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Authors

Gordon, John E.
Tormey, Daniel
Wignall, Rachel
[et al.](#)

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NEW PERSPECTIVES ON GEOCONSERVATION
IN PROTECTED AND CONSERVED AREAS

ROGER CROFTS, GUEST EDITOR

**Climate change will challenge the management of
geoheritage in protected and conserved areas***John E. Gordon, Daniel Tormey, Rachel Wignall,
Vanessa Brazier, and Roger Crofts***ABSTRACT**

Climate change presents challenges for the management of geoheritage in protected and conserved areas at all scales from individual geosites to whole landscapes, affecting all areas of the planet. Direct impacts will principally arise through the effects of climate changes on geomorphological processes and vegetation cover, while indirect impacts will result from hard structures engineered to mitigate risks from natural hazards. Options for mitigation and adaptation should as far as possible work with nature.

INTRODUCTION

Climate change is a natural phenomenon well documented over different time scales in geological records, but is now being significantly accelerated by anthropogenic release of greenhouse gases

(IPCC 2021). Such change is an additional stress on geoheritage interests, compounding the effects of other threats, such as urban, commercial, industrial, and infrastructure developments; mineral extraction; changes in land use; coastal protection; and river engineering for flood defenses. The IUCN World Heritage Outlook 3 identified climate change as the most common threat to natural World Heritage sites listed under criterion viii, geology (Osipova et al. 2020). Since climate change will affect types and locations of geoheritage interests in different ways, climate action plans for protected and conserved areas (PCAs) will need to consider appropriate management, mitigation, and adaptation measures

Rising sea level will increase erosion of coastal sand dunes, Outer Hebrides, Scotland, UK. © JOHN GORDON

for geoheritage in conjunction with those for biodiversity interests.

IMPLICATIONS OF CLIMATE CHANGE FOR GEOHERITAGE IN PROTECTED AND CONSERVED AREAS

According to projections by the United Nations Intergovernmental Panel on Climate Change (IPCC 2021), global mean temperatures will continue to increase over the 21st century. Under the intermediate greenhouse gas emissions scenario (remaining around current levels until the middle of the century), global mean surface temperature by the end of the present century is very likely to be 2.1°C to 3.5°C higher compared with the average for 1850–1900. On a geological time scale, global surface temperature was last sustained at such a level 3 million years ago. Global precipitation will increase, with a likelihood of more intense rainfall. There will be changes in the cryosphere as glaciers recede and permafrost thaws, deserts expand, and risk of wildfires, changes in river flow, and sediment transfer regimes increases. More frequent and intense extreme geomorphological events, such as droughts, floods and landslides, and changes in landscape disturbance regimes may be expected, with less recovery time between events. However, since such changes will not be globally uniform, projections need to be developed at national and regional scales for planning management responses, a process known as “downscaling” the global models to local conditions. For example, in the USA, downscaled climate change projections for California indicate minor change to average annual total precipitation amounts, but more intense cycles of both droughts and floods.

At the coast, sea level will continue to rise as a consequence of ice sheet melting and ocean expansion in a warmer world. For example, by 2100, under the intermediate greenhouse gas emissions scenario, global mean sea level is likely to rise by 0.44–0.76m relative to 1995–2014, but could approach 2m under a very high emissions scenario (IPCC 2021). However, rates will vary geographically according to gravitational effects, ocean circulation factors, and variations in vertical land movements arising from glacio-isostatic adjustments and tectonic factors, with effects exacerbated regionally by storm surges.

To address geoconservation challenges these changes present, PCA managers will need, first, to

assess the risk and impacts of climate change on geoheritage in their areas, and, second, to develop adaptation planning and implementation as outlined, for example, in the adaptation frameworks of Parks Canada (Nelson et al. 2020) and the US National Park Service (National Park Service 2021).

ASSESSING THE RISK AND IMPACTS OF CLIMATE CHANGE ON GEOHERITAGE IN PROTECTED AND CONSERVED AREAS

Each geosite in a PCA should be categorized according to factors that help to determine its risk from climate change. Site type (e.g., active or relict, finite or extensive) and location (e.g., quarry, river reach or foreshore) are key to identifying many likely pressures (Prosser et al. 2018; Wignall et al. 2018; Crofts et al. 2020). A key part of risk assessment is to define for each geosite feature a condition, or range of conditions, that is considered to encompass its desirable conservation state or “favorable condition” (e.g., that key rock units in an exposure should remain visible and accessible, or that a particular assemblage of landforms and geomorphological processes should continue to exist unimpeded by artificial barriers). Pressures or threats projected to put the geosite outside of its acceptable condition will trigger management intervention. In addition to scientific value, many geosites may have other values (e.g., for geotourism or supporting special habitats and species) that should be factored into management responses to climate change.

Direct impacts from climate change will principally arise through changes in geomorphological processes and in vegetation cover. Features may be lost to greater erosion or become obscured by sediment deposition, rising water levels, or increased vegetation cover. Active process features may become more or less dynamic, and processes may change entirely or cease to operate. Some features may also shift location, including migrating outside the PCA boundary. Because many changes in geomorphological processes will also impact biodiversity, climate change action plans for nature conservation require an integrated approach.

Geoheritage sites at the coast are particularly at risk from sea level rise, compounded by likely changes in the intensity and frequency of storm surges, with associated impacts on coastal erosion and flooding. Sites may undergo accelerated cliff retreat, foreshore

lowering, and possible burying of foreshore exposures by landslide debris or increased longshore sediment transfer.

River systems may become more dynamic as the magnitude and frequency of storms and rainfalls increase, resulting in more erosion, channel changes, and changes in sediment transport. There may be less recovery time between extreme events, and changes in dominant processes resulting in new patterns of erosion and deposition (Brazier et al. 2012). Increased erosion may destroy geoheritage features and change the dynamics of geomorphological processes, but may also reveal new exposures.

Changes in groundwater may affect preservation of organic deposits or increase landslide risk. In more arid climates, increased droughts, soil desiccation, and desertification may lead to increased aeolian

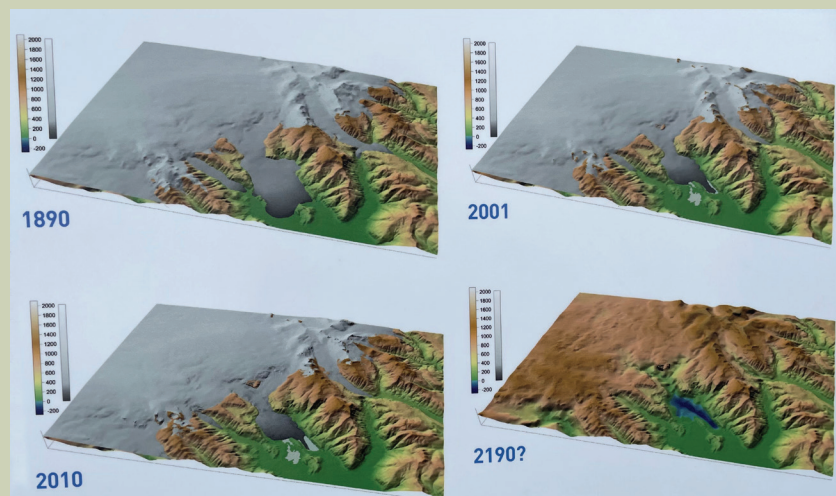
activity and sand movements that cover or erode geoheritage interests, and a higher risk of flash flooding and erosion during extreme precipitation events, which may create new features. Where droughts persist, loss of vegetation cover from increased wildfires will increase soil erosion risk.

Changes in the cryosphere are likely to result in the faster retreat and disappearance of many glaciers from the world's mountain ranges. This is already happening for example in Iceland and elsewhere (Box 1), representing a significant loss of geoheritage, as well as impacting hydrological systems downstream. Permafrost thawing is already accompanied by more rockfalls and landslides in high mountain areas, accelerated mass wasting (collapse and downslope movements of rock and soil) in the Arctic and on the Tibetan plateau, and increased coastal erosion in the Arctic (IPCC 2019).

Box 1. Vatnajökull National Park and World Heritage Site, Iceland: A natural classroom for demonstrating climate change

Vatnajökull is the largest ice cap in Europe. It is highly sensitive to changing climatic conditions and is an outstanding natural classroom demonstrating the effects of current global warming on glacier extent. The diversity of glacial landforms associated with the individual outlet glaciers is particularly well demonstrated and records not only the glacial processes but also the history of glacier responses to climate change over recent millennia. In addition, the interaction of volcanic features and glacial features offers both tourism and educational interest. This interaction takes many forms, but the largest and most devastating is the *jökulhlaup*: a sudden flood of water, caused by activation of a hot spot under the ice cap, finding its way under the ice and onto the surrounding land. Over several days, the equivalent of up to 10 times the flow of the Amazon can be released during these events, leading to distinctive sedimentary landforms, including broad outwash plains, braided river systems, and deeply incised canyons.

The Vatnajökull glaciers have been generally retreating overall since the late 19th century though with some periods of advance in the 1970s, but the rate of retreat has accelerated since 1980 (Björnsson 2017). Paradoxically, this retreat has resulted in greater geodiversity through the formation of new landforms such as moraines, fluted till surfaces, eskers and ice-cored features, and, increasingly, proglacial lakes with icebergs. These landforms provide a particularly striking demonstration of the reality of



Interpretation display showing past, present, and projected ice margins and proglacial lake extension at Hoffellsjökull, a southeastern outlet glacier of Vatnajökull ice cap. © ROGER CROFTS

climate change expressed through glacier retreat. Interpretation displays of past, present, and projected future ice-margin retreat are now provided at many sites along the southern outlet glaciers of Vatnajökull. There has been some loss of aesthetic and scenic appeal, with glacier retreat and thinning accompanied by increased supraglacial rock debris, as well as increased hazards for visitors seeking to walk on or close to the glaciers, but there are now more paths to view the sites, which are moved in the light of changing hazard assessments.

Sea level rise and increased storminess are also causing problems of coastal retreat in places, such as at Jökulsárlón, which will require re-routing of power lines and probably the main road. These changes will have an impact on the geoconservation features.

There will also be indirect impacts from human responses to increased natural hazards, with demands for coast protection and river management to mitigate erosion and flooding. In some places these actions actually may represent the greatest threat to geoheritage (Prosser et al. 2010). Where responses involve heavily engineered solutions, rock exposures may be sealed by hard protection structures along coasts or river banks, while there may be catchment- and coastal-scale changes and knock-on effects (e.g., erosion of beaches and dunes due to reduction in sediment supply from newly armored coastal sections). Changes in land use (e.g., afforestation to enhance carbon capture and offsetting, or to mitigate flooding) may affect visibility, access, and geomorphological processes through changes in sediment or water discharges into rivers and cave systems.

A further concern for managers of geoheritage in PCAs is the risk of increased geophysical hazards, particularly where sites have high value for visitors and geotourism. These hazards include rockfalls, landslides, and slope failures from thawing permafrost or increased heavy rainfall, glacial lake outburst floods, rock or ice avalanches, abrupt changes in weather, flash flooding, and higher-than-normal waves at the coast (IPCC 2019). Loss of features, such as glaciers, will also affect scenic value.

The vulnerability of a feature to climate change impacts will depend on its geographic location, including its latitude, altitude, and proximity to water bodies such as coasts and rivers that are likely to respond dynamically to climate change. Changes that cause severe damage to fragile sites, however, may have little impact on more robust ones. Erosion of a relict feature (e.g., a fossil bed) is irreversible,

and easily erodible material will make the site more fragile. Active process sites may appear more robust, with an ability to renew landforms (e.g., river gravel bars). However, they may reach a tipping point where the system changes or is left in a state of perpetual readjustment and instability, such as changes in sinuosity of a river system responding to increased sediment load from enhanced erosion upstream. Some active process features (e.g., patterned ground in periglacial areas) depend on the current climate conditions, and such process environments may become relict or disappear under warmer climates. For other features, the continued evolution of natural processes may be the key geoheritage interest, and they will tend to be more robust. Understanding landscape history and learning from past changes recorded in landforms and sediments will also help to indicate how geomorphological systems will adapt to the speed and scale of projected climate changes.

Overall, the greatest need for management responses to climate change will be at sites that are both fragile and vulnerable. In these cases, risk of degradation can be established by identifying the likely severity of damage from each identified climate change impact separately, using standard risk assessment procedures based on likelihood of occurrence and predicted severity. The resulting climate change risk rating will then indicate where the greatest management responses are likely to be needed, and the cause of greatest risk at any geosite will also be identifiable (Wignall et al. 2018).

ADAPTATION PLANNING AND IMPLEMENTATION

Adaptation to climate change requires assessment of management options and contingency planning (see Nelson et al. 2020 and National Park Service 2021 for more detailed treatments). For geoheritage,

management options range from “do nothing” to various levels of intervention depending on the particular situation (Sharples 2011; Wignall et al. 2018).

At the landscape scale (e.g., whole mountain regions or river catchments), management interventions may be impractical, ineffective, or too costly (Sharples 2011). The natural dynamics of land systems should simply be allowed to evolve under a stable or changing climate. This “do nothing” approach will be more straightforward where human activity and infrastructure are absent and there is space for the systems to adapt. Where the changes impinge on human activities, it may be necessary to create space and adapt to the consequences of more active geomorphological processes (e.g., relocating vehicle tracks, buildings, and visitor access routes or removing existing barriers). This may require extending site boundaries to accommodate mobile geomorphological systems, or establishing new PCAs to encompass the evolving relocations of features. For example, removal of barriers to coastal sediment movement may enable re-creation of new landforms and habitats by longshore extension as well as by landward migration. It may also mean accepting the loss of particular landforms due to changes in dominant processes (Brazier et al. 2012). This means “managing for change,” both in evolutionary and spatial terms, rather than attempting to temporarily preserve the existing landscape.

In other cases, where management intervention is necessary to protect vital infrastructure or unique geoheritage of limited extent, nature-based solutions or “soft” forms of intervention (e.g., beach nourishment and restoration of salt marshes, mudflats, sand dunes, and floodplain wetlands) are recommended (Crofts et al. 2020). Working with nature in this way also maintains ecosystem services and provides benefits for biodiversity and society (Brazier et al. 2012; Cohen-Shacham et al. 2016). “Fix and control” should be considered only as a last resort, especially where PCAs provide an opportunity to demonstrate what giving space for landforming processes can achieve for hazard reduction, such as using floodplains for floodwater storage. PCAs should typically allow greater scope for nature-based adaptation since available space is less likely to be restricted by essential human infrastructure than elsewhere. In undertaking any

intervention, it is essential to consider the wider geomorphological implications and connectivity. For example, changes to the management of headwater catchments can alter downvalley water flow regimes and sediment transfer, which in turn may impact fluvial geomorphology features, cave systems, and the sediment replenishment of coastal landforms.

More frequent management may be required to maintain visibility of, and access to, exposure sites. This might include targeted or small-scale vegetation or talus clearance when needed. Where small exposure sites are physically threatened, excavation of replicates may be considered where the feature of interest is extensive. In exceptional circumstances where the feature is very limited in extent, burial and re-excavation for research purposes may be an option. Where this is not possible, it may be necessary to offset the loss by recording the feature for posterity (e.g., through photographs, logging of data, or 3D scanning), and, where appropriate, rescuing features, such as fossils, for curation in museum collections. In exceptional circumstances, also, some form of hard installation may be considered as a last resort.

The indirect impacts of climate change on geoheritage resulting from human responses are a significant concern. Managing sites for visitors should be done with consideration for geoheritage features. An example would be re-routing visitor access rather than implementing rock-face stabilization measures. In the case of natural hazards where there are likely to be extreme effects, such as glacier lake outburst floods in populated valleys, engineering interventions may be essential to reduce risk. In other cases, adaptive responses that work with geomorphological processes, and are based on understanding geomorphological connectivity at a landscape scale, should be preferred. Liaison with stakeholders can help embed geoconservation in solutions for adapting to climate change, and raise awareness of good practice. However, truly adaptive responses to climate change will require changes in society’s perception of what adaptation means, and changes in negative attitudes to processes such as localized erosion and allowing floodplains to flood. As part of developing holistic adaptive management, geoconservation will also need to be integrated with wider stakeholder engagement and strategic planning (Box 2).

Box 2. Climate Change Adaptation Action Plan development: Lake Tahoe Basin, California/Nevada, USA



Enjoying the unique geodiversity of Lake Tahoe, California, USA. © CHRIS MERTENS

Lake Tahoe is the largest alpine lake in North America, the second deepest, and is second only to the Great Lakes as the largest by volume in the United States. It is prized as a geoheritage wonder for the stunning clarity of its waters and the granodiorite mountains that rim the basin. The effects of climate change, however, are accelerating changes to the hydrology and aquatic and upland ecosystems, and are profoundly altering this national treasure. The Lake Tahoe Basin has annual visitation similar to that of a national park, but over 65,000 year-round residents also live within its borders. This combination makes it an intense testing ground for California's ability to adapt to climate change, as small communities and road networks are intimately woven throughout the basin's spectacular waters, mountains, and forests.

To facilitate a basin-wide planning effort, the California Tahoe Conservancy has focused on increasing the basin's resilience and adaptive capacity to climate change. The technical foundation of the planning focuses on the linkages between the key resources in the Tahoe Basin, taking a systems-based approach in assessing its collective vulnerability and those actions that can provide multiple benefits. A systems-based approach also encourages effective adaptation management through multi-jurisdictional cooperation among agencies.

Central to the technical effort is convening a science and engineering team of local experts who have conducted research for many years in the Tahoe Basin. In addition to developing a purpose-built climate model, downscaled from the IPCC global effort to one specific to the Lake Tahoe Basin, the expert group led to a consistent, consensus-based set of predicted climate change attributes for the basin. From these, the expert group developed a vulnerability assessment quantifying resource sensitivity, adaptive capacity, and responses and implications. This assessment offers a holistic view of vulnerable areas in the basin that

may require targeted actions to improve resilience, subdivided into three systems: lake, forest, and built environments.

Using the vulnerability assessment as a base, the objectives of the Climate Change Adaptation Action Plan are to enhance the basin's resilience to climate change, including the ability of its communities, resources, assets, and landscape to withstand and adapt to climate-amplified disturbances and extreme events; to align public and private efforts to take climate change into account in planning and investment decisions; and to inform and increase the awareness of public agencies, stakeholders, and local communities on the anticipated impacts of climate change. As a mountain geoheritage area, another consideration is managing an expected influx of local "climate refugees" from the hotter valley areas of California and Nevada, leading to spiking of visitor numbers and associated stress on the resilience of the natural system.

Implementing adaptive measures will be informed by site condition monitoring at appropriate intervals and using indicators to provide evidence to trigger management interventions if required. There are many possible measurements to assess the state of geoheritage features (Crofts et al. 2020). Three broad aspects of geoheritage features that may be used as condition indicators are: physical attributes (extent, composition, and morphology), visibility, and process dynamics (Wignall et al. 2018). In the UK, there has been a formal program for monitoring and reporting the condition of geoheritage features for over 20 years, with UK country government agencies responsible (e.g., <https://www.nature.scot/professional-advice/protected-areas-and-species/protected-areas>). In Spain, a national program called Apadrina Una Roca (Adopt a Rock) utilizes volunteers to visit sites annually and report threats or incidents to the Geological Survey of Spain (<http://www.igme.es/patrimonio/ApadrinaUnaRoca.htm>). Such approaches can provide early warning of threats or significant site condition deterioration.

CONCLUSIONS

Key points to consider in adaptive management planning for geoheritage in PCAs are the nature of the geoheritage interest and site characteristics and their different vulnerabilities to climate change stressors.

Information will be required at a scale relevant to PCA managers to help implement adaptation, integrating downscaled climate projections with local geoheritage inventories and risk and vulnerability assessments.

While most geoheritage features and sites will, as far as possible, continue to require conservation as unique records of events or processes in Earth's geological history, some loss may be inevitable, and a flexible approach to the adaptive management of active geomorphological sites will be required. This will present particular challenges as the natural systems evolve and may mean accepting the loss or relocation of particular features and the emergence of new ones in some areas. It may mean that where loss is inevitable, collection of samples and geological recording are required to preserve key aspects of the geological record under threat. Adaptive planning and management that involve working with nature, and informed by learning from the past and monitoring of changes unpredictable in scale and effect, will be an essential part of integrated PCA climate action plans. Consideration will also be required of cross-boundary effects from landscape changes outside PCAs, and the interactions of geomorphological changes with other interests within PCAs, such as biodiversity and visitor attractions.

John E. Gordon, *University of St. Andrews* • **Daniel Tormey**, *Catalyst Environmental Solutions*
Rachel Wignall, *NatureScot* • **Vanessa Brazier**, *NatureScot*
Roger Crofts, *IUCN World Commission on Protected Areas, Geoheritage Specialist Group*

CORRESPONDING AUTHOR

John E. Gordon
School of Geography and Sustainable Development
University of St. Andrews
St. Andrews KY16 9AL Scotland, UK
jeg4@st-andrews.ac.uk

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On the cover of this issue

The precipitous rock spires of Meteora World Heritage Site in Greece have a complex geological history. Over the centuries a number of Eastern Orthodox monasteries were built atop them, and today's World Heritage Site recognizes this cultural history as part of the overall geoheritage. | [STATHIS FLOROS](#)