Part 5

Geology and geomorphology

Introduction

Compared to biodiversity and human infrastructure, the impacts of climate change on geological and geomorphological features and processes (sometimes referred to as 'geodiversity'[42]) are not as well considered. This is despite their critical role in providing the resources necessary to support human society and ecosystems.

The wide-ranging relevance of geological and geomorphological sites and processes include:

- the provision of resources (e.g. building materials, oil & gas, minerals and water);
- the parent-materials needed to form soil and cultivate food;
- scientific evidence that allows us to understand the processes that shaped and continue to shape our planet (e.g. recording evidence for past climate change and the consequences);
- cultural and aesthetic value (e.g. underpinning the landscape in which we live);
- providing the abiotic component of ecosystems.

Furthermore, a diversity of landscape features and natural geomorphological processes also provides resilience to climate change, for example, providing natural buffering to coastal and river flooding, and providing a range of microclimates and abiotic ecosystem services to support biodiversity and allow species to adapt to change.

The need to protect geological and geomorphological features and processes is widely recognised at spectacular or famous geosites (e.g. Jurassic Coast, Cheddar Gorge). However, other less prominent sites also require recognition and protection. In recent work by Scottish National Heritage, 8.8% of nationally and internationally important geosites in Scotland were found to be at high risk from climate change. The UK is a world leader in geo-conservation and has over 2000 geological Sites of Special Scientific Interest (SSSIs), seven geo-parks, two geological UNESCO World Heritage Sites, and an active and engaged community of professional and amateur geo-conservationists.

Often, it is the human response to climate change that poses the greatest risk to geodiversity, and particularly to active geomorphological features and processes. For example, hard coastal protection and river management schemes significantly disrupt natural processes and obscure geological exposures. Ironically, the resulting loss reduces our ability to model and predict future climate change as the geological record that gives us insights into these processes (e.g. peats, sediments, stalagmites, etc.) are destroyed.

This chapter examines the impacts of climate change on geological and geomorphological sites and considers appropriate approaches to managing sites in a changing climate. Where appropriate, links to case studies are given as examples. This chapter should be considered in conjunction with related biological habitats, which are intimately related to the underlying geology and to active geomorphology and soils.

In general, 'geodiversity' can be split into two broad categories, **static** and **active**:

42 Geodiversity: the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes.

Static sites - geological sites and caves

Static geological sites come in all shapes and sizes and we have split them into three sub-categories: **Extensive**, **Integrity** and **Finite**.

Extensive sites are those where the deposit is horizontally or laterally extensive behind or below the exposed site. These sites include quarries and pits, coastal cliffs and foreshores, river and stream sections, inland outcrops, exposures in underground mines and tunnels, extensive buried features, and road, rail, and canal cuttings. If damaged or destroyed, extensive features can (theoretically) be re-exposed or accessed at another location and/or destruction will simply expose a new, fresh face of the outcrop.

Integrity sites are more sensitive than extensive sites and are all geomorphological in nature. They include caves, karst and static (fossil) as well as active geomorphological sites (see section below). Here, activities in one part of the site, or indeed outside the site may adversely affect the whole site. Therefore, whole site or system management is essential to the successful conservation of integrity sites. In the case of static geomorphological sites, such as landforms created by past glaciations, the process that created the feature is no longer operating. Therefore these relict features are extremely sensitive and once destroyed are irreplaceable. Activities such as coastal protection, building and quarrying can be particularly damaging for integrity sites.

Finite sites are those with a limited lateral and horizontal extent, for example small scale features (e.g. particular mineral deposits or geological structures), fossils, some mines and tunnels, mine dumps, caves, karst (e.g. limestone pavement), static (or fossil) geomorphological features (e.g. drumlins, eskers, kettle holes), finite buried sites below ground, and sites of archaeological significance. If damaged or destroyed, finite deposits cannot be accessed or re-exposed elsewhere - they are permanently lost.

It is important to recognise that extensive, integrity and finite sites may be found together. For example, the main exposed rock beds in a quarry may be 'extensive', while other features (e.g. small scale features such as channel infills, tailings, or 'mineral dumps) can be finite. If the quarry is exploiting aggregates in a landform e.g. a glacial outwash fan, this is an integrity feature. Similarly, while coastal cliffs and foreshore may be extensive, sand dunes are integrity sites and dinosaur footprints and sea arches are considered finite. Furthermore, it is also important to recognise that the nature of a geological material will impact on how it behaves; for example, soft sediments (e.g. sand, gravel, and organic deposits such as peat) are usually more vulnerable to damage than hard rocks.

Active processes: geomorphology and soils

Geomorphology concerns physical, chemical, or biological processes that operate at or near the Earth's surface (e.g. aeolian, fluvial, glacial, periglacial, hillslope, mass movement, coastal/marine, and biological processes). Processes can be categorised as those that generate regolith by erosion and weathering, transport material, deposit material, and/or are strongly related to landforms (e.g. river meanders, kettle holes, eskers, sea arches) and sediment deposition. Their study by geomorphologists helps us to understand landscape history and dynamics.

Geomorphology is dynamic, with sites and processes evolving over a wide range of spatial and temporal scales. For example, the formation of glacial valleys occurs over millennia, while cliff retreat resulting from wave attack can sometimes be measured in metres per hour during storm events, and mass movement such as landslides and cliff collapse can occur in seconds. It is particularly important to recognise that geomorphology occurs on a landscape scale. For example, changes to the flow regime in the upper reaches of a river will impact on the river flow rate downstream, which in turn will impact on the evolution of the water course through sediment erosion, transport, and deposition, and flood plain processes. In the context of this manual, active geomorphology is considered to include the formation and evolution of soils. Active process sites are considered to be integrity sites, where a whole system approach to management is needed for effective conservation.

Potential climate change impacts

Geological sites are often perceived to be 'permanent' features, while active geomorphological processes are either seen as something to be maintained in their current form, or something that requires engineering to reduce impact on people and infrastructure. However, both environmental change and human modification pose a significant threat to our geological and geomorphological heritage and assets. In particular, the impacts of global climate change risks damaging these features irreparably, with wide ranging implications for landscape resilience, natural resource availability, and biodiversity. The table below outlines the main consequences and potential impacts of climate related change on both static and active geological and geomorphological sites, processes, features, and soils.

Cause	Consequence	Potential Impacts	
		Geological Sites and Caves	Geomorphology and Soil
Hotter summers and milder winters	■ Increased vegetation growth. ■ Decrease in freeze/thaw processes	■ Increased vegetation may damage or obscure exposures and/or limit access. ■ Reduction in damage to geological features.	■ Increased vegetation may affect natural processes. ■ Disruption to geomorphological processes (e.g. reduced sediment transport and deposition). ■ Changes to the formation and evolution of soils. ■ Loss of patterned ground development.

Cause	Consequence	Potential Impacts	
		Geological Sites and Caves	Geomorphology and Soil
Drier summers	■ More frequent droughts. ■ Increased risk of wild fire. ■ Reduced water levels in rivers, streams, lakes, and reservoirs ■ Vegetation loss. ■ Drying out of peat deposits.	■ Drying out of sediments (particularly 'soft' sediments) may increase vulnerability to erosion. ■ Exposure of previously obscured geological sites. ■ Possible collapse of poorly consolidated sedimentary exposures (e.g. sand.) ■ Erosion may expose new geological sites for extensive deposits. Finite sites may be damaged. ■ Fires may damage or re-expose geological sites. ■ Vegetation loss may increase the vulnerability of geological sites to erosion and/or re-expose new sites. ■ Drying out of peat sites may destroy fossils through oxidation and therefore damage these archives of palaeo-environmental change.	■ Sediments and soils become more vulnerable to erosion, particularly during flooding events. ■ Fires may result in vegetation loss and a subsequent increase in vulnerability to soil erosion. ■ Vegetation loss may increase vulnerability to soil erosion, in turn leading to greater sediment transport and deposition. ■ Drying out of peat sites may destroy fossils through oxidation and therefore damage these archives of palaeo-environmental change.
Wetter winters	■ Increased water levels in rivers, streams, lakes, reservoirs, caves, and ground water. ■ Waterlogging of soils and sediments.	■ Flooding may damage or obscure exposures and/or limit access. ■ Increased flow in streams and rivers may increase erosion and remove material or re-expose geological sites. Finite sites could be damaged. ■ Increase in slope instability and possible collapse of poorly consolidated sediments. Increased mass movement on coastal cliffs may remove material or re-expose geological sites. Finite sites could be damaged. ■ More frequent occurrence of sink holes. ■ Re-deposition of sediments may obscure geological sites. ■ Increased rainfall may support and protect peat deposits. ■ An increase in landslides and slope failures may re-expose and/or obscure geological sites. Finite sites could be damaged. ■ Altered hydrology in cave sites may affect the extent and distribution of flooded passages, and expose or remove cave sediments.	■ Flooding may alter the landscape by washing away soils, changing the position of river channels, and initiating the formation of new geomorphological features. ■ Increase in sediment transport and deposition. ■ Groundwater flooding may become more frequent. ■ An increase in landslides and slope failures may alter the landscape and alter natural processes. New geomorphological features such as sink holes may be created. ■ Increased rainfall may support and protect peat deposits.

Cause	Consequence	Potential Impacts	
		Geological Sites and Caves	Geomorphology and Soil
Increased frequency of extreme events	■ High winds. ■ Highly concentrated rainfall episodes. ■ Rapid freeze/thaw and/or wetting/ drying. ■ Water-logging of soils and sediments ■ Reduced landscape recovery times between events	■ Overturned tree roots may damage underlying geology. At soft sediment sites, sediments exposed beneath overturned trees may be vulnerable to increased erosion. ■ Flooding may damage finite sites or obscure exposures and/or limit access. ■ Increased flow in streams and rivers may increase erosion at geological sites leading to damage to finite sites or improvement of the exposure in extensive sites. ■ Re-deposition of sediments may reveal or obscure geological sites. ■ Erosion may expose new geological sites. ■ Impacts to outcrops may destroy or expose geological features and/or increase vulnerability to erosion. ■ An increase in landslides and slope failures may re-expose and/ or obscure geological sites or reveal new sites. Finite sites may be damaged.	■ Erosion of exposed soils. ■ Flooding may wash away soils and alter the landscape (e.g. change the position of river channels). ■ Increase in sediment transport and deposition. ■ Increased generation of new soils. ■ Increase in landslides and slope failures may alter the landscape and alter natural processes. ■ Amplification of the above consequences.
Increased atmospheric CO_2 concentration	■ Increased vegetation growth. ■ Changes in the acidity of meteoric water.	■ Increased vegetation may damage or obscure exposures and/or limit access. ■ Dissolution of karst features and caves.	■ Increased vegetation may affect natural processes. ■ Change in soil chemistry and other properties may increase vulnerability to erosion.
Global increase in temperature	■ Rising sea level. ■ Changes in wave action.	■ Foreshore lowering (where the low water mark moves inland faster than the high water mark, so that the foreshore becomes steeper and narrower) may reduce the area of exposed coastal geology. ■ Geological sites may become damaged and/or obscured. New geological sites may become exposed. ■ Reduced duration of access to geological sites at low tide. ■ Erosion and foreshore lowering may expose new geological sites. ■ Increase hazards associated with accessing coastal geological sites. ■ Erosion may expose new geological sites.	■ Geomorphological features such as spits may be damaged and/or obscured. ■ New geomorphological features such as beaches and spits may form. ■ Alteration to natural processes may change estuary processes and features and alter the landscape. ■ Increase in hazards associated with accessing coastal geomorphological sites. ■ Increased erosion may result in more landslide activity. ■ Changes in coastal processes such as sediment movement will lead to the creation and destruction of coastal landforms.

Cause	Consequence	Potential Impacts	
		Geological Sites and Caves	Geomorphology and Soil
Human responses to climate change	■ Hard engineering schemes, such as sea walls, river bank defences, flood barriers, and drainage schemes.	■ Netting and/or concrete walls used to support cliff faces may damage, obscure or reduce access to geological sites, and may also prevent erosion. ■ Altering the position of sediment deposition may obscure geological sites or reveal new sites. ■ Increased flow in engineered streams and rivers may increase erosion and damage or re-expose geological sites. ■ Flooding of alternative locations may damage or obscure exposures and/or limit access.	■ Alteration to natural processes (e.g. disruption of sediment transport along coastline, preventing flooding of rivers onto natural flood plains) may increase the severity of climate related problems in the future (e.g. more intensive flooding) and/or impact on adjacent areas (e.g. loss of neighbouring beaches).

Adaptation responses

Natural systems are dynamic and the most sustainable management approach requires an acceptance of the inevitability of change by, for example, allowing rivers to shift their course or the renewal of cliff exposures through erosion and collapse. Providing a space for natural processes to proceed (e.g. the re-creation of flood meadows in river basins) is not only practical, but has broader benefits for society (e.g. avoiding the unintended consequences of hard engineering schemes such as the redistribution of sand resulting from groyne installation). Sustainable management requires an adaptive long-term view that works with the changing landscape, focusing on conserving and ensuring a diversity of geological sites and geomorphological features and processes.

Given the global driving forces behind climate change and the scale of the impacts, preventing or completely mitigating against damage to geosites is unrealistic, and practically, socially and financially unsustainable. In particular, the engineering requirements for such an approach would be likely to inflict greater damage on the diversity of geological and geomorphological features, not only at the site in question but also within the wider landscape (e.g. further downstream of a river defence project) and should be avoided. In addition, attempting to preserve geosites in their current state is not only impractical but also counter-intuitive, as change is often the norm for geodiversity sites, which by their very nature are the products of an ever-evolving climate and environment. In fact, the impacts of climate change on geosites can often be positive and provide new opportunities, for example by exposing new features. Therefore, active conservation efforts are only encouraged for finite sites where loss or damage is inevitable, in which case a policy of rescue and/or record should be encouraged (i.e. remove key specimens, analyse, write up, and archive material and documents).

The following strategies should be considered when addressing the issue of climate change adaptation at geosites (see also Wignall *et al* (2018 a,b):

1. Identify the climate projections for the local area, specifically those variables that are likely to affect geosites, such as projected changes in rainfall, temperature and water levels.
2. Undertake an audit of geological and geomorphological features of interest. Many stakeholders are unaware of the breadth of geomorphological processes and features, soil

types and geological outcrops within an area of interest. Before conservation efforts can be considered, these should be identified and if possible mapped. Audits should be as detailed as possible, and include an assessment of relevant site characteristics, for example:

- The location and nature of geosites and features of interest on a particular site.

  Case studies:

  Geological Conservation Review (audit of nationally and internationally important geosites in Great Britain which is the evidence base for geological SSSIs);

  North Pennines Area of Outstanding Natural beauty (AONB) **Geodiversity audit and action plan**.

- The magnitude and frequency of past events (e.g. landslides, floods, changes in the position of river channels) using all available data (e.g. Ordnance Survey and other historical maps, local archives, local knowledge, comparison of Google Earth images).

  Case studies:

  Palaeo-flooding recorded in Brotherswater sediments,

  Flooding of the Feshie and Spey alluvial fan (Werritty, Hoey & Black, 2005);
  Slope instability at Giant's Causeway.

- Analysis of soil characteristics such as chemistry and structure to assess vulnerability to erosion and remobilisation, and/or the analysis of sediment/outcrop characteristics to assess vulnerability to erosion or collapse (e.g. level of water saturation, cohesion between sediment grains).

  Case study:

  Derwent Valley Mill World Heritage Site (Howard *et al* 2016).

- Record of geosites in their current state (e.g. photographs, maps, diagrams, measurement of key features, stratigraphic logs of geological exposures, sample collection from different geological units).

3. Using site categories, identify those sites, or features and areas within sites, most vulnerable to the impacts of climate change. Use a risk assessment approach to evaluate the likelihood and severity of impacts.

4. Consider mitigation and management options. For many sites there may be no practicable options to prevent and reduce the impact of climate change. At such sites, management options should focus on creating the space to allow natural features to evolve unimpeded. Where possible for extensive sites, identify new geological exposures or areas to access the geological interest in buried sites that may replace those damaged or obscured, for example, a new river-bank section formed by the change in a river's course or an outcrop obscured by vegetation that can be re-exposed. If necessary, intervene by, for example, clearing vegetation where roots are damaging geological material or where plants obscure a site, artificially protecting small-scale features (e.g. using wind breaks or drainage ditches), and, where loss is inevitable, rescue and/or record small-scale features such as fossils and archaeological remains.

   Case studies:

   Rescuing fossils on the Jurassic Coast - **The West Runton Elephant**;

   Preservation of rock-art in Northumberland (Giesen *et al* 2014)

A heavily vegetated section at Barnfield Pit (Swanscombe Skull Site SSSI and National Nature Reserve in Kent) which was re-exposed using a mechanical excavator for the European Society of Human Evolution (ESHE) visit in September 2015. The section exposes the Boyn Hill Terrace (Boyn Hill Gravel Member) deposits of the Lower Thames which were deposited during the Hoxnian Interglacial (MIS 11) approximately 400,000 years ago. (Simon Lewis/Queen Mary University of London).

5. Draw up climate change adaptation plans. Wherever possible, climate change adaptation plans for geodiversity should aim to:

- Work with natural processes and avoid 'hard' engineering solutions such as concrete cladding or thick wire netting that can damage or obscure cliffs, or beach groynes that interrupt the natural movement of sediment along the coast. Where engineering solutions are considered necessary, priority should be given to 'soft' approaches that use natural materials, and as far as possible mimic the natural environment. Examples include planting natural hedgerows as windbreaks, creating flood meadows to alleviate pressure during periods of high river flow, and restoring coastal wetlands to buffer the impacts of sea level rise.
- Be integrated with biodiversity management. Examples include keeping records that link particular species to specific geological or geomorphological environments; integrating geological and biological monitoring programmes; and promoting landscape heterogeneity.
- Engage with local stakeholders to foster a landscape-scale approach to adaptation. This is particularly important for geomorphological processes that cross boundaries and are impacted by actions carried out at distant locations, such as river flow regimes and sediment transportation at the coast.

6. Site monitoring. Where possible, implement a monitoring system to detect change, such as periodic fixed-point images. Monitoring data should be stored in an easily accessible location and format, and should be regularly analysed to identify rates and processes of change. In general, finite sites should be prioritised.

   Case studies:

   Windbreaks at North Doddington Farm,

   Preservation of rock-art in Northumberland.

Relevant Countryside Stewardship Options

Funding to support adaptation for geodiversity is available through the **Countryside Stewardship scheme**. The following options are relevant for protecting geological and geomorphological features and processes:

FM1 Management of geodiversity features

This supports positive land management schemes that aim to protect sensitive geological features from damage. This programme is only available for Sites of Special Scientific Interest (SSSIs).

HE1 Historic and archaeological features protection

Many geological features also have a historic and/or archaeological significance (e.g. mine-related features, Quaternary deposits containing archaeological artefacts). This option supports physical works that aim to conserve or protect individual historic features in the landscape.

SB3 Tree removal

One of the most common issues at geological sites is overgrowth from trees and other vegetation. This option supports the removal of trees to restore environmental features. A related option, SB6 (rhododendron control), can be used for rhododendron removal from environmental sites.

BN11 Planting new hedge

The planting of a new hedgerow can reduce soil erosion and runoff.

TE10 Coppicing bankside trees

The coppicing of trees can be used to stabilize the banks along streams and rivers, which may be de-stabilised by increased water flow from high rainfall.

RP9 Earth banks and soil bunds

Support for the construction of earth banks and soil bunds is available in areas targeted for a reduction in water pollution from agriculture or in areas targeted for flood risk reduction. These structures slow the movement of water, slow flows during high rainfall, reducing the risk of soil erosion and downstream flooding and control water levels. Related options include BN3 (earth bank creation) and BN4 (earth bank restoration).

RP10 Silt filtration dams or seepage barriers

Support for the construction of silt filtration dams or seepage barriers is available in areas targeted for a reduction in water pollution from agriculture or in areas targeted for flood risk reduction. These features slow the movement of water, thereby protecting against soil erosion and downstream flooding.

RP11 Swales

Support for swale construction is available in areas targeted for a reduction in water pollution from agriculture. However, they also help to reduce the risk of soil erosion and runoff.

Further information and advice

Advice on geological features and their conservation is available from a number of sources.

National

At the UK level, support for geodiversity action is coordinated through the **UK Geodiversity Action Plan**, the **English Geodiversity Forum**, the **Scottish Geodiversity Forum** and Geodiversity Charters in **England** and **Scotland**. Various national bodies can provide information on the extent and significance of geological and geomorphological features and can often provide advice on conservation measures. These bodies include the **British Geological Survey** (BGS) and Natural England (and its equivalent agencies in Scotland and Wales, Scottish Natural Heritage and Natural Resources Wales). Relevant resources include Natural England's **Geological conservation guide to good practice** and various freely available geological tools published by the BGS, including the **Geology of Britain viewer**; the **iGeology and mySoil** apps, **borehole records**, the archive of **geological photographs**, and the BGS **maps portal**.

Geology groups and associations

There are many geological societies, local geology groups and university departments that hold information about local geological and geomorphological features, and which may be able to offer advice on conservation measures. Examples include **Geoconservation UK**, the association of local geoconservation groups; the **Geological Society of London**: the **Geologists' Association**; the **Quaternary Research Association**; and the **Geology Trusts**, representing county-based geoconservation groups.

The River Restoration Centre

The **River Restoration Centre** provides information and advice on best practice for river restoration and catchment management. Its website includes numerous case studies covering different river processes and restoration techniques.

Relevant case studies

Cheviots flood impacts study

Commissioned by the Cheviot Futures project, a detailed study was conducted into the impacts of severe and rapid flooding within the Breamish and Till river catchments, Northumberland (Oughton, Passmore & Dilley 2009). These are geomorphologically active lowland rivers draining the impermeable bedrock of the Cheviot Hills. They are in formerly glaciated landscapes with high bed load and high channel mobility. The nationally important river and floodplain habitats are closely related to the active geomorphological processes operating. Here there has been a notable shift in approach from active management/engineering during the 1980s and 1990s, to working with the river during the 2000s and 2010s. This has been exemplified by the response to extreme rainfall events in 2008, December 2015 and January 2016, which led to flooding and channel avulsion (rapid channel shift) (see photograph below). This damaged infrastructure including powerlines and roads. The new approaches adopted include whole catchment/floodplain approaches, soft engineering and positive partnership working between landowners, government agencies, utility companies and others through the Tweed Forum and River Till restoration project. Through this, trials of innovative flood management techniques are taking place and work is being carried out to identify and adapt infrastructure at risk. To date, benefits have included improvements to habitats and improvement in the mobility of the rivers and connections with their floodplains.

Double channel avulsion on the River Coquet (River Coquet and Coquet Valley Woodlands SSSI) in Northumberland, which occurred in January 2016 as a result of extreme rainfall. © Natural England /Robert Cusson

Palaeo-flood records from Brotherswater, Cumbria

Organic sediments in Brotherswater, a temperate lake in Cumbria's Lake District, were used to investigate the frequency and magnitude of past flooding events. In particular, changes in sediment chemistry and particle size allowed for the identification of flood deposits. These palaeo-flood data were compared to local river discharges to identify detection thresholds for flood events in lake sediments.

Preservation of open-air rock art in Northumberland

This case study (Giesen *et al* 2014) is explicitly focused on rock-related archaeological sites. However, the approach could be adapted for finite geological sites at threat from environmental change (e.g. small scale fossils or structural features in a geological exposure, and karst sites).

Rock art includes the use of pictographs (paintings) or petroglyphs (engravings and carvings) on natural rock surfaces. In Northumberland, over 1200 rock-carving sites have been identified, usually on open-air isolated geological outcrops. These outcrops are threatened by environmental factors, including wind exposure, freeze/thaw cycles, air pollution, changes in vegetation cover, and changes in local soil chemistry. A study was conducted to assess a range of ambient geochemical and physical descriptors at rock panels with different levels of deterioration. Data were then used in conjunction with present and past environmental conditions to assess how rock art sites are affected by environmental change. Finally, a four-step approach to managing rock-art sites was developed: 1) collection of data on ambient conditions at a site; 2) identification of specific weathering mechanisms at work; 3) prioritisation of sites based on relative importance and state of preservation; 4) development of management strategies (e.g. reduction in wind exposure, improved site drainage, immobilization of soil salts).

Derwent Valley Mill World Heritage Site, Derbyshire

In the Derwent Valley, the changes in geomorphological processes that accompany climate change, such as changes in the flow and position of rivers and flood plains, pose a management challenge. In particular, there is a need to predict and monitor the continued release of heavy metals, originally released during historic mining activity and now trapped within soils and sediments. Increased flooding from higher rainfall and more frequent extreme weather events can remobilise these heavy metal deposits. To improve the management of this issue, an integrated approach was used to assess the spatial distribution of areas of concern. This study (Howard *et al* 2016) utilised multiple data sources (e.g. Environmental Agency, British Geological Survey, Ordnance Survey, local council archives, and the National Archives) to recreate river flood records in order to predict future events.

River Dulais bank protection

To combat bankside erosion, a soft engineering approach was utilised to stabilise a highly mobile reach of the Dulais river, Wales. Tree trunks were laid sideways and sunk into the riverbank, with the tree roots projecting out from the bank into the river flow. Tree roots deflected the flow of water, reducing erosion along the banks.

Erosion of a mine dump at Tynebottom mine
Erosion of mine spoil at Tynebottom mine by the River South Tyne (River South Tyne and Tynebottom Mine SSSI) was a cause for concern because of the loss of scientifically important mineral samples, loss of land and the potential for pollution to the river system. An engineered 'logjam' was proposed as a created 'natural' solution. Tree stumps were driven into the bank, with their roots pointing back into the river. The area behind the stumps was back-filled with large gravel and river sediments and vegetation started to accumulate in the roots (see photograph below). This approach was quite innovative and initially worked very well. Unfortunately in December 2015 the extraordinary weather conditions produced by Storm Desmond partially destroyed the 'log jam' leaving the site vulnerable again. However, the weight of water travelling down river caused the river channel to switch and erosion has now naturally lessened in the area of the mine spoil.

Engineered 'log jam' - soft engineering solution preventing erosion of the nationally important Tynebottom Mine spoil (River Tyne and Tynebottom Mine SSSI). © Natural England /Simon Stainer

Geomorphological Sensitivity Zoning at the Feshie and Spey Alluvial Fan, Scotland
To balance the needs of conservation and flood management within an alluvial fan at the confluence of the Feshie and Spey rivers, geomorphological sensitivity zoning was carried out. Assessment focused on the probability of an area becoming destabilized by floods within a given timeframe (Werritty, Hoey & Black 2005). Each area of the fan was classified as one of the following: 1) highly sensitive and dynamic where no engineering works should be attempted; 2) medium sensitivity where permitted engineering works require careful management and monitoring; or 3) low sensitivity where appropriate river engineering is permitted.

Scottish Geosites and the management of climate change impacts

Work recently undertaken by Scottish Natural Heritage has provided numerous examples of geological and geomorphological sites at risk from climate change and for each considered possible management actions. Examples include: managed re-alignment of a flood embankment at Gruinart Flats SSSI to reduce the impacts of coastal squeeze on saltmarsh; shoreline woodland conservation and/or tree planting at Endrick Mouth and Islands SSSI to protect against erosion caused by water level rise in the loch; promotion of 'natural space' and resisting of plans for river engineering along the River Clyde in order to protect natural meandering processes, and the establishment of monitoring programmes at Abernethy Forest and Tynaspirit to check for signs of drying out of bog pollen features.

Slope instability and site management implications at Giant's Causeway, Northern Ireland

The nature and rate of change associated with dynamic coastal processes at the Giant's Causeway has evolved and intensified as a result of climate change. These processes threaten to damage or destroy the unique geological outcrops at the site, and to impede access to the site along coastal paths. To ensure the continued effective management of this World Heritage Site, a mapping study was conducted to provide base-line information and establish protocols for assessing future environmental change. In particular, interactive site maps were produced using GPS and GIS. These maps are updatable, allowing site managers to conduct continuous monitoring of change.

Rescuing Fossils on the Jurassic Coast

Part of the Jurassic Coast World Heritage Site, the Undercliffs National Nature Reserve (NNR) near Lyme Regis in Dorset is well known for its foreshore 'Ammonite Pavement'. In early 2017 winter storms broke up part of the pavement, and the Natural History Museum, in collaboration with Natural England, rescued a number of the larger loosened ammonite blocks. Some are now on display locally and the remainder are at the Natural History Museum. This is part of an on-going research project looking at late Triassic - early Jurassic faunal and environmental changes. Rescuing the storm damaged blocks has provided an opportunity to examine the fossil fauna and palaeoecology at a level of detail that previously was not possible.

Rescuing the ichthyosaur in the Undercliffs NNR on the Jurassic Coast World Heritage Site in Dorset. © Richard Edmonds

Also in the Undercliffs NNR, the recent discovery of an ichthyosaur led to a spectacular rescue of the specimen. The cliff location of the ichthyosaur presented the risk of loss due to erosion and cliff fall. Given the potential importance and rarity of the fossil, Natural England gave permission for its rescue. Once removed, it was carefully conserved and then analysed at Bristol University. The specimen, which is currently on display at the Charmouth Heritage Coast Centre, was particularly well preserved (including skin preservation) and is potentially a new species.

The West Runton mammoth

Following a storm in December 1990, local residents in West Runton, on the North Norfolk coast, discovered a large bone sticking out of the cliff. They contacted Norfolk Museums Service who confirmed it was the pelvic bone of a steppe mammoth *Mammuthus trogontherii*. In January 1992 an exploratory dig was carried out, followed by a major rescue excavation in 1995. This excavation not only removed the mammoth's skeleton, but also sampled the sediments surrounding it, which contained fossils of snakes, frogs, small mammals and birds. The entire excavation took 3 months and if it had not taken place, the mammoth would have been lost to the sea in less than a decade.

The soft sediment Ice Age cliffs at West Runton SSSI, North Norfolk, where an almost complete mammoth skeleton was discovered in 1990, and rescued during a major excavation in 1995. © Natural England /Naomi Stevenson

References and further reading

Anderson, M.G. & Ferree, C.E. (2010) Conserving the stage: climate change and the geophysical underpinnings of species diversity. PLoS ONE 5(7): e11554.doi:10.1371/journal.pone.0011554

Ashwin, T., & Stuart, A .J., (1996) 'The West Runton Elephant', Current Archaeology 149, 164-168.

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

Brown, E.J., Prosser, C.D. & Stevenson, N.M. (2012) **Geodiversity, Conservation and Climate Change: Key Principles for Adaptation**, Scottish Geographical Journal, DOI:10.1080/14702541.2012.725859

Bruneau, P. M. C., J. E. Gordon, & S. Rees. (2011). Ecosystem sensitivity and responses to climate change: understanding the links between geodiversity and biodiversity at the landscape scale. JNCC Report, No. 450.

Comfort. M.D. (2014) Macquarie Island World Heritage Area Geoconservation Strategy. Nature Conservation Hobart Report Series 14/2, Resource Management and Conservation Division, Department of Primary Industries Parks Water and Environment

English Nature (2006) **Aggregates Levy Sustainability Fund (ALSF): Review 1 April 2002 - 31 March 2005 (CORP24)**, English Nature Report

Erikstad, L. (2013) **Geoheritage and geodiversity management – the questions for tomorrow**. Proceedings of the Geologists' Association, 124(4), 713–719

Giesen, M.J., Ung, A., Warke, P.A., Christgen, B., Mazel, A.D. & Graham, W.R. (2014) **Condition assessment and preservation of open-air rock art panels during environmental change**. Journal of Cultural Heritage, 15(1), 49–56

Gordon, J., Kirkbride, N., Rennie, A. & Bruneau (2008) **Climate change: why geodiversity matters**. Earth Heritage, 30, 7–10

Gordon, J.E., Crofts, R., Diaz-Martinez, E., Sik Woo, K. 2017. Enhancing the role of geoconservation in protected area management and nature conservation. Geoheritage (in press) https://doi.org/10.1007/s12371-017-0240-5

Gray, M. (2013) Geodiversity: Valuing and Conserving Abiotic Nature. Second edition. Chichester: John Wiley.

Gray J.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.

Howard, A.J. (2012) **Managing global heritage in the face of future climate change: the importance of understanding geological and geomorphological processes and hazards**. International Journal of Heritage Studies, DOI:10.1080/13527258.2012.681680

Howard, A.J., & Challis, K., Holden, J., Kincey, M. & Passmore, D.G. (2008) The impact of climate change on archaeological resources in Britain: a catchment scale assessment. Climate Change, 9, 405–422

Howard, A.J., Knight, D., Coulthard, T., Hudson-Edwards, K., Kossoff, D. & Malone, S. (2016) Assessing riverine threats to heritage assets posed by future climate change through a geomorphological approach and predictive modelling in the Derwent Valley Mills WHS, UK. Journal of Cultural Heritage, 19, 387–394

Larkin, N. The West Runton Elephant: Steppe Mammoth Mammuthus trogontherii. Norfolk Museums and Archaeology Service. 12p.

Lloyd's (2012) Geomorphology and Changing Flood Risk in the UK

Natural England (2012) Planning for climate change adaptation: North Doddington Farm. Natural England Technical Information Note TIN108

Oughton, E., Passmore, D. & Dilley, L. (2009) Cheviots Flood Impact Study, A report by the Centre for Rural Economy, Newcastle University.

Prosser, C.D., Burek, C.V., Evans, D.H., Gordon, J.E., Kirkbride, V.B., Rennie, F.A. & Walmsley, C.A. (2010) Conserving Geodiversity Sites in a Changing Climate: Management Challenges and Responses. Geoheritage, December 2010, Volume 2, Issue 3–4, pp 123–136

Prosser, C., Murphy, M. & Larwood, J. (2006) Geological conservation: a guide to good practice, English Nature

River Restoration Trust (2013) Manual of river restoration techniques

Sharples, C. (2011) Potential climate change impacts on geodiversity in the Tasmanian Wilderness World Heritage Area: A management response position paper. Nature Conservation Report Series 11/04, Resource Management and Conservation Division, Department of Primary Industries Parks Water and Environment, Hobart

Schillereff, D. N., Chiverrell, R. C., Macdonald, N., & Hooke, J. M. (2014). Flood stratigraphies in lake sediments: A review. Earth-Science Reviews, 135, 17-37.

Schillereff, D.N., Chiverrell, R.C., Macdonald, N. & Hooke, J.M. (2015) Hydrological thresholds and basin control over paleoflood records in lakes. Geology, 44(1), 43–46, 10.1130/G37261.1

Schreve, D. (2016) Chapter 4: Terrestrial Fluvial Landscapes, in White, M., Bates, M., Pope, M., Schreve, D., Scott, B., Shaw, A. &Stafford, E. (2016) Lost Landscapes of Palaeolithic Britain. Project Report. Oxford Archaeology

Smith, B.J., Pellitero Ondicol, R. & Alexander, G. (2010) Mapping Slope Instability at the Giant's Causeway and Causeway Coast World Heritage Site: Implications for Site Management. Geoheritage, 3, 253–266

United Nations Development Programme (2010) Designing Climate Change Adaptation Initiatives: A UNDP

Werritty, A., Hoey, T.B. & Black, A.R. (2005) **The geomorphology and management of a dynamic, unstable gravel-bed river: the Feshie/Spey confluence, Scotland**, in Garcia, C. & Batalla, R.J. (eds) Catchment dynamics and river processes, pp. 213–224, Elsevier, Amsterdam

Wignall, R.M.L., Gordon, J.E., Brazier, V., MacFadyen, C.C.J. & Everett, N.S. 2018a. **A qualitative risk assessment for the impacts of climate change on nationally and internationally important geoheritage sites in Scotland**. Proceedings of the Geologists' Association.

Wignall, R.M.L., Gordon, J.E., Brazier, V., MacFadyen, C.C.J. & Everett, N.S. 2018b. **A climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland including all Earth science features in Sites of Special**. Scottish Natural Heritage Research Report No. 1014.

Worboys, G.L., Lockwood, M., Kothari, A., Feary, S. & Pulsford, I. (eds) **Protected Area Governance and Management**, pp. 531–568, ANU Press, Canberra