk to 35 Site Categories (rather than ~900 individual sites), and during the evaluation of additional factors when ~70 sites had to be considered individually (Table 7). Therefore, although the approach adopted appears to be resource intensive and requires expert assessment at various stages, the magnitude of the task was significantly less than if the data had needed to be compiled from scratch. Expert overview of the overall risk ratings concluded that all sites where concerns over present or future climate change impacts had been raised and are considered to be well-founded, obtained a 'high' risk rating. This indicates that the assessment method is highlighting the correct sites for climate change mitigation and adaptation actions. Protected area managers elsewhere should be able to test the wider applicability of the methodology and to adapt it to their own suites of geoheritage sites, the scale of effort depending on the level of availability of comparable data and detailed knowledge of local sites.

Despite careful application of the methodology, there may be anomalous sites or sites incorrectly assigned to Site Categories. This is primarily because the original ESCC coding was not designed with applications to climate change risk assessment in mind. For example, extent of features is not coded as ‘extensive’ or ‘finite’ with respect to likely climate change processes. Similarly, coding for inland outcrop in largely coastal or river and stream section sites, and river and stream section coding in largely coastal sites, though taken to imply that the feature extends inland, do not necessarily mean that the inland extent of the feature is significant with respect to likely coastal or river erosion and sea-level rise. The relatively extensive nature of some finite fossil and mineral sites was taken into account by amending individual ESCC codes. However, if anomalies become apparent, some limited re-coding may need to be done in future on an individual site basis. In addition, some individual risk ratings may need updating over time in the light of new knowledge about the sites or from monitoring.

Since the objective of this study was to develop a risk-assessment methodology to inform the development of indicative geoheritage climate change actions for 'high' risk features, with the minimum necessary expert input, expert opinion was not employed to check that sites were correctly assigned between the low', 'medium-low', or 'medium' risk categories. Also, for prediction of detrimental impact, a precautionary minimum rating of ‘low’ was assigned to all sites where any likelihood of impact was predicted, with no attempt to separate cases where it could be argued that there is likely to be no detrimental impact at all. Consequently, there are more likely to be anomalies in the risk ratings assigned among lower risk features than among 'high' and 'medium-high' risk features.

Although indicative geoheritage climate change actions will be based on the best currently available information on both climate change and the nature of geoheritage sites in Scotland, factors such as the interests and requirements of biodiversity features that overlap spatially, resource implications and other priorities have not been considered. The indicative geoheritage climate change actions described in this report are specifically designed to highlight actions to mitigate and adapt to the impacts of climate change on geoheritage sites and should not be pursued in isolation; but instead should be taken into account and incorporated appropriately in wider integrated climate change action plans for the relevant sites or regions. For individual geoheritage sites, or groups of geoheritage sites, new information may require revision of either the assigned risk ratings or the proposed actions. For example, the relatively few inland soft-sediment exposure Quaternary sites in Scotland are currently considered more at risk from increased vegetation cover than erosion caused by increased rainfall, and these sites are not currently rated as being at high risk from climate change. However, enhanced slumping or slopewash due to changes in rainfall should be kept under review through monitoring and may lead to a revised assessment in the future. Therefore, both assigned risk ratings and the proposed actions need to be kept under review and updated as and when appropriate, both before and after incorporation into any wider climate change action plans.

Effective implementation of any of the indicative geoheritage climate change actions incorporated into agreed climate change action plans will be heavily dependent on monitoring, and feedback from monitoring is likely to be crucial in adapting and improving action plans (Figure 1). The SNH SCM Programme has a cycle of 6 to 7 years between site visits and up to 21 years between full assessments. Any increases in this monitoring frequency will clearly have resource implications. However, it may be possible to involve local volunteers to monitor such sites (e.g. by taking photographs from fixed positions to record the rate and magnitude of changes) and to trigger appropriate management action. Such a citizen-science approach is being successfully deployed in the monitoring and recording of archaeology sites at risk from coastal erosion in Scotland (Dawson, 2015, 2016). Similarly, it should be possible to enlist academics and museums to research and record high-vulnerability sites and to undertake rescue work.

5.2 Management considerations

From a management perspective, there are a number of challenges. First, it may need to be accepted that in practical terms some sites are simply not conservable in the face of climate change, or that the resources required are too great. Consequently, some hard decisions may be required and early intervention instigated to ensure that the loss is offset through rescue and record. This will require collaboration across the geoscience and geoconservation communities.

Second, the conservation of sites identified or designated for their active geomorphology presents some particular challenges. Maintaining the natural dynamics of these sites so that their geomorphological systems evolve naturally is the key objective, whether under a stable or changing climate. This approach safeguards natural processes above the individual features, and fits within the concept of 'nature's stage' (Beier *et al*., 2015; Lawler *et al*., 2015; Hjort *et al*., 2015). This approach is sustainable, in allowing natural systems to adapt, as they have during past climate changes, through landform change, loss and creation. However, where erosion is involved, there may be conflicts with adjacent 'static' interests, and some form of trade-off may be required, possibly involving conservation through rescue and record. Management of active geomorphological sites in proximity to infrastructure will present significant challenges and will require alternative 'soft' approaches working with the natural processes as far as possible. Recent investigations of the protective function of Scotland's coast identified £13bn of assets being protected by natural coastal defences (beaches and salt marshes), compared with £5bn of assets behind man-made defences (Hansom *et al*., 2017; http://www.dynamiccoast.com/).There are also benefits for both geoheritage and biodiversity in developing integrated approaches with complementary objectives, for example involving natural floodplain and coastal restoration founded on an understanding of physical processes, as part of nature-based solutions to hazards such as flooding (Brazier *et al*., 2012; Gray *et al*., 2013; Cohen-Shacham *et al*., 2016).

Third, the indirect impacts of climate change, resulting from human responses to direct impacts, are as much a concern and need to be factored into climate change action plans Hence, there is a need for engagement with wider stakeholders at all scales from local to national (Prosser *et al*., 2010). Geoheritage conservation cannot be detached from wider social, cultural and economic systems, and it can be part of the solution for adapting to our changing climate (Prosser *et al*., 2010; Henriques *et al*., 2011; Gray *et al*., 2013).

6. CONCLUSIONS

Addressing the potential impacts of climate change on geoheritage features in protected areas is a growing priority. A relative risk rating (low to high) was derived for groups of similar geoheritage features, using a systematic approach that involved a combination of current understanding of how climate change will affect the features, and knowledge of the characteristics of geosites in Scotland. The latter was partly encapsulated in currently assigned coding for GCR block, Earth Science Conservation Classification and Water Dependence Classification, and partly gained from expert knowledge of individual sites. While, the results of the risk assessments were largely as expected on intuitive grounds in terms of confirming the Site Categories at 'high' risk, the methodology adopted ensured a systematic and consistent approach that provides a foundation for adaptation and mitigation action. This risk-assessment approach and the development of indicative geoheritage climate change actions, as recommended in this report, will form a sound basis from which to incorporate climate change planning for geoheritage sites into local and regional climate change action plans within Scotland. The indicative geoheritage climate change actions described in this report are specifically designed to highlight actions to mitigate and adapt to the impacts of climate change on geoheritage sites and should not be pursued in isolation; but instead should be taken into account and incorporated appropriately in wider integrated climate change action plans for the relevant sites or regions. This detailed site-level approach builds on and advances the development of higher-level actions and general principles (Prosser *et al*., 2010; Sharples, 2011; Brazier *et al*., 2012; E.J. Brown *et al*., 2012; Crofts & Gordon, 2015).

7. REFERENCES

Addison, P.F.E., Cook, C.N. & de Bie, K. 2016. Conservation practitioners' perspectives on decision triggers for evidence-based management. *Journal of Applied Ecology,* **53**, 1351-1357.

ASC. 2016. UK Climate Change Risk Assessment 2017 Evidence Report – Summary for Scotland. Adaptation Sub-Committee of the Committee on Climate Change, London.

Beier, P., Hunter, M.L., & Anderson, M. (*Eds*.). 2015. Special Section: Conserving Nature's Stage, Introduction. *Conservation Biology*, **29**, 613-617.

Brazier, V., Bruneau, P.M.C., Gordon, J.E. & Rennie, A.F., 2012. Making space for nature in a changing climate: the role of geodiversity in biodiversity conservation. *Scottish Geographical Journal,* **128**, 211-233.

Bridgland, D. R. 2013. Geoconservation of Quaternary sites and interests. *Proceedings of the Geologists' Association,* **124**, 612-24.

Brooker, R., Castellazzi, M., Gimona, A., Poggio, L., Ahrends, A., Ellis, C., Bond, C., Harding, A., Kirkbride, V., Wignall, R. & Rowan, J. 2014. Summary Report: Climate Change Risk-Based Assessment for Notifiable Features in Scotland. [Online]. Available at: http://www.climatexchange.org.uk/files/7014/2132/8263/CXC_Risk_Assessment_summary_report_update_Dec_14.pdf [Accessed August 2017].

Brown, E.J., Prosser, C.D. & Stevenson, N.M. 2012. Geodiversity, conservation and climate change: key principles for adaptation. *Scottish Geographical Journal,* **128**, 234-239.

Brown I., Ridder, B., Alumbaugh, P., Barnett, C., Brooks, A., Duffy, L., Webbon, C., Nash, E., Townend, I., Black, H. & Hough, R. 2012. Climate Change Risk Assessment for the Biodiversity and Ecosystem Services Sector. Available at: http://randd.defra.gov.uk/ [Accessed August 2017].

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S. (Eds.), 2016. Nature-based Solutions to Address Global Societal Challenges. IUCN, Gland, Switzerland. Available at: https://portals.iucn.org/library/sites/library/files/documents/2016-036.pdf. [Accessed August 2017].

Crofts, R. & Gordon, J.E. 2015. Geoconservation in protected areas. In: Worboys, G.L., Lockwood, M., Kothari, A., Feary, S., Pulsford, I. (*Eds.*). *Protected Area Governance and Management*. ANU Press, Canberra, pp. 531-568.

Dawson, T. 2015. Taking the middle path to the coast: how community collaboration can help save threatened sites. In: Harvey, D.C., Perry, J. (*Eds.*). *The Future of Heritage as Climates Change.* Loss, Adaptation and Creativity. Routledge, London & New York, pp. 248-268.

Dawson, T. 2016. Community rescue: saving sites from the sea. *Arquelogia Publica: Online Journal in Public Archaeology*. Special Volume **2**, 5-42.

Defra, 2009. Adapting to climate change: UK climate projections June 2009. Department of Environment, Food and Rural Affairs (Defra), London.

Ellis, N. 2004. Common Standards Monitoring Guidance for Earth Science Sites. Joint Nature Conservation Committee, Peterborough, UK. Available at:

http://jncc.defra.gov.uk/pdf/CSM_earth_science.pdf [Accessed August 2017].

Ellis, N. 2011. The Geological Conservation Review (GCR) in Great Britain - rationale and methods. *Proceedings of the Geologists' Association*, **122**, 353-362.

Ellis, N.V., Bowen, D.Q., Campbell, S., Knill, J.L., McKirdy, A.P., Prosser, C.D., Vincent, M.A. & Wilson, R.C.L. 1996. An Introduction to the Geological Conservation Review. *Geological Conservation Review Series* No. 1. Joint Nature Conservation Committee, Peterborough.

European Commission. 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy (EU Water Framework Directive). [Online]. Available at: http://ec.europa.eu/environment/water/water-framework/index_en.html [Accessed June 2016].

Gordon, J.E., Kirkbride, V., Rennie, A.F. & Bruneau, P.M.C. 2008. Climate change: why geodiversity matters. *Earth Heritage Magazine*, **30**, 8-10.

Gray, M., Gordon, J.E., Brown, E.J. 2013. Geodiversity and the ecosystem approach: the contribution of geoscience in delivering integrated environmental management. *Proceedings of the Geologists' Association,* **124**, 659-673.

Hansom, J.D., Fitton, J.M., Rennie, A.F. 2017. Dynamic Coast – National Coastal Change Assessment: National Overview. CREW – Scotland's Centre of Expertise for Waters. CRW2014/2.

Harrison, P.A., Berry, P.M. & Dawson, T.P. (*Eds.*). 2001. *Climate changes and nature conservation in Britain and Ireland: modelling natural resource responses to climate change (the MONARCH project)*. UKCIP Technical Report, Oxford.

Henriques, M.H., Pena dos Reis, R., Brilha, J. & Mota, T. 2011. Geoconservation as an emerging geoscience. *Geoheritage,* **3**, 117-128.

Hjort, J., Gordon, J.E., Gray, M. & Malcolm, L.H. JR. 2015. Why geodiversity matters in valuing nature's stage. *Conservation Biology*, **29**, 630-639.

HR Wallingford, AMEC Environment & Infrastructure UK Ltd (formerly Entec UK Ltd), The Met Office, Collingwood Environmental Planning, Alexander Ballard Ltd, Paul Watkiss Associates, Metroeconomica. 2012. *A Climate Change Risk Assessment for Scotland*. Report to Defra. Available at: http://randd.defra.gov.uk/. [Accessed August 2017].

Jenkins, G.J., Murphy, J.M., Sexton, D.S., Lowe, J.A., Jones, P. & Kilsby, C.G. 2009. *UK climate projections: briefing report*. Met Office Hadley Centre, Exeter.

Land Use Consultants. 2011. An assessment of the impacts of climate change on Scottish landscapes and their contribution to quality of life: Phase 1 - Final report. *Scottish Natural Heritage Commissioned Report No. 488*. Available at: http://www.snh.gov.uk/publications-data-and-research/publications/search-the-catalogue/publication-detail/?id=1868. [Accessed August 2017].

Lawler, J.L., Ackerly, D.D., Albano, C.M., Anderson, M.G., Dobrowski, S.Z., Gill, J.L., Heller, N.E., Pressey, R.L., Sanderson, E.W. & Weiss, S.B. 2015. The theory behind, and the challenges of, conserving nature's stage in a time of rapid change. *Conservation Biology*, **29**, 618-629.

May, V.J. & Hansom, J.D. 2003. Coastal Geomorphology of Great Britain. *Geological Conservation Review Series* No. 28. Joint Nature Conservation Committee, Peterborough.

Orford, J.D. & Pethick, J. 2006. Challenging assumptions of future coastal habitat development around the UK. *Earth Surface Processes and Landforms*, **31**, 1625-1642.

Orr, H.G., Wilby, R.L., McKenzie Hedger, M., Brown, I. 2008. Climate change in the uplands: a UK perspective on safeguarding regulatory ecosystem services. *Climate Research*, **37**, 77-98.

Prosser, C., Murphy, M. & Larwood, J. 2006. *Geological Conservation: A Guide to Good Practice*. Natural England, Peterborough, UK. Available at: http://webarchive.nationalarchives.gov.uk/20140605115700/http://publications.naturalenglandd.org.uk/publication/83048 [Accessed August 2017].

Prosser, C.D., Burek, C.V., Evans, D.H., Gordon, J.E., Kirkbride, V.B., Rennie, A.F. & Walmsley, C.A. 2010. Conserving geodiversity sites in a changing climate: management challenges and responses. *Geoheritage*, **2**, 123-136.

Ramsbottom D., Sayers P. & Panzeri M., 2012. Climate Change Risk Assessment for the Floods and Coastal Erosion Sector. Available at: http://randd.defra.gov.uk/ [Accessed August 2017].

Scottish Government, 2004. Nature Conservation (Scotland) Act (2004). [Online]. Available at: http://www.legislation.gov.uk/asp/2004/6/contents [Accessed August 2017].

Scottish Government, 2009. Climate Change Scotland Act (2009). [Online]. Available at: http://www.legislation.gov.uk/asp/2009/12/contents [Accessed August 2017].

Scottish Government, 2014. Climate Ready Scotland: Scottish Climate Change Adaptation Programme. Scottish Government, Edinburgh. ISBN 9781784124748. Available at: http://www.gov.scot/Publications/2014/05/4669 [Accessed August 2017].

Scottish Natural Heritage. 2011. Summary of the effects of climate change on landscape and quality of life in Scotland. [Online]. Available at: http://www.snh.gov.uk/docs/B988942.pdf [Accessed August 2017].

Scottish Natural Heritage. 2015. Site Condition Monitoring. [Online]. Available at: http://www.snh.gov.uk/protecting-scotlands-nature/protected-areas/site-condition-monitoring/ [Accessed August 2017].

Scottish Natural Heritage. 2016. Climate Change and Nature in Scotland. Scottish Natural Heritage, Battleby, Perth. Available at: http://www.snh.org.uk/pdfs/publications/corporate/Climatechangenaturescotland.pdf [Accessed October 2017].

Sharples, C. 2011. Potential Climate Change Impacts on Geodiversity in the Tasmanian Wilderness World Heritage Area: A Management Response Position Paper. Resource Management and Conservation Division, Department of Primary Industries Parks Water and Environment, Hobart, *Nature Conservation Report Series* 11/04.

Stocker, T..F, Qin, D., Plattner, G-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (*Eds.*). 2013. *IPCC 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Walmsley, C.A., Smithers, R.J., Berry, P.M., Harley, M., Stevenson, M.J. & Catchpole, R. (*Eds.*). 2007. *MONARCH – Modelling Natural Resource Responses to Climate Change – a synthesis for biodiversity conservation*. UKCIP, Oxford.

Werritty, A. & Chatterton, J. 2004. *Future Flooding: Scotland. Foresight Programme, Office of Science and Technology*, London.

Werritty, A. & Sugden, D.E. 2012. Climate change and Scotland: recent trends and impacts. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **103**, 133-147.

8. APPENDIX 1 – GCR SITE AND SSSI CLIMATE CHANGE RISK-BASE ASSESSMENT SITE CODES DATA

The data used in this report relating to ESCC, WDC, 'Additional Site codes' and final Risk-based assessment ratings for GCR sites and corresponding SSSIs are contained in the separate Excel spreadsheet 'CR1014 - Appendix 1 - Site codes data'.

9. APPENDIX 2 – EARTH SCIENCE SITES IN SCOTALND ASSESSED AS BEING AT 'HIGH' RISK FROM CLIMATE CHANGE

Key to SNH areas: AOH = Argyll and Outer Hebrides, F = Forth, NINH = Northern Isles and North Highland, SH = South Highland, SS = Southern Scotland, SA = Strathclyde and Ayrshire, TG = Tayside and Grampian.

Entries in *italics* are unnoitifed GCR sites.

9.1 A1 – finite or restricted soft sediment active coastal features

5 notified features (5 GCR sites) in 5 SSSIs.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Dunnet Links	572	Coastal Geomorphology of Scotland	Dunnet Bay	227	NINH
Gruinart Flats	751	Coastal Geomorphology of Scotland	Loch Gruinart, Islay	2961	AOH
St Ninian's Tombolo	1475	Coastal Geomorphology of Scotland	St Ninian's Tombolo	1930	NINH
Tayport - Tentsmuir Coast	1523	Coastal Geomorphology of Scotland	Tentsmuir	1070	F
The Ayres of Swinister	1528	Coastal Geomorphology of Scotland	The Ayres of Swinister	1538	NINH

9.2 B3 – restricted, active soft sediment river features

3 notified features (3 GCR sites) in 3 SSSIs; and 1 unnotified GCR site.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Lower River Spey	1107	Fluvial Geomorphology of Scotland	Lower River Spey	2227	TG
River Clyde Meanders	1357	Fluvial Geomorphology of Scotland	River Clyde Meanders	2207	SS
River Feshie	1361	Fluvial Geomorphology of Scotland	Glen Feshie	2217	SH
Not in SSSI	*N/A*	*Fluvial Geomorphology of Scotland*	*Upper River Nairn and Allt Mor [also 'Allt Mor (River Nairn)']*	*2223*	*SH*

9.3 D1 – finite coastal exposed Quaternary features

9 notified features (10 GCR sites) in 9 SSSIs; and 2 unnotified GCR sites.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Fugla Ness – North Roe	661	Quaternary of Scotland	Fugla Ness	181	NINH
Muckle Head and Selwick	1207	Quaternary of Scotland	Muckle Head and Selwick	3045	NINH

Nigg Bay	1224	Quaternary of Scotland	Bay of Nigg	178	TG
Rhu Point	1348	Quaternary of Scotland	Rhu Point	381	AOH
Sel Ayre	1415	Quaternary of Scotland	Sel Ayre	2751	NINH
South Shian and Balure	1456	Quaternary of Scotland	South Shian and Balure of Shian	905	AOH
Tolsta Head	1541	Quaternary of Scotland	Tolsta Head	176	AOH
Upper Solway Flats and Marshes	1583	Quaternary of Scotland	Newbie	384	SS
			Redkirk Point	385	SS
Firth of Forth	8163	Quaternary of Scotland	Dunbar	182	F
Not in SSSI	N/A	Quaternary of Scotland	Borve	1439	AOH
		Quaternary of Scotland	North-west Coast of Lewis	1450	AOH

9.4 D3 – finite or restricted river/lake exposed Quaternary features

2 notified features (2 GCR sites) in 2 SSSIs*; and 1 unnotified GCR site.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Endrick Mouth and Islands (Portnellan - Ross Priory - Claddochside*)	610 (1309)	Quaternary of Scotland	South Loch Lomond: Portnellan, Ross Priory and Claddochside [formerly 'Portnellan-Ross Priory-Gartochraggan']	834	SA
Nith Bridge	1225	Quaternary of Scotland	Nith Bridge	368	SA
Not in SSSI	*N/A*	*Quaternary of Scotland*	*Dalcharn*	*3046*	*SH*

*The Quaternary feature in Endrick Mouth and Islands SSSI is part of the Quaternary feature in Portnellan - Ross Priory - Claddochside SSSI; however the Portnellan - Ross Priory - Claddochside SSSI extends further including parts of the Quaternary feature that are not water-exposed, so overall the feature codes as d5 and not as 'High risk' in the initial CXC assessment. However, the SSSI is included here as there are sediment sections only in the Portnellan etc. SSSI that are equally vulnerable to those in the Endick Mouth and Islands SSSI section.

9.5 D7 – Soft sediment landforms at the coast (with no water-exposed sediment element)

3 notified features (3 GCR sites) in 3 SSSIs; and 3 unnotified GCR sites.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Glenacardoch Point	728	Quaternary of Scotland	Glenacardoch Point	948	AOH
Rubha a Mhail to Uamhannan Donna Coast	1390	Quaternary of Scotland	Rubha a' Mhail to Rubha Bholsa Coast (Northern Islay)	980	AOH
West Coast of Jura	1605	Quaternary of Scotland	West Coast of Jura (Bagh Gleann Speireig - Carragh an t-Sruith)	979	AOH
Not in SSSI	*N/A*	*Quaternary of Scotland*	*Moss of Achnacree and Achnaba Landforms [also 'Achnaba - Moss of Achnacree']*	*982*	*AOH*

		Quaternary of Scotland	*Munlochy Valley [formerly 'Munlochy Bay']*	*1954*	*SH*
		Quaternary of Scotland	*Barnyards*	*1955*	*SH*

9.6 D9 – Inland soft-sediment landform sites prone to damaging slope failure

2 notified features (2 GCR sites) in 1 SSSI.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Parallel Roads of Lochaber	1272	Quaternary of Scotland	Glen Roy and the Parallel Roads of Lochaber	350	SH
		Fluvial Geomorphology of Scotland	Glen Roy	2946	SH

9.7 D11 – Active freeze-thaw features

10 notified features (8 GCR sites) in 10 SSSIs.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
An Teallach	61	Quaternary of Scotland	An Teallach	174	SH
Ben Wyvis	195	Quaternary of Scotland	Ben Wyvis	175	SH
Cairngorms	288	Quaternary of Scotland	The Cairngorms	2284	SH & TG
Eastern Cairngorms	593	Quaternary of Scotland			TG
Northern Corries, Cairngorms	1243	Quaternary of Scotland			SH
Fannich Hills	627	Quaternary of Scotland	Sgurr Mor (Fannichs)	372	SH
Hoy	798	Quaternary of Scotland	North Hoy (Ward Hill, Enegars Corrie and Dwarfie Hamars)	2741	NINH
Ronas Hill – North Roe	1370	Quaternary of Scotland	Ronas Hill	2752	NINH
Rum	1396	Quaternary of Scotland	Sron an t-Saighdeir - Ard Nev (Western Hills of Rum) [also 'Rum, Western Hills']	173	SH
Tinto Hills	1540	Quaternary of Scotland	Tinto Hills	401	SA

9.8 E2 – Bog pollen features away from the coast

13 notified features (13 GCR sites) in 13 SSSIs; and 1 unnotified GCR site.

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Abernethy Forest	9	Quaternary of Scotland	Abernethy Forest	367	SH
Allt na Feithe Sheilich	45	Quaternary of Scotland	Allt na Feithe Sheilich	924	SH
Ardmeanach	74	Quaternary of Scotland	Gribun	1936	AOH
Caenlochan	282	Quaternary of Scotland	Coire Fee	2746	TG
Din Moss and Hoselaw Loch	512	Quaternary of Scotland	Din Moss	2745	SS

Kingshouse	854	Quaternary of Scotland	Kingshouse	958	SH
Merrick Kells	1148	Quaternary of Scotland	Loch Dungeon	925	SS
Mollands	1176	Quaternary of Scotland	Mollands	1933	F
Morrone Birkwood	1190	Quaternary of Scotland	Morrone	2750	TG
Muir of Dinnet	1212	Quaternary of Scotland	Muir of Dinnet	370	TG
St Kilda	1471	Quaternary of Scotland	Gleann Mor, Hirta	1996	AOH
Tynaspirit	1575	Quaternary of Scotland	Tynaspirit	1934	F
Whitlaw Mosses	1636	Quaternary of Scotland	Beanrig Moss	2531	SS
Not in SSSI	*N/A*	*Quaternary of Scotland*	*Pulpit Hill*	*1957*	*AOH*

9.9 E3 – Peat/bog pollen features near the coast

3 notified features (3 GCR sites) in 3 SSSIs.

SSSI name	MIDAS code	Feature name	GCR site name	GCR no.	SNH area
Philorth Valley	1285	Quaternary of Scotland	Philorth Valley	1958	TG
Aith Meadows and Burn of Aith	10240	Quaternary of Scotland	Burn of Aith	1991	NINH
Quoys of Garth	1323	Quaternary of Scotland	Garths Voe	1992	NINH

9.10 F1 – Finite area or restricted, coastal-only water-exposed fossil and mineral features

7 notified features (10 GCR sites) in 5 SSSIs; and 3 unnotified GCR sites

SSSI name	MIDAS code	Feature name	GCR site name	GCR no.	SNH area
Eigg - Laig to Kildonnan	602	Jurassic-Cretaceous Reptilia	Kildonnan and Eilean Thuilm, Eigg	2851	SH
Elgol Coast	606	Mesozoic Mammalia	Loch Scavaig	777	SH
Garron Point	674	Silurian-Devonian Chordata	The Toutties	356	TG
Rosemarkie to Shandwick Coast	1376	Mesozoic Palaeobotany	Eathie Fishing Station	2350	SH
Firth of Forth	8163	Palaeozoic Palaeobotany	Oxroad Bay	365	F
			Pettycur	856	F
			Wardie Shore	1107	F
		Permian/Carboniferous Fish/Amphibia	Wardie	1370	F
			Cheese Bay	2916	F
		Arthropoda (excluding insects and trilobites)	Granton Shore	2805	F
Not in SSSI	*N/A*	*Permian/Carboniferous Fish/Amphibia*	*Inchkeith*	*172*	*F*
		Jurassic-Cretaceous-Reptilia	*Lub Score*	*3257*	*SH*
		Jurassic-Cretaceous-Reptilia	*An Corran*	*3271*	*SH*

9.11 G1 – Finite area or restricted, coastal-only igneous, metamorphic and stratigraphic water-exposed features

9 notified features (10 GCR sites) in 6 SSSIs. No unnotified GCR sites

SSSI name	MIDAS Code	Feature name	GCR site name	GCR no.	SNH area
Ardmeanach	74	Hettangian, Sinemurian, Pleinsbachian	Aird na h-Iolaire, Mull	16	AOH
Ardrossan to Saltcoats Coast	79	Carboniferous-Permian Igneous	Ardrossan to Saltcoats Coast	2076	SA
Corrie Foreshore and Limestone Mines	404	Permian Triassic (red beds)	Corrie Shore to Brodick	1524	SA
		Upper Carboniferous (Namurian (part) - Westphalian]	Corrie Foreshore	2836	SA
Girvan to Ballantrae Coast Section	690	Caradoc-Ashgill	Girvan Foreshore	1175	SA
		Ordovician Igneous	Slockenray Coast	2411	SA
Largs Coast Section	909	Non-marine Devonian	Largs Coast	1815	SA
Firth of Forth	8163	Lower Carboniferous [Dinantian - Namurian (part)]	Joppa Shore	1553	F
			Queensferry Shore	1571	F
		Upper Carboniferous (Namurian (part) - Westphalian]	Joppa Shore	2392	F

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