Guidelines for Cave and Karst Protection

Second Edition

Xe Bang Fai cave, Laos

Photo by Steven Bourne

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2022

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Union Internationale
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Guidelines for Cave and Karst Protection
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About UIS

The *Union Internationale de Spéléologie* (International Union of Speleology or UIS) is the international body for caving and speleology. The UIS is a non-profit, non-governmental organisation which promotes interaction between academic and technical speleologists of a wide range of nationalities to develop and coordinate international speleology in all of its scientific, technical, cultural and economic aspects. The UIS remains the principal global scientific and sporting body promoting the conservation of caves at the international level. It engages with the international Union for Conservation of Nature (IUCN). If requested, the UIS supports international speleological events, member countries' efforts to protect their caves and karst features, applications to UNESCO for World Heritage listing, applications to governments for the establishment of karst institutions and cave explorers and scientists in their efforts to raise funds for their projects. The UIS, in partnership with 57 member countries and over 250 institutions and organisations around the world, has proclaimed an International Year of Caves and Karst in 2021–22.
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About IUCN

The *International Union for Conservation of Nature* – IUCN is a membership Union uniquely composed of both government and civil society organisations. It provides public, private and non-governmental organisations with the knowledge and tools that enable human progress, economic development and nature conservation to take place together.

Created in 1948, IUCN is now the world's largest and most diverse environmental network, harnessing the knowledge, resources and reach of more than 1,400 Member organisations and some 18,000 experts. It is a leading provider of conservation data, assessments and analysis. Its broad membership enables IUCN to fill the role of incubator and trusted repository of best practices, tools and international standards.

IUCN provides a neutral space in which diverse stakeholders including governments, NGOs, scientists, businesses, local communities, indigenous peoples organisations and others can work together to forge and implement solutions to environmental challenges and achieve sustainable development.

Working with many partners and supporters, IUCN implements a large and diverse portfolio of conservation projects worldwide. Combining the latest science with the traditional knowledge of local communities, these projects work to reverse habitat loss, restore ecosystems and improve people's well-being.

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Document scope

These guidelines provide an update and expansion of the original 'Guidelines for Cave and Karst Protection', published by the International Union for Conservation of Nature – IUCN in 1997 (see Further Reading). In 2021, the International Union of Speleology (UIS) agreed to publish a second edition of the guidelines, with the IUCN subsequently agreeing to sponsor the publication. The original guidelines were primarily concerned with geoheritage, and while this remains an important consideration in the second edition, we also cover the biological issues involved in cave and karst conservation.

The protection of surface and underground karst ecosystems is particularly relevant to Goal 15 of the *UN 2030 Agenda for Sustainable Development* (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss). These guidelines also have relevance for Sustainable Development Goal 6 (Ensure availability and sustainable management of water and sanitation for all), as ~10% of the world's population gain their water supplies from karst, either from discrete springs or from karst groundwater. The new guidelines build and expand on the *Guidelines for Geoconservation in Protected and Conserved Areas*, published by IUCN in 2020, by specifically considering the protection and conservation of geodiversity, geoheritage and ecology in karst and cave areas, wherever they occur.

It is appropriate that this publication appears during the International Year of Caves and Karst (IYCK) 2021–22, which is organised by the International Union of Speleology, the worldwide organisation of cave and karst explorers, scientists, managers and educators. The three central themes of the IYCK are Explore, Understand and Protect, and whilst this publication focuses on the third of these themes, our aim is to increase understanding of the sensitivity of caves and karst. Whilst there has been a welcome increase in caves and karst knowledge since the first edition was published, they continue to be threatened by human activities around the world. In fact, there are exceptional, irreplaceable and hydrologically, ecologically, and culturally important cave and karst landscapes that are being damaged or threatened on a continuous basis.

The editors and many of the contributors of the guidelines are members of the IUCN-WCPA Caves and Karst Working Group (CKWG), which is part of the Geoheritage Specialist Group. Other members of the CKWG, members of the IUCN SSC Cave Invertebrate Specialist Group and members of the global community of karst specialists have reviewed this publication. We have provided lists of Further Reading materials, useful Internet Resources and the Scientific References used to produce this document. We hope these guidelines will make a significant contribution to knowledge of the special management considerations essential for effective protection of caves and karst. The 1997 guidelines were a 'first step' on the road and this second edition reflects our increased knowledge at a general level. The challenge now is for more national and site-specific strategies to be developed in karst areas around the world.

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The Nature of Karst Systems

Introduction: Karst, caves and their protection

Karst and caves have been silent witnesses of Earth's evolution and the rise of human civilisations. Caves and karst have retained and protected important pieces of Earth's long and tumultuous geological past. These range from ancient mineral deposits, long gone oceans and early forms of life, to unique cave adapted organisms, extinct megafauna remains and the early manifestation of human art. Without caves and karst, such information would have been largely unavailable to us. Karst and caves are among the most exquisite and valuable landscapes in our planet, with intrinsic touristic and economic value. Protecting caves and karst is vital to the preservation of our history and that of the planet. Karst and cave knowledge is essential to safeguarding a healthy coexistence between karst and our civilisation, minimising and avoiding environmental impacts that will, ultimately, be reflected upon us. The safe and sustainable use of karst and caves, and how to properly protect and manage them, is the subject of this book. We aim to convey an update of global best practice that is accessible to general readers, while providing technical details of interest to the specialist.

What is karst?

The Cares Gorge in the Picos de Europa National Park and UNESCO Biosphere Reserve, Spain is a fine example of bare surface karst in an alpine setting. Photo by David Gillieson.

The term 'karst' derives from an ancient word, *karra/gara*, meaning stone, and was first used scientifically in the present border region of Slovenia and Italy, now commonly known as 'classical karst'. This region has distinctive landforms and contains large areas of bare limestone that was – at least in part – exposed due to soil erosion following over-grazing. Subsequently, karst has been globally applied to a variety of settings, some of which have little in common with classical karst, and for many of which there is little or no bare surface rock. There have been numerous, and sometimes contradictory, definitions of karst, but a good starting point is to say that karst areas are characterised by distinctive landforms and hydrology resulting from a combination of high rock solubility and underground water movement along preferential pathways (channels). Groundwater flow through the smaller channels is laminar and cannot transport sediment. Over time, the channels are enlarged by dissolution; when large enough for turbulent flow (commonly at a void width of ~10 mm), they are known as conduits. The distinctive surface landforms in karst areas include enclosed depressions such as dolines (commonly known as sinkholes) and the larger flat-floored *polje*.

Sinking streams, dry valleys and springs are also common. The United States Environmental Protection Agency has produced a useful Lexicon of Cave and Karst Terminology (see Internet Resources).

In contrast to the Cares Gorge, most of the karst in the humid-temperate New Zealand King Country lies beneath a thick mantle of volcanic ash. Much of the native forest has been removed and replaced by pasture. Photo by John Gunn.

What is a cave?

A cave is a naturally formed void in an earth material (rock or sediment) that is large enough for human entry. This definition distinguishes caves from artificial tunnels and other constructed underground voids – sometimes incorrectly referred to as caves. The minimum void dimension is arbitrary, depending on the size of the human explorer, but a diameter of 0.3 m is a reasonable approximation. An arbitrary minimum void length of 5 m is also commonly applied, although caves shorter than 5 m may be remnants of once longer passages, most of which have been shortened by erosion. As discussed in the previous section, karst caves are formed by dissolution and are part of a spectrum of void sizes that range from around 1 mm to tens of metres. A broad distinction is commonly made between epigenic and hypogenic caves. Epigenic caves are formed where water descends from the surface under gravity and dissolves soluble rocks. In the case of carbonate rocks, dissolution is by carbonic acid formed when carbon dioxide is dissolved in water. In contrast, hypogenic caves are formed by upwards-flowing fluids that recharge the cavernous zone from lower rock units and are not dependent on locally derived surface sources of acidic water. These fluids originate either from distant sources (confined by lower-permeability strata) or from deep sources (commonly geothermal) and are independent of recharge from the overlying or immediately adjacent land surface. As a result, most hypogenic caves have little or no surface expression. A third type of karst cave forms where carbonate rocks crop out at the coast and dissolution occurs at the interface of fresh and salt water. These are termed flank margin caves.

In addition to karst caves (formed by dissolution), there are a variety of caves formed by other non-chemical agents together with constructional caves (see Appendix 1). In the marine realm, virtually every hard rock coast contains littoral caves (sea caves) that are largely formed by mechanical processes. On land, wind may contribute to cave development and subsurface mechanical erosion of sediment commonly forms pipes, some of which may achieve cave dimensions. Globally, there are many thousand volcanic caves (lava caves) that form during episodes of lava eruption, and as many of these are formed close to the surface, collapse dolines are common. Caves also form in ice under glaciers and may be entered, as at Vatnajökull National Park in Iceland. Constructional caves that form during deposition are also found in tufa and travertine, as observed at Huangguoshu in Guizhou, China.

An example of an active epigenic cave with speleothems and clastic sediments. Baradla Cave is in the Caves of Aggtelek and Slovak Karst UNESCO World Heritage Property, Hungary. The cave is also a UNESCO Biosphere Reserve and a Ramsar Site. Photo by Csaba Egri.

Protection of caves and karst

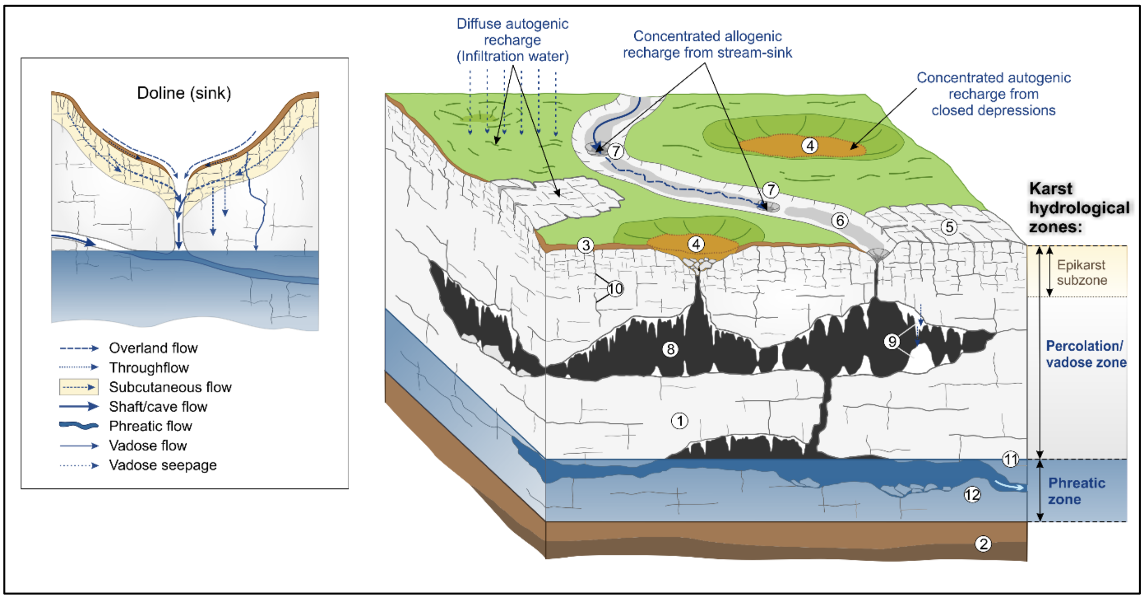
The IUCN defines a Protected Area as "a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values". They have expanded on this by setting out six management categories and four governance types (see Internet Resources). Landforms and caves are specifically mentioned under Category III, Natural monument or feature, as "areas set aside to protect a specific natural monument, which can be a landform, sea mount, marine cavern, geological feature such as a cave, or a living feature such as an ancient grove". It is expected that surface karst landforms and caves in this type of protected area would be well documented and explicitly protected. However, those caves and karst areas that are present in each of the other categories may not receive the same degree of attention particularly if they only form a small part of the overall Protected Area or the objective is to protect other features of interest. This problem occurs throughout the range of sizes and types of Protected Area. For instance, a wildlife organisation may purchase an area of land with the primary aim of managing the flora and fauna. If carbonate rocks crop out in part of the area, then there are likely to be karst landforms and caves that may not be of any direct interest to the owners. This can be seen at the international scale, where protection is offered through the four protected area designations of the United Nations Educational, Scientific and Cultural Organization (UNESCO), containing areas of carbonate or evaporite karst: Biosphere Reserves (23%), Ramsar Sites (5%), World Heritage Properties (7%) and UNESCO Global Geoparks (38%). However, these figures mask a great deal of internal variability, as some sites are almost entirely karst (e.g., the Škocjan Caves WHP in Slovenia, which is also a Ramsar Site and a Biosphere Reserve), whereas in others the majority of the site may be non-karstic, with small areas of limestone (e.g., the Tassili n'Ajjer WHP in Algeria). A further issue arises where a site that contains caves or karst is protected primarily for other features; for example, several WHP that contain caves or karst were designated as such for their cultural interest. It is important that all of the protected areas that contain karst, whether designated by IUCN or other organisations, are managed in a manner that respects the special nature of karst environments, as described in these guidelines.

Karst and rock solubility

The main group of rocks with high natural solubility are carbonates (limestone, dolomite and marble) and evaporites (salt, gypsum and anhydrite). Under certain conditions, silicate rocks are sufficiently soluble that karst surface landforms and caves may form. Caves are more common in carbonate and evaporite rocks, though there are some extensive karst areas with no caves. In England, UK, there are surface karst landforms such as dry valleys and dolines, and even some sinking streams, in areas underlain by Cretaceous and Jurassic limestones. Groundwater tracing has demonstrated rapid flow to their springs, however, there is only one hydrologically active cave system that is over 50 m in length.

Where carbonates and evaporites dip down beneath non-karstic rocks water circulation will continue, and caves may form. In Kentucky, USA, the limestone is overlain by sandstones. For much of its length, Mammoth Cave, Kentucky, the world's longest cave and a World Heritage Property, extends beneath these non-limestone cover rocks. In cases of interstratal karst, closed depressions in non-karstic rock (caprock dolines) at the surface are caused by collapse of karstified rocks at depth. Elsewhere, there may be no surface evidence of the extensive cave passage present below, with one of the best examples being Ogof Draenen, Wales, UK. Less than 15% of the 70 km of known passages are beneath areas where carbonate rocks outcrop at the surface and the remaining cave passes beneath areas that would not be considered to be karst on the basis of the surface landforms.

Epigenic caves are formed where water descends from the surface and in the case of carbonate rocks dissolution is by carbonic acid that is formed when carbon dioxide is dissolved in water; evaporite rocks do not require acid and dissolve in pure water. In contrast, hypogenic caves are formed by acidic thermal waters rising from depth. Hypogenic caves commonly have little or no surface expression. Lying beneath a landscape with few surface karst features, and only accessible via a single shaft formed by collapse, Lechuguilla Cave in Carlsbad Caverns National Park, a World Heritage Property in New Mexico USA, extends over 242 km of cave passage, with a 480 m vertical range. In some cases, hypogenic processes have formed large chambers that subsequently collapsed to form depressions that can be several hundred metres wide and deep, as observed with the *obruks* of Turkey, which pit an otherwise flat and featureless limestone plateau.



Schematic of a karst hydrological system. Diagram by Maria-Laura Tîrlă and John Gunn; inset content modified from Gunn (1985). Key: 1 – Carbonate bedrock (e.g. limestone); 2 – Impervious bedrock; 3 – Soil cover; 4 – Doline; 5 – Karren; 6 – Dry valley; 7 – Ponor (sink); 8 – Cave; 9 – Speleothems; 10 – Joints or fractures; 11 – Groundwater level; 12 – Sump (water-filled conduit).

In summary, the landforms most commonly thought of as being karst have distinctive landforms on the surface (dolines, dry valleys, karren) with caves beneath. However, there are areas with karst landforms on the surface but which lack caves, and other areas with caves at depth but which lack surface karst landforms, or which have only interstratal karst landforms.

The most obvious karst settings occur where carbonate and evaporite rocks outcrop at the surface over an extensive area (open karst), but in many areas they are covered by unconsolidated sediments accumulated during landscape evolution. These are termed mantled or covered karsts; distinguished from buried karsts where the landscape evolved but was then infilled and buried by sedimentation or younger rocks. In most cases, this burial reduces the transmission of fluids and sediment and these settings may be described as fossil karst or palaeokarst. Passages with inactive streams are sometimes called 'fossil' though this common usage is not strictly correct. These passages are simply 'relict', as in most cases they are still evolving as a consequence of percolation water inputs that feed speleothems (a general term for all mineral deposits formed in caves) or of mechanical breakdown of the passage roof or walls.

Spectacular gypsum speleothems in the Chandelier Ballroom, Lechuguilla Cave (Carlsbad Caverns World Heritage Property), New Mexico, USA. Lechuguilla is a hypogenic cave where over 200km of passage are accessed via a shaft. Photo by Rainer Straub

Some values of karst and caves

In addition to the importance of retaining examples of karst landforms and landscapes as part of a strategy to safeguard global biodiversity and geodiversity, karst areas commonly have economic, scientific and cultural values. There may be a diversity of demands that have the potential to conflict with one another.

Karst terrains contain many natural resources and provide valuable ecosystem services, such as fresh water for human consumption; aquatic ecosystems and agricultural irrigation; great biodiversity both on the surface and in the underground environment; landscapes and caves with high recreational and cultural value; and soils that provide the basis for agricultural production. Karst terrains act as natural sinks for carbon dioxide (CO_2), thus helping mitigate climate change. All these resources and ecosystem services cannot be considered as isolated as they are intensely interconnected. Because of these complex feedback mechanisms, impacts on isolated elements of the karst ecosystem can have unexpected impacts on other elements or even on the entire ecosystem.

Karst water resources have been important to humankind for thousands of years, including for human consumption, in agriculture (irrigation and aquaculture) and, over the course of the last hundred years, in the generation of hydroelectric power. As karst springs tend to be larger and more reliable than those from other rocks, so settlement patterns have been strongly influenced by these water sources. By 450 BCE, karst springs were being used for irrigation in China, while the Mayan people of Central America made extensive use of caves and *cenotes (*water-filled dolines). In 2019, it was estimated that around 10% of the world’s population, about 700 million people, gained their potable water supplies from karst, either from discrete springs or via boreholes. The largest consumer of karst water is China, with around 150 million people depending primarily on karst groundwater. The United States is the second largest, with around 50 million people, mainly in rural areas. The Edwards Aquifer, Texas, USA, supplies several million people, including large cities such as San Antonio.

Substantial infrastructure is required to transport karst groundwater from springs to users. Over 2,000 years ago eleven long aqueducts delivered spring water to the old city of Rome over distances ranging from 16 to 91 km. The largest karst water supply system in Europe is that which supplies 1.7 million citizens in Vienna, Austria, where the first of two main aqueducts was inaugurated in 1873. During the 20th and 21st centuries CE, similar major engineering works were undertaken in many karst areas, most notably in the Dinaric karsts of Croatia and Bosnia-Herzegovina, and in China. Upstream of springs, karst areas are characterised by an absence of surface water which has restricted development. In those areas where the limestones have a relatively high porosity and permeability, boreholes may provide a good supply (for example in the Cretaceous limestones in England), but in many limestones it has been estimated that there is only a 1% – 2% chance of a borehole being productive. Both industrial and agricultural pollutants can be transported rapidly through the subsurface networks of karst, making effective land use management critically important.

Karst areas continue to be used as a source of limestone for cement manufacture, with an increasing pace of urban development creating great demand for high purity limestone, and as an aggregate. Limestone is also used for agricultural lime, as a flux for iron and steel production and as a filler in the paint, plastics and pharmaceutical industries. Quarrying has the potential to destroy caves and their contents, to eliminate cave organisms and to degrade water quality, however, with careful management impacts can be minimised. The mining of saltpetre (potassium nitrate) in caves in the Americas (primarily in the USA and Brazil) was essential for the production of gunpowder during the 18th and 19th centuries CE. Thousands of caves had their nitrate rich soil content removed and the Portuguese crown even published instructions on how to regenerate the leached soil by placing it back in the caves.

The mining of cave guano deposits for fertiliser was a worldwide phenomenon. Prior to the introduction of artificial or chemical fertilisers, natural or organic fertilisers were widely used from sources such as bird and bat guano. Bird guano was mined on Pacific islands, such as Nauru and Christmas Island in the Indian Ocean, and bat guano is still mined in some caves in Texas, as a source of organic fertiliser. In Niah Cave, Borneo, cave swiftlet guano is still mined for fertiliser, as well as the more lucrative swiftlet nests on the walls. There is widespread extraction of minerals hosted by karst terrains, such as bauxite, lead-zinc, and coal in China, while in the Chapada Diamantina area, Brazil, there was extensive diamond mining inside caves in the 19th and early 20th centuries CE. Speleothems, especially stalagmites and stalactites, have also been taken illegally for sale as souvenirs.

Karst landscapes commonly have high geodiversity, with large internal topographic variation. They thus provide a greater variety of potential habitats than most non-karst landscapes and are often relatively isolated from their surroundings, such as in tower karst landscapes. Being largely protected from the elements, caves can provide unique 3D views of geological relationships that cannot otherwise be seen due to the lack of suitable outcrops or that have been obliterated by weathering at the surface or covered by soil and vegetation. Since the late 20th century CE, they have been used as easily accessible surface analogues of carbonate petroleum reservoirs. In tropical environments, they often host great biodiversity of animal and plant species, including rare and endemic species both above and below the ground. Some karsts have served as refuges for species that have persisted underground through environmental changes which have eliminated their surface-dwelling relatives or on the surface in cool damp microclimates formed by dolines and cave entrances.

Bats are probably the creatures most commonly associated with caves, but many other, often endemic vertebrate and invertebrate animals inhabit karst, some of which may have only small population numbers or are highly adapted to the constancy of the underground environment. In many, but not all karsts, environmental conditions underground can be nearly constant and cave species may have little tolerance to subsurface environmental change. In Vietnam, Delacour's langur (*Trachypithecus delacouri*), an endangered primate species, is endemic to some karst areas. In the extensive karst on the border between Vietnam and Laos, large blocks of limestone terrain are separated by rivers, which provide effective barriers to species dispersal. There are at least six species of Leaf-eating langurs (*Trachypithecus* spp.), each endemic to a specific block of limestone. Similarly, in Guangxi Province, China, habitat fragmentation separates populations of the White-headed langur (*Trachypithecus leucocephalus*). Unique underground environments may be formed by hypogene caves developed by sulphuric acid speleogenesis, which host equally exceptional communities or ecosystems, often completely isolated and which have evolved completely independent from the surface environment. The H_2S-rich Movile Cave in Romania, is home to at least 51 species, of which 34 are endemic. The Edwards Aquifer is host to more than 60 species, including highly adapted fish and salamanders, with some species known only from water wells more than 250 m deep.

The sheltered depositional environment in caves facilitates the preservation of fossil bone material and associated DNA. Animals may fall, enter in search of water, or be washed into caves where their accumulated remains provide a record of changing faunas over time. Bat colonies and owl roosts in caves contribute to the bone accumulation and provide a good sample of the smaller vertebrate fauna. The use of caves by mammals as shelters, hibernation sites or dens for young, with the inevitable death *in situ* of some individuals, allows growth series and predator-prey relationships to be studied. Clues from the depositional environment of all these remains builds a picture of long-term faunal change against climate, which can help develop tools for predicting where species can exist in light of rapid modern climate change, human expansion and habitat fragmentation. The fossil record provides the only means for assessing long-term patterns of faunal change against climate and supplying meaningful data for such predictive models.

Estimates of past climatic conditions have long held interest for the natural sciences, in that they provide some explanation for the changing patterns of distribution of plant and animal species on the planet, including our own species. Since the 1960s, there has been renewed interest in past climate reconstruction as a means of providing analogues for the atmosphere likely to result from global warming. The discipline of speleothem science has developed to provide long archives of palaeoclimate. Within caves stalagmites are built up layer by layer, often on an annual basis, and thus a longitudinal section through such a stalagmite provides a micro-stratigraphy that can span thousands to tens of thousands of years. Uranium-series dating provides an absolute chronology that can extend from up to ~650,000 years (U-Th) and several million years (U-Pb) ago. Stable isotope analyses can provide surrogates for climate variation over these timescales. Oxygen isotope records from Chinese caves have provided long-term data on changes in both the strength of the East Asian monsoon and global climate generally. The extended Chinese record covers the past 640,000 years from several sites and is one of the longest continuous climate records on the planet. Speleothem overgrowths in the Mediterranean coastal caves are exceptional detailed archives of past sea-level changes, going back in time to the Pliocene epoch. In the Amazon rainforest, carbon isotopes from stalagmites yielded crucial information about the resilience of the forest. These cave deposits are able to provide clues on future climate predictions, highly valued given the inevitable issue regarding the disappearance of heavily populated coastal terrains, due to global sea level rise.

The deposition of calcite in speleothems from dripwater provides a valuable long-term archive of changes in oxygen isotope chemistry and thus a proxy record of past climates. Photo by Csaba Egri.

Karst and caves have very high scenic and recreational values. At the end of 2021, there were 76 World Heritage Properties in forty-four countries and 68 UNESCO Global Geoparks in twenty-six countries with carbonate karst and caves. Tourism is thus a major economic activity in some karsts, including the use of both developed and undeveloped caves, and surface scenery, thereby generating local employment. The growth of cave tourism, from modest beginnings in the late 19th century CE with candle lanterns until today, when LED lights and electric trains are employed, has drastically expanded both the use and the range of impacts on caves. There are approximately 1,600 show (tourist) caves worldwide with some receiving several hundred thousand visitors each year, for instance Mammoth Cave World Heritage Property, USA receiving 500,000 visitors, and Postojna Cave, Slovenia receiving over one million. These statistics probably underestimate the number of show caves in China, where there may be more than 300 open to the public. In 2019, there were 150 million visitors to show caves, and as many as 70,000 people may be employed globally in cave tourism. Remote appreciation is also possible by means of online sites with interpretation, videos and photographs, the production of which can be a significant component of some local economies. Such media reinforce the value of caves and karst for tourism and as environments needing care.

Caves have always been used as shelters, as living spaces, and as refuges in times of conflict. They are used as shrines or temples – as sacred spaces that engender feelings of awe and veneration, and facilitate religious observances by being places set apart from daily living. Caves are often regarded as ambiguous spaces, offering both protection and shelter, but can also trap and imprison people. In many cultures, a location within the earth is identified as female, and caves have been identified as representing the womb of Mother Earth and are associated with birth and regeneration. There are myths about people who enter caves and become trapped, only to be released after some ordeal. Although sacredness may be invested in many other natural forms and objects, such as trees, springs and mountains, the earliest known sacred places in prehistory were in naturally-formed caves, such as those in the Dordogne valley of France. Thai Buddhist monks seek out caves as quiet refuges in which to practice meditation. If the monk becomes a famous meditation master, then his followers may develop the cave into a more ornate shrine in his memory.

Natural caves have long been a focus of veneration and appear frequently in both mythological and religious stories. The philosopher Porphyry (234–305 CE) held that before there were temples, all religious rites took place in caves. He argued that the architecture of temples emulated the darkness and single entry of most caves, and that the penetration of light into a cave at certain times of the year had ritual significance. A sacred cave may also contain a sacred spring thought to possess special healing or divinatory properties.

In Catholic countries such as Brazil, shrines and even entire churches inside caves represent popular pilgrimage sites, with the large cave of Bom Jesus da Lapa containing two churches that have been sites of worship since the late 1600s and are visited each year by over one million people. Lourdes Cave, France, is recognised by the Roman Catholic church as the site of an appearance by the Virgin Mary in 1858, receiving millions of tourists each year, many in search of healing or spiritual growth.

Caves and karst have very high scenic and recreational values. Two speleologists explore a pristine subterranean lake in Krizna Jama, Slovenia. Photo by Csaba Egri.

There are many cave temples in south-east Asia, both because they are convenient cavities close to towns and because they have an air of mystery with hidden chambers. Many caves in Thailand, Laos and some in China contain Buddhist shrines, with several Taoist and Buddhist temples in caves near Ipoh in northern Malaysia, while in India and Malaysia many caves are used as Hindu temples. The best-known cave temple is in the Batu Caves complex outside Kuala Lumpur (Malaysia), which serves as the focus of the Hindu community's annual Thaipusam festival. It has become a pilgrimage site not only for Malaysian Hindus, but also for Hindus from other countries including India, Australia and Singapore. On the Japanese island of Okinawa, several Shinto shrines are located in cave entrances.

Buddhist cave shrine, Nam Ou River, Laos. Photo by David Gillieson

The criteria used to evaluate the significance of an individual cave may therefore include:

- *geological considerations* – such as specific features that relate to structure, stratigraphy, palaeontology or mineralogy.
- *geomorphological considerations* – such as passage morphology, clastic sediment sequences and speleothems, particularly where they provide evidence of past surface environments.
- *hydrological considerations* – such as the presence of major underground streams or lakes, underground breaches of surface drainage divides, or key elements in understanding the conduit network.
- *biological considerations* – relating to species richness, the presence of rare and endangered species, unusual trophic structures or key bat maternity sites.
- *archaeological and cultural considerations* – such as the presence of deep, well stratified deposits, the cave's role in regional prehistory evolution, examples of historic cave use, such as mining or water management, or its spiritual and religious significance.
- *geographical considerations* – remoteness and wilderness values, proximity to park infrastructure, such as roads and camping grounds, recreational opportunities and accessibility from major population centres.

Auler et al. (2018) have provided one approach to the prioritisation of caves for environmental protection by rigorously assessing the levels of significance. They used 70 parameters covering the above considerations across a sample of 401 caves, which they analysed statistically. Their results indicated that biotic parameters, along with broad dimensions of length and area, were the most useful. This approach could be adapted and refined for other karst areas given an availability of relevant data.

Guidelines

(1) Effective planning for karst regions demands a full appreciation of all their economic, scientific and human values, within the local cultural and political context.

(2) Managers should recognise that in karst catchments, surface actions result in direct or indirect impacts underground or further downstream.

(3) A good understanding of cave characteristics and their unique values is essential to the improved management of any karst area.

The special nature of karst environments and cave systems

Soluble rock and the development of underground drainage through conduits, which integrate surface and subterranean processes, give rise to the complexity and many of the special features of karst landscapes. This high level of connectivity means that any change or impact at the surface is rapidly transferred underground to affect the cave environment and its dependent terrestrial and aquatic life.

Surface environments on karst can be harsh. Karst environments are periodically arid on the surface, even in humid climates, because rainwater quickly drains underground. Unless the bedrock is overlain by superficial deposits, karst surfaces tend to be rocky, with shallow and patchy soils. The amount of soluble minerals, such as calcite and dolomite, in carbonate bedrock is often as high as 90% – 99%. Accordingly, the total content of insoluble minerals, which lead to the formation of soil, is only 1% – 10%. Thus, the vegetation found on carbonate karst tends to be adapted to rocky soils, high calcium (alkalinity) and dry conditions. The exception to this is where the soluble rocks have been overlain by externally derived (allogenic) superficial deposits such as glacial till (in the northern United States), loess (in the English Peak District) or volcanic ash (in the New Zealand King Country karst). In tropical areas, soil covered karst is more common under rainforest or savannah vegetation and may have significant soil mantles derived from volcanic ash.

Surface ecosystems in karst are often quite different from adjacent landscapes in terms of topography, geomorphology, hydrology, soils and vegetation. Karst landscapes, with their rugged topography and harsh environmental conditions, offer a greater variety of different habitats than non-karst landscapes. Therefore, they foster a greater biodiversity of plants and animals, including rare and endemic species. In Laos, there are 21 known species of caperbush (*Capparis* spp. L.), with most being endemic to a single karst site. Similarly, about 90 species of bent-toed gecko (*Cyrtodactylus* spp.) are endemic to karst sites across their range, from India, throughout south-east Asia, to Melanesia.

Subterranean environments in karst are distinctive and more fully developed than in non-karstic rocks. All rock types permit some degree of groundwater movement as fracture flow, but it is only in karst rocks that dissolution by water enlarges the fractures to form conduits, or caves, that route much or all of the surface drainage underground. Caves in carbonate rocks are generally larger, longer and deeper than caves in other rock types, such as sandstone (quartzite), conglomerate, lava or evaporites. Deer Cave, Sarawak, and Hang Son Doong Cave, Vietnam, are amongst the world’s largest caves in terms of sustained passage size, while Mammoth Cave, USA, is the longest cave, and Veryovkina Cave, Georgia, is the deepest (all as of January 2022).

In addition to caves of explorable dimensions, there is a little surveyed, but likely extensive, subterranean habitat within karst of conduits with a diameter of less than 0.3 m, thus inaccessible to humans. This is the mesocavern habitat. Although it has received little study to date, it is thought likely of great significance to subterranean biota, and in some karst terrains may harbour the population bulk of many species described as 'cave fauna'. Above the water table, air-filled mesocavern habitats are likely to experience more stable microclimates than larger diameter caves and may therefore provide cave fauna with more optimal conditions. Most general discussion of anthropogenic impacts or the mitigation of impacts on 'cave' habitats or stygofauna may be assumed to affect such smaller-diameter conduits and their fauna.

Some caves are largely relict, receiving only percolation water from the surface, while others are active, with water and sediment inputs from surface streams, including some periodic flooding. The absence of sunlight for primary production means that most organic material for the cave food web must come from the surface environment. Some cave ecosystems rely on geochemical energy sources, however, such as sulphide oxidation.

The most obvious features of the cave environment are the reduced to generally absent light levels and a near-constant temperature regime away from entrances. Life in total darkness requires that other senses – principally those of touch and smell – become dominant. Thus, fully cave-adapted fauna have greatly enlarged antennae or elongated appendages, as well as specialised organs to detect vibration. Eyes may be greatly reduced in size or even absent. These features are termed troglomorphy, and terrestrial animals of this kind are termed troglobionts, while their aquatic counterparts are termed stygobionts.

Subterranean fauna have been classified according to the position and duration of their dwelling in caves as troglo- or stygobites (obligate cave dwellers), -philes (facultative cave dwellers), and -xenes (cave visitors). Blind cave fish provide a good example of a cave-adapted stygobiont. However, there are exceptions to this and there are obligate cave dwelling animals that show little or no adaptation to the dark.

Subterranean fauna, and particularly stygofauna, can be found in non-karst environments, but caves and karst groundwater systems offer a greater diversity of habitats and larger voids. Therefore, the subterranean fauna of karst generally has a higher biodiversity than in non-karst subterranean environments. Subterranean communities are often characterised by a high number of rare and endemic species, because of their high degree of isolation. Unable to leave their underground habitats, troglobites are thus often restricted to a single karst area or cave system.

Karst drainage areas are not easily delimited. The drainage basins and routes followed by karst water are not obvious, because drainage paths are largely subterranean and groundwater basins commonly do not follow surface divides. Furthermore, groundwater divides in karst are best considered as zones, because their plan position can shift between high and low water conditions. Much of the water passing through karst is introduced by sinking streams. If these streams originate on impervious rocks that lie beyond the boundary of the karst area, they are termed allogenic streams, as opposed to autogenic streams (or water) derived entirely from karst rocks.

Karst ecosystems are fragile because environmental conditions can be extreme, and because the high degree of interconnectivity in karst ecosystems means that direct impacts on a single element of the karst ecosystem can have serious indirect consequences for other elements or the entire karst ecosystem. These conditions result in many karst ecosystems having low resilience, meaning they have a low capacity to respond to disturbances by resisting damage or recovering afterwards. Karst groundwaters are particularly vulnerable to contamination due to their hydrogeological structure, such that contaminants can easily enter through thin soils and the epikarst, via dolines or sinking streams. The term 'epikarst' refers to the upper few metres of bedrock in which most dissolution takes place and which, therefore, has more voids than deeper rock. Once underground, water moves much more rapidly in conduits (kilometres per day) than in most non-karst groundwaters (metres per year), so contaminants can spread over large distances and impact subterranean species and ecosystems. Pollutants may become trapped in karst aquifers and then be released over time at springs.

Soils on karst are often fragile and vulnerable to essentially irreversible erosion, at least on a human time scale. The removal or degradation of vegetation (e.g., by logging, livestock grazing or crop agriculture) can cause severe soil erosion and lead to 'rocky desertification', a major environmental problem in the Dinaric Karst of Europe and the South China Karst. Degradation of natural vegetation and soil erosion are interrelated, (i.e., vegetation degradation can cause erosion and *vice versa*). Soil erosion and vegetation degradation can result in habitat loss and thus a decline in surface karst ecosystem biodiversity. Soil erosion and the associated decline of vegetation and biological activity reduces the efficiency of karst landscapes or act as a natural sink for atmospheric CO_2. Karst dissolution constitutes up to 29.4% of the terrestrial CO_2 sink or 10.4% of total anthropogenic CO_2 emissions.

Safeguarding natural processes, especially the hydrological system, is fundamental to the protection and management of karst landscapes. This implies the need for an holistic approach, with careful management of the vegetation and soils of entire water catchment areas, for groundwater protection and biodiversity preservation. The need for total catchment management is more vital for karst landscapes than in many other lithologies. Water quality management of allogenic streams draining into karst and the protection of dolines that provide point-recharge are the major issues in the management of all karst areas.

There are now relatively few places where the opportunity exists to safeguard truly pristine karst landscapes. In addition to preserving and maintaining such sites, the focus must be placed on correcting the negative impacts of past and present management, including the restoration of natural vegetation and faunal habitat in degraded karst landscapes. These types of improvements can help restore natural karst processes.

Guidelines

(4) Safeguarding natural processes, especially the hydrological system, is fundamental to the protection and management of karst landscapes.

(5) Pre-eminent amongst karst processes is the cascade of carbon dioxide (CO_2) from low concentrations in the external atmosphere through greatly enhanced concentrations in the soil atmosphere to reduced concentrations in cave passages. Elevated soil carbon dioxide concentrations are a result of plant root respiration, microbial activity and healthy soil invertebrate fauna. This cascade must be maintained for the effective operation of karst solution processes.

(6) The need for total catchment management is more vital for karst landscapes than many other lithologies.

(7) There are now relatively few pristine karst landscapes and those that remain must be preserved and maintained as a high priority. Elsewhere, the focus must be on the correction of any negative impacts from past and present management practices.

Scales of management in karst areas

There is a growing realisation that management prescriptions need to take account of the natural and imposed variations in the structure and function of karst systems. A single management prescription applied to a complex karst hydrological system (or complex integrated cave system) is unlikely to adequately protect ongoing geomorphological and ecological processes in different parts of the system, and therefore management planning must take account of scale factors in the karst system. Even in arid karst areas, there may be a strong gradient in microclimate and energy sources extending into a cave system from the entrance. Therefore, management prescriptions must take account of natural variations in the ecology of caves.

For a non-karstic catchment, where water flows are predominantly on the surface, the river continuum concept argues that a river's biological and chemical processes are intimately related to its physical attributes, most notably water temperature, flow regime and sediment transport. Thus, biological communities change predictably in a downstream direction, just as the river itself does. This implies that biological communities adapt to the particular conditions of a short section of stream, or 'stream reach', where there are similar geomorphological and ecological conditions.

For such a catchment, we could conceptualise the spatial scales of management as:

*Whole catchment > sub-catchment (defined by stream order, lithology) > **stream reach** (similar gradient, substrate, flow regime) according to the river continuum concept.*

However, for a karst catchment our conceptualisation would be:

*Contributing non-karst catchment > karst catchment > karst sub-catchments > **cave passage** (various types of connectivity and energy levels) > spring.*

Food and energy accession from external sources becomes critical to the survival of viable populations of the organisms comprising cave ecology. The principal external source is organic debris washed into the cave by running water, either as percolation or as discrete cave streams. This material may be fine humus, readily utilised by cave biota, or coarser debris (twigs, leaves, and branches), which must first be broken down by bacteria and fungi in order to be useable. The cave is thus equivalent to the upper reaches of a surface stream. Sites within a rarely flooded cave may, therefore, be expected to be depauperate in fauna, while sites along main streams with a direct external connection may be quite rich in species and have a high total number of organisms. Though these species and organisms may be washed out by large floods, populations can recolonise from the rock crevices or meso-cavities. Another significant source of external material is from air-fall processes below dolines, shafts or fracture systems open to the surface. This is especially important for higher-level dry passages remote from water sources or for caves in dry climates. Tree root penetration into cave passages provides a very important energy source in most tropical and some temperate caves. Bats and birds can be an important external energy source, in the form of guano and cadavers, and in some ecosystems will be the major or only source of energy.

The frequency and magnitude of energy inputs into the cave ecosystem become very important for the maintenance of populations of organisms. In cold climate areas with water movement restricted to the spring thaw, biological activity is phased to follow the major influx of water and organic matter, while at other times may be largely dormant. In areas with strongly seasonal precipitation, organisms may have to adapt to survive desiccation for up to six months; perhaps longer if the climatic variability is high. Cave fauna in tropical areas is less restricted and may be active throughout the year, though reproduction may be phased such as to reduce resource competition. It is important to recognise that species richness associated with organic matter does not always reflect a richness of troglobitic fauna where the organic matter is present. Troglobites occur most often in food-poor cave areas and are less frequently found in tropical caves where organic material is more widely dispersed. Major changes to the magnitude and frequency of water inputs may have serious consequences for cave biology, and are common in rural areas where karst water is diverted or over-utilised, or if surface changes such as vegetation clearance alter percolation water quantity and quality.

The cave passage or conduit becomes the equivalent of the stream reach, as well as the fundamental unit of management. A passage with a flowing stream will have to be managed differently from a higher-level passage which rarely, if ever, has flowing water in it. The connectivity of these different types of passage becomes very important for understanding the flows of mass and energy in any cave system. Cave passages that are relict, are of hypogene origin or in palaeokarst have low or zero connectivity and have little or no capacity for recovery after a disturbance. Passages that flood periodically have some capacity for recovery, depending on the disturbance frequency. Active stream passages with a significant flux of sediments, organic carbon and some particulates may cope with disturbance and support resilient ecosystems.

There may be water filled cavities at depth in karst which have a hypogene origin (formed by ascending groundwater). In the Edwards Aquifer, Texas, there are many locations in the aquifer that may be more than 1,000 m below the water table and have always been waterfilled. With the greatest known number of aquifer-adapted species, they have unique fauna not derived from surface inputs. They are susceptible to water well extraction, and to the potential impacts of poorly maintained and abandoned water wells. More than sixty other aquatic species are only known from flowing artesian wells, including two blind catfish.

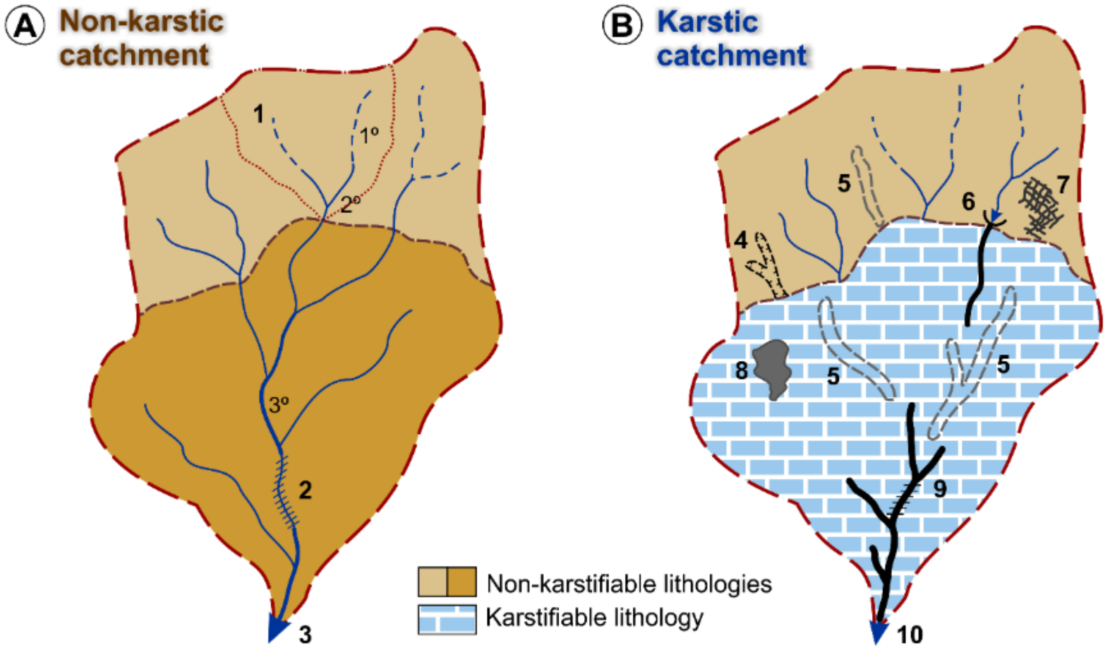
An individual karst hydrological system (or cave system) may contain several components or types of passage, from active stream passages to inactive, higher-level ones, as well as poorly connected relict passages. Each requires a different management prescription, but should be integrated at a catchment or sub-catchment level where considerations of flow paths, energy sources, disturbance types and regimes, and mitigating strategies can be enunciated. At the broadest level of the whole contributing catchment, both karst and non-karst components should be evaluated in terms of flows of matter and energy, and likely disturbance and/or pollution sources.

Scheme of connectivity and energy levels for components of karst systems

Karst system component	**Connectivity with the surface**	**Energy levels and flux**
Active stream sink	High	High, regular flooding bringing coarse woody debris, particulates and dissolved organic carbon (DOC)
Other source of concentrated recharge, primarily closed depressions	High	High, water volumes are commonly lower than those of sinking streams but transport vegetal debris, particulates and DOC
Active stream passage	High	High, regular flooding bringing some particulates and DOC
Spring	High	High, regular outputs of DOC and common particulates
Inactive stream passage (higher level)	Medium	Medium, periodic flooding bringing dissolved organic carbon
Relict cave (ancient stream passage)	Medium	Percolation water brings in DOC in humid areas; carbon flux is limited in drier areas with limited percolation. Guano may be significant
Meso-cavities or shallow subterranean habitats	Medium	Connectivity with stream passages, important refuge
Hypogene cave	Low	Sulphur and Iron based ecosystems, localised carbon flux
Palaeokarst	Low	Very low, flux absent

One method of achieving this management scaling is through the use of spatial models. The Karst Disturbance Index, first developed by van Beynen and Townsend (2005), is a method for evaluating human impacts on karst landscapes. It employs five categories of environmental indices – geomorphology, hydrology, atmosphere, biota and cultural – from which levels or ranges of disturbance can be defined. In principle, the indicators in each category have to be inexpensive to obtain, easily reproducible, and responsive to changes in environmental condition. Data sources have included field surveys, spatial data, topographic maps, aerial photography, and expert opinions from local cavers and government officials. Scoring of indicators can be either semi-quantitative (ranked data, categorised areas or percentage cover) or qualitative (type of settlement or type of cave development). An indicator can be discarded if not relevant to the area concerned. The Total Disturbance Index is calculated by taking the sum all obtained scores and dividing by the total possible maximum score, to produce a fraction. The advantage of an index is that stakeholders can examine each indicator and see how it was derived, while the overall state of the karst environment is reduced to an easily comparable category for environmental managers and policymakers.

Karst hydrological systems are particularly vulnerable to contamination because of the rapid connections between the surface and aquifer. Intrinsic vulnerability is determined by properties of the karst environment that influence the degree of vulnerability. These relate to the 'plumbing' of the karst in terms of soil thickness and infiltration rates, the fracture density of the epikarst zone, the distribution of dolines and the variations in hydraulic conductivity. In combination, these determine the potential vulnerability, while adding land use and infrastructure (roads, water supply, landfills or point pollution sources) creates the specific vulnerability. These approaches to assessing vulnerability are spatially integrated in groundwater vulnerability models (GVM), which aim to quantify aquifer vulnerability to human-induced contamination. One of the more well-accepted GVMs, EPIK has been specifically designed for karst aquifers. Any user of GVM needs to have confidence in the validity of the input parameters being used, as some are very hard to quantify.



Comparison of the spatial organisation of non-karst and karst catchments. Key: 1 – sub-catchment; 2 – stream reach; 3 – drainage basin outlet; 4 – unroofed cave; 5 – relict cave; 6 – active sink; 7 – hypogene cave; 8 – palaeokarst; 9 – cave passage; 10 – karst spring. Diagram by Maria-Laura Tîrlă.

Guidelines

(8) *A single management prescription applied to a complex karst hydrological system (or complex integrated cave system) is unlikely to adequately protect ongoing geomorphological and ecological processes across different parts of the system. Management planning must therefore take account of scale factors in the karst system.*

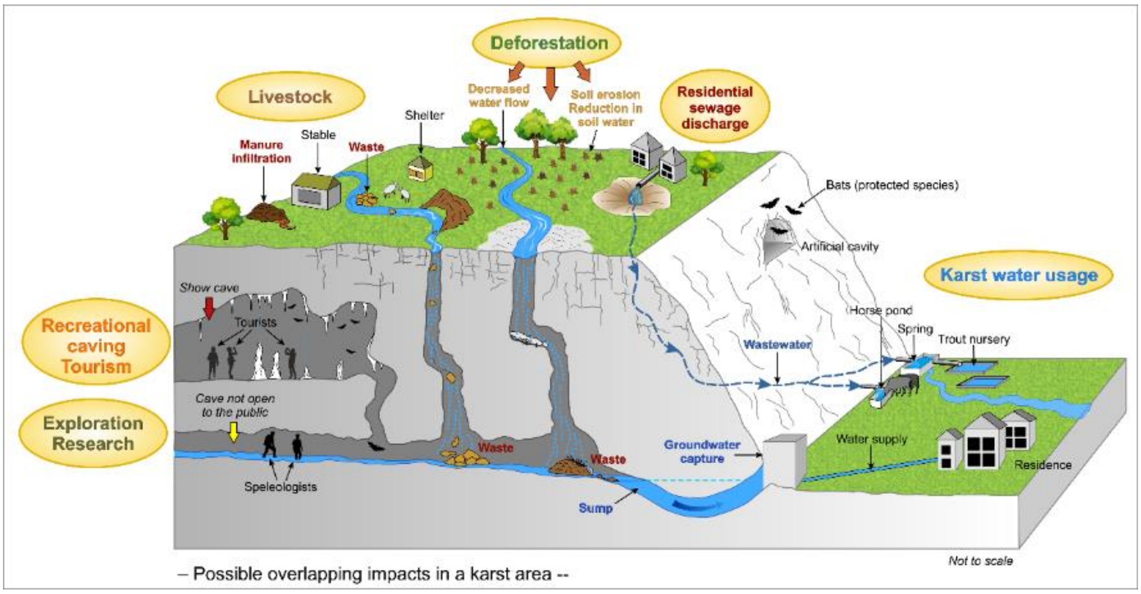
(9) *The biology of most caves is largely dependent on food sources brought in from the surface environment. The accession of food and energy from external sources is critical to the survival of viable populations of organisms, and the frequency and magnitude of energy inputs into the cave ecosystem is essential to the maintenance of organism populations.*

(10) An individual karst hydrological system (or cave system) may contain several components or types of passage, from active stream passages to inactive, higher-level ones, as well as poorly connected relict passages. Each will require a different management prescription.

(11) Within a karst area, some sections may be highly sensitive to groundwater contaminants, while other areas may be less sensitive. Comprehensive land-use planning is therefore needed to protect karst groundwater resources.

A highly active section of cave passage that experiences regular flooding in Škocjanske Jame, Slovenia. The river Reka which flows through the cave can rise by over 50m, reaching the level of the tourist path which is seen in the top left corner. Škocjanske Jame is a Ramsar Site that lies within the Škocjan Caves World Heritage Property and The Karst UNESCO Biosphere Reserve. Photo by Csaba Egri.

Human Activities on Karst: Impacts and Mitigation



Some of the impacts from human activities on a karst area. Diagram by Maria-Laura Tîrlă and Bogdan Bădescu.

Recreational and adventure caving

Introduction

Humans have visited caves since the origins of our species, as evidenced by the art and artefacts left behind. Entrances were most widely used as they provided good shelter but there were also visits into the dark zone beyond the entrance, most probably for ritual purposes or in search of water, as was done by the Maya in Central America. Although humans have continued to live in the entrance areas of caves through to the present day, this early phase was followed by one in which caves became subjects of myths and were commonly feared as the home of imagined monsters and evil spirits or provided gateways to Hell. In Europe, this period dominated by ignorance and superstition continued to the 16th century CE, which was a time of travel, investigation and the beginning of the natural sciences, at least for those who had sufficient wealth and resources for these pursuits.

Historic cave visits for investigative purposes were mainly documented in Europe, but also took place in China, where Xu Xiake (1587–1641 CE) was that region's first karst scientist and speleologist. Gradually, people began to see the underworld as a place to be explored and enjoyed rather than a place to be feared. Caves were initially studied by scientists such as archaeologists, biologists, geologists and geographers who primarily worked outside caves. By the 19th century CE, some individuals began to focus primarily on caves and to refer to themselves as speleologists. Around the same time there was a growth in 'exploration', with visits to 'foreign lands', mountain ascents and, inevitably, cave descents. In the 21st century CE, there remain few readily accessible places on earth that have not received a visit from humans, and few mountains that remain unclimbed, but every year cavers explore and survey many tens of kilometres of previously un-entered caves. Behind the first explorers came others whose visits were purely for recreation and pleasure, which was the case for caves as for much of the earth's surface. There is a saying, reputedly from the 15th century CE; "No sooner does one man find a way of enjoying himself than another finds a way to make money from it", and an industry has grown in which guides offer their services to those who wish to take part in outdoor (including underground) adventures. The oldest known show cave in the world is believed to be the Reed Flute Cave in China, which contains inscriptions from 792 CE, in the time of the Tang Dynasty. The first recorded cave tour in Europe was at Postojna Cave, Slovenia in 1213 CE. Vilenica Cave, also in Slovenia, has collected entrance fees from visitors since 1633 CE.

With this history in mind, in the 21st century CE, we can identify several broad groups of individuals who enter caves:

- the general public either visiting show caves or visiting for religious purposes.
- speleologists engaged in cave exploration and documentation.
- recreational cavers (free access).
- adventure cavers (instructor-led) trips.
- scientists who undertake underground research or use material from caves in their research.
- 'incidental' users of caves for whom the cave is not the primary purpose of their visit, for example those who take part in running events that include a section of cave passage.

Show caves and caves that are used for religious purposes generally have artificial lighting and walkways making them suitable for visitation by any member of the public who is sufficiently mobile, with some going further and providing disabled access. In contrast, those on adventure, recreational and exploratory caving visits usually wear a helmet-mounted individual light source and have varying amounts of protective clothing and equipment. Recreational caving involves visits to sites that have already been explored and surveyed, while cave explorers aim to gain access to previously unknown passages and to survey and document their discoveries. This may be achieved in various means, including mounting an expedition to an area previously unexplored, removing blockages at the end of known passages, internal climbing or diving. These categories of cave users may be useful in examining impacts and management needs. It should be recognised that an individual person may partake in more than one of the activities. For example, a caver may spend part of their time in exploration but also enjoy recreational caving visits, as well as taking part in (or be involved in leading) adventure caving trips, and are likely to enjoy visits to show caves.

From a management viewpoint, any karst area is likely to have several cave use types. First will be show caves and caves of religious significance. Secondly will be adventure caving sites, many of which will have received some degree of modification to enhance visitor safety. Lastly, the bulk of sites are those reserved for recreational caving and exploration. Show caves of religious significance are considered elsewhere, so this section focuses on adventure caving, recreational caving and exploration. For many undeveloped caves or 'wild caves', the activity of caving is the most immediate risk factor to be considered when addressing their conservation, especially where protected area status provides for sympathetic catchment management.

Cave exploration and documentation

In contrast to other landforms, the extent of documented cave passage grows by many kilometres every year as a result of the efforts of cave explorers. These efforts may be divided into two broad groups, 1) exploration via an open entrance or an open passage in a known cave, and 2) exploration that requires modification of cave entrances and passages. In most countries with a long history of caving activities, there are very few, if any, open cave entrances that have not been explored and documented. Elsewhere, most notably in the tropics and at high latitudes, caving expeditions are still able to document substantially unknown cave systems. In tropical areas, the caves are likely to have been entered by local people, unless access is particularly difficult, for example in deep shafts or entrances at the bottom of steep-sided dolines. Explorers of these caves have a responsibility both to document their discoveries, including information on features of particular scientific interest, and to take steps to ensure the cave, if newly discovered, is conserved (see the UIS Code of Ethics). In particular, it is essential that local peoples are fully engaged, in order to learn of cave locations from them, as well as any sacred or other values they may have, to provide information on the cave values for the explorers and the broader community, and to inform them how these combined values can be protected.

Within known caves, there may still be passages not entered by the original explorers, the most common reason being that the passage could not easily be reached, usually because it is high above the known passage, or that it is filled by sediment or water. High level passages are accessed by cave-climbers who usually have to place bolts or other fixed aids to ensure a safe ascent. This inevitably results in minor scarring of passage walls. Exploration of water-filled passage is undertaken by cave divers who may gain access to air-filled passages. Where these passages are extensive, there may be pressure from non-divers for the development of alternative entrances that do not involve diving, which can be problematic if the new passages are of high aesthetic or scientific value.

Many 'new' cave passages are found by passage modification, commonly known as 'digging'. The techniques employed may include sediment removal, engineering to stabilise routes through areas of collapse, the diversion of streams, the drainage of static sumps (water-filled passages) and the use of explosives to enlarge narrow passages. Such works should be restricted to the minimum modification required in order to gain access and only after there has been both a full consideration of potential impacts in both the short and long term, and if the importance of the discovery will outweigh the impacts caused by the modifications.

Exploring a deep shaft in the Abisso Michelle Gortani, Canin plateau, Italy. Photo by Csaba Egri.

In protected areas, it is important for managers to require the consent for all digging activities and, in some countries, specific guidelines have been developed. A document produced by the Derbyshire Caving Association in partnership with Natural England – the UK Government's advisor on nature conservation – specifically addresses digging in Sites of Special Scientific Interest (see Internet Resources). In considering applications, it should be recognised that successful digs enhance the scientific interest of a site by providing access to new passage and interest features. However, those making applications for digs should demonstrate a commitment to minimising impacts, for instance, by careful trenching through a sediment-filled passage rather than total removal of the sediment. If the dig is successful, there should be a requirement to fully document and describe the discoveries, including a map and photographs. This information should be sent to the protected area manager, who can then decide if follow-up scientific investigation is required. At the time a new cave or section of cave is entered, consideration must be given as to how it can best be conserved. Where the discovery contains sensitive areas, the explorers should consider the best route through those areas and ensure this is clearly marked for those who follow. There should be a requirement to remove all redundant equipment on completion of a dig, particularly if the dig is unsuccessful. Excepting remote areas, newly discovered caves and passages may attract strong interest within the caving community and the window of opportunity to protect the site before it becomes impacted may be quite short.

Cave exploration sometimes requires removal of sediment to access the passage beyond. Both images show shafts being sunk through sediment and the use of scaffolding bars and planks to prevent collapse. In the left image, the shaft was excavated for 4 m depth to an open rift leading to 50 m of passage with fine speleothems. In the right image, the pipe to the left of the figure was installed to improve ventilation. No sediment was removed from the cave but was instead was bagged and stacked in available space. After about 5 m, the dig broke into open passage of high scientific value. Both digs were in Sites of Special Scientific Interest and were undertaken with permission from the statutory authorities. The dig on the right is at the end of a show cave and was undertaken with encouragement from the owner. Photos by Rob Eavis.

The majority of those involved in cave exploration publish details of their discoveries in journals, newsletters or, increasingly, online. These reports commonly contain detailed maps and descriptions that provide important information sources about the cave resources. In many karst areas, virtually everything known about the caves is the result of caving group efforts. Whilst some protected areas depend on the caving community for cave information and in some cases partner with them in aspects of management, a less reactive style of management is possible where state agencies develop in-house speleological expertise. This can be done by employing specialist scientific staff to advise on cave-related matters and by developing caving capacity at the operational level through staff training.

The upstream entrance of the Xe Bang Fai Cave, Hin Nam No National Park, Laos. The cave has been open for adventure tours since 2012. Photo by John Spies.

Recreational caving

Recreational caving (sometimes referred to as sport caving) is essentially 'going caving purely for the pleasure of going caving' and involves visits to known caves. As such, it is similar to other outdoor leisure pursuits such as walking or climbing. In many American and European countries, recreational caving (as opposed to exploration) began in the early 20th century CE and was undertaken in clubs or groups ranging from a few like-minded individuals to large well-organised bodies. With an increased availability of personal equipment, and particularly following the adoption of static rope techniques, it became possible for small numbers of individuals to undertake visits to deep and complex caves without having to rely on a club for support. Nevertheless, in the 21st century CE, globally most recreational cavers remain members of at least one caving club. Access to caves is a key requirement for recreational caving and in many countries caving clubs have joined together to form regional or national bodies with a key objective of maintaining and seeking to improve cave access, with most seeing cave conservation of equal importance. National bodies also commonly provide members with insurance cover, as well as for landowners with caves on their property. In 1965, the Union Internationale de Spéléologie (UIS) was formed as the international body for caving and speleology, and as of January 2022, there were 57 member nations. Within the UIS, there is a Karst and Cave Protection Commission, members of which have contributed to these Guidelines.

Whilst most recreational cavers now appreciate the beauty, fragility and scientific importance of the underground environment, this has not always been the case and many caves have suffered severe damage both deliberately and through ignorance. A particular problem in the 21st century CE has been an increase in what may be termed 'speed-caving', where the objective is to reach a particular point in a cave and return back to the surface in the shortest possible time, with little consideration of the potential impacts to the cave. Deliberate vandalism commonly involves removal of speleothems as souvenirs, destruction of clastic sediment sequences during mud-fights or to create sculptures and slides, and the inscription of graffiti. Where a cave is protected, or situated in a protected area, legal action can sometimes be taken if the culprits are identified (there have been successful prosecutions in the USA), but this cannot compensate for the loss. On a human timescale, speleothems and clastic sediment sequences are irreplaceable. Inadvertent damage results from a failure to understand and respect the cave environment. In particular, many cavers who instantly recognise the value of speleothems and the need to protect them generally fail to appreciate the scientific importance of clastic sediments, instead treating them as 'mud'.

Delicate straw speleothems in Castle Grotto, Hollow Hill Cave, Waitomo, New Zealand. These have been protected by a careful access policy and minimal impact caving guidelines. Photo by John Gunn.

From the mid-1990s, concern over the impacts of cavers on caves has led to the development in many countries of Codes of Ethics, Cave Conservation Codes and Minimal Impact Caving Codes. The aim of these codes is to encourage cavers to think about each trip they make in terms of conservation, as well as safety, highlighting the important conservation role of many national and local caving bodies. In a country with an established code, cavers should be required to be familiar with and follow that code. In protected areas, adherence to the code should be mandatory. In those countries where there is no established code, then protected area managers should establish a code for caves in their area drawing on relevant material from published codes. Examples of these are given below.

EXAMPLES OF CAVING CODES

The International Union of Speleology (UIS) has a 'Code of Ethics for Cave Exploration, and Science in Foreign Countries' [*https://uis-speleo.org/wp-content/uploads/2020/03/Code-of-Ethics-of-the-UIS-English-Language.pdf*]. The title is somewhat misleading as this is an important document that covers 'Caving Expeditions to Foreign Countries' as well as 'Adventure, Geo- and Eco- Tourism' and 'General caving in your own country'. There are also guidelines for the 'Development of Show Caves' and for 'Scientific Sampling', both of which are separate topics in the UIS document.

The Australian Speleological Federation produced one of the earliest 'Minimal Impact Caving Codes' in 1995 and the latest version (2010) is at *https://www.caves.org.au/administration/codes-and-standards.* This code is divided into two sections: one relating to general cave visits and the other relating to the exploration of a newly discovered cave or section of cave.

The British Caving Association (UK) produced 'Minimal Impact Caving Guidelines' in partnership with Natural England, the UK Government's adviser for the natural environment in England [*https://british-caving.org.uk/our-work/cave-conservation/]*. The guidelines aim to minimise impact, but also include recommendations for conservation and restoration work both in caves and on the surface.

The New Zealand Department of Conservation has a 'Caving care code' https://www.doc.govt.nz/parks-and-recreation/things-to-do/caving/caving-guidelines/ that promotes caving in a way that minimises impact on the environment and other people.

The National Speleological Society (USA) has a set of 'Minimum-Impact Caving Guidelines' that are regularly updated, most recently in February, 2021, to take into account the Covid pandemic [*https://caves.org/conservation/cavingcode.shtml*]. The authors make the important point that guidelines should be updated as more is learned about cave environments and cavers evaluate and redefine their caving conduct.

During the early to mid-20th century, it was common for cave information, including the entrance locations, to be restricted to members of caving clubs, which provided a degree of protection. This is still the case in some countries, particularly for fragile caves or caves undergoing exploration. In the USA, the 1988 Federal Cave Resources Protection Act covers caves on federal lands, stating that the location of significant caves may not be made available to the public. However, elsewhere, the growth of interest in recreational caving has led to the publication of guidebooks providing basic and, in some cases, quite detailed location information. The internet has seen a huge increase in the availability of cave information, including exact entrance locations enabling anyone with a GPS to easily locate them. At the same time, there has been a massive growth in the use of social media and with it a growth in the number of individuals and groups lacking training or experience, but who decide to visit caves and to post videos of their visits online. An inevitable consequence has been an increase in accidents and in damage to caves both deliberate, such as graffiti and the removal of 'souvenirs', and inadvertent including the failure to follow routes around clastic sediments or areas with profuse speleothems, as well as attempts to record the route out of the cave using cairns or marking the cave walls. This type of activity provides a particular challenge for protected area managers as the individuals are not part of the caving community and therefore unaware of cave conservation codes. Signage at cave entrances or within caves may help, but the only means to provide full protection is to secure either the entrance to the cave or access to sensitive area(s) within the cave (see Cave classification as a management tool). The design of cave gates requires careful consideration in order to ensure they are secure, and do not unnecessarily detract from the aesthetics of the site, impede movement of fauna, air or water, or inhibit the extraction of an injured person.

Cave diving is most commonly an exploratory tool and, as such, is discussed in Cave exploration and documentation, but in some countries, is undertaken as a recreation in its own right. In contrast to exploratory cave diving, which is largely undertaken by individuals with caving experience, recreational cave diving is most commonly undertaken by open-water divers who may not fully understand the risks that the cave poses to them or the risks that they pose to the underwater cave environment.

Recreational cavers involved in the sport for more than a few years often specialise in aspects of speleology, such as underground photography, cave mapping, cave rescue, cave science or cave exploration. This has wider benefits, in that cave photography can help foster community awareness of cave values, supporting conservation efforts; cave maps are essential tools for managers, scientists and rescue personnel; rescue preparedness has safety and conservation benefits; and collaborations between cavers and scientists adds to our knowledge of these systems and reduces the risk of caves being impacted by researchers. Caving groups are also known to initiate 'karstcare' projects to clean up cave rubbish or restore damaged features. Whilst cavers' attitudes vary, there are many examples of highly constructive relationships between management and local caving groups. Building these relationships has obvious benefits, not the least being that this encourages compliance with access conditions. Some protected areas approach this in a structured way by involving stakeholders in cave management committees or working groups. This creates opportunities for dialogue around contentious issues including the key one for many cavers, restrictions on cave access. Any imposition of new access restrictions will likely be negatively received, and may not be complied with if the rationale is not understood by the caving community.

Lake Chandelar, Lechuguilla Cave, Carlsbad Caverns National Park World Heritage Property, New Mexico, USA. As the cave has a high scientific value and is vulnerable to damage by explorers, access is limited to approved scientific researchers, survey and exploration teams, and National Parks Service management-related trips. A management plan has been published (see Internet Resources). Photo by Rainer Straub.

Adventure caving

Adventure caving (also referred to as 'instructed caving' or 'wild caving') encompasses a wide range of very low key to highly organised commercial underground experiences. Many of those offering an adventure caving experience are freelance (self-employed) instructors who perform a similar role to that of mountain and trail guides, and other related occupations on the surface. Members of the public who would like a caving experience and, less commonly, recreational cavers who would like a guide in a complicated cave system, employ instructors who provide all the requisite equipment for the chosen cave. Caving instructors are also employed at outdoor education centres that largely cater for school groups, although there are also centres and groups providing corporate 'team-building' and 'management' experiences to adults. In addition, some show caves offer adventure caving as an adjunct to the tour(s) available to the general public. Whilst the majority of cave instructors receive payment for their services, there are some who provide an adventure caving experience in a voluntary capacity, most notably for organisations such as the Scout Movement.

In developed countries, a high level of safety training for instructors is often either a legislative or insurance requirement. In Australia and New Zealand, instructors are required to undertake specific training, usually via a one-year full-time course that covers all aspects of adventure guiding, including first aid, rescue and interpretation. While the safety of those who are being guided is of paramount importance, it is essential to give equal weight to the safety of the cave, emphasising the importance of conserving geoheritage and ecosystems. Unfortunately, some caves still bear the marks of past bad practice, when it was common for instructors to encourage their group to participate in mud-fights, as to 'enhance' the underground experience. This resulted in damage to important clastic sediments and mud adhering to speleothems and cave walls.

Where there is a national caving body, this organisation is likely best placed to provide instructor certification and to ensure that safety and conservation are given equal attention. The British Caving Association (BCA) offers two nationally recognised certifications for caving instructors and guides who lead people underground – the Local Cave and Mine Leader Assessment Scheme (LCMLA) and the Cave Instructor Certificate (CIC). The LCMLA Scheme "provides an award recognising the competence of those wishing to take responsibility for others underground, for the benefit of employers or others in authority. The main considerations are equally the safety of the group and the conservation of a fragile environment". There are also local groups of instructors in the United Kingdom, such as the Peak Instructed Caving Affiliation (PICA), which covers the English Peak District caving area and is affiliated to the Derbyshire Caving Association, one of the BCA regional councils. Part of the PICA remit is "To disseminate safety and conservation information about the caves and mines that can be used for LCMLA and CIC led trips in our region".

Brejões Cave, in semi-arid Brazil, is frequently used for adventure tourism. It has large passages and massive speleothems. Photo by Philippe Crochet.

The reference to sites that can be used for instructor led trips is very important because it implicitly recognises that there are sites that may be unsuitable for adventure caving either because there are unacceptable safety risks for those who are not experienced cavers or because there is a risk of damage to the underground environment. A complementary approach in more extensive caves is to undertake a vulnerability assessment and to use this to divide the caves into zones. Those passages that are considered robust, with few interesting features susceptible to damage, may be zoned for the type of adventure caving that involves individuals with little or no previous underground experience. Passages with medium value are likely only to be appropriate for adventure caving if the participants have some experience or if the ratio of instructor(s) to participants is such that the risk of damage can be minimised. There will be some caves, and some cave areas, where the risk of damage to geoheritage or ecosystems is so high that they are not suitable for adventure caving. In undertaking vulnerability assessments, it is important to consider the carrying capacity of a cave, as human visitation inevitably has cumulative impacts on both the physical and biological values of a cave or cave section.

While small-scale activities account for the majority of adventure caving globally, there are a growing number of commercial enterprises that offer what may be termed 'high-end' adventure caving experiences, for example, those offering 'blackwater rafting' and similar experiences in the Waitomo area of New Zealand. One of the longest, and most expensive, guided cave tours is the four-day experience offered by the Oxalis Adventure Company in Hang Son Doong, Vietnam, which has one of the world's largest cave passages by volume and lies within the Phong Nha-Ke Bang National Park and World Heritage Property. These commercial enterprises have more in common with show caves than other forms of adventure caving, in that they require substantial investment in infrastructure, visitor numbers are high and there has usually been significant modification of cave infrastructure in order to improve safety or to add to the visitor experience. Examples include the installation of fixed climbing aids and of ziplines within the cave.

Adventure caving now includes visits to ice caves with their own special set of challenges. Eiskogelhöhle, Austria. Photo by Csaba Egri.

Cave classification as a management tool

In order to manage caves it is necessary to 1) have an inventory of caves and their contents and to 2) have a classification system to identify suitability for different uses. For caves where there is a restricted range of features or limited horizontal or vertical extent, the whole cave is the logical management unit for many purposes. However, for longer caves, and particularly those that have marked internal variability in their values and sensitivity to visitor impacts, a zoning approach is likely to be more appropriate. An active stream passage subject to regular flooding, for example, is likely to be more robust to visitor impacts than a dry upper-level passage. When considering the whole cave level, the site should be considered in relation to the immediate area that surrounds it, to the rest of the karst area in which it is located, and to its national and global context. Within the cave, the following approach is recommended for caves and protected areas where no system is in place at present:

1. Undertake an inventory of the cave(s) and mark features of particular interest on a survey.
2. Assess the vulnerability of each feature type, i.e., cave passage morphology is generally robust, whereas speleothems and clastic sediments are more likely to be easily damaged.
3. Identify potential uses of the cave, such as for Recreational Caving, Guided Adventure Caving, Exploration and Research.

4. Based on points 1 to 3, identify zones within the cave that are suitable for particular uses. A simple scheme that can be adopted to suit local factors is to grade passages or cave areas as:
    - *A – Low sensitivity*. Areas of the cave that are considered robust and able to withstand all but deliberate destruction. These are suitable for all uses.
    - *B – Moderate sensitivity*. Areas where there are interesting features that could be easily damaged unless basic precautions and care are used. These areas are suitable for recreational cavers who are cognisant of, and abide by, a minimal impact caving code. They are not suitable for introductory adventure caving but can accommodate small groups of adventure cavers with a suitably qualified leader. Exploration with the aim of finding new passage and scientific research can be allowed, subject to a project proposal and impact assessment.
    - *C – High sensitivity*. Areas with high value, easily damaged features. Use of these areas should be minimised and there should be controls to minimise impacts. Recreational cavers may be required to provide good reason for requesting access (i.e., photography) and may be required to visit with a leader who has specific knowledge of the cave or its interesting features. Exploration with the aim of finding new passages and for scientific research should only be allowed after a form of 'cost-benefit' analysis that assesses the risk of damage against the likelihood of a successful outcome and the value of the discoveries.
    - *X – Extremely Sensitive*. A section of cave that is of very high value where there is a high risk of damage. These sections should be off-limit other than in exceptional circumstances, i.e., research that aims to understand a particular feature in the sensitive area.

Cave rescue

As with all forms of outdoor recreation, there is a risk of an incident occurring in a cave that places an individual or individuals in a position where they need to be rescued. There are four main objective dangers in caves: hypothermia, material collapse, floodwater and dangerous gases. All other dangers are subjective and connected to visitors. Examples include medical emergencies, such as a heart attack, which could occur elsewhere but which happens while the individual is underground, an individual or group entering a cave and being unable to find their way back to the entrance or being trapped by floodwater, and accidents resulting in a person becoming incapacitated. In most countries where there is a long history of caving, there are national or local cave rescue organisations that either undertake underground rescue directly or assist the state's emergency services in carrying out a rescue. Cave rescues are generally difficult, particularly if they involve the transport of an injured person, and have the potential to impact the cave. The first priority in any rescue is the safety and well-being of the rescuers and those being rescued but, insofar as it is practicable, the rescue should minimally impact the cave environment. Where the rescue team is largely or totally made up of experienced cavers, they will want to minimise their impacts on the cave and there is at least one 'Minimal Impact Cave Rescue Code', which was produced in 2006 by the Australian Cave Rescue Commission with a major revision in 2019 (see Internet Resources).

Biological impacts of cave visitation

Caves provide habitat for a variety of animals. Bats are the best known and most widely present globally. Other notable vertebrates are cave fish and salamanders, while specialised cave-adapted invertebrates are the most common. Many of these animals have highly restricted distributions. Caving activity can adversely affect cave animals directly, as in the case of small invertebrates injured or displaced by people moving through a cave, or indirectly, as in the case of the introduction of pathogens, nutrients or by alterations to habitat. The consequences for biodiversity of these impacts are unlikely to be fully appreciated without adequate research. Potential conservation strategies include species conservation plans; information products to raise awareness of minimal impact caving practices for fauna protection; habitat restoration; and restrictions on access to critical habitats through zoning. Some caves are medium or low-energy environments, with essentially little input of energy on a human timescale. The entry of a single caver into these caves can change the energy balance by affecting the heat, light, and nutrients therein. One factor that has only become apparent since the 1990s is the potential introduction of microflora and microfauna by cavers. The effects of visitors to caves are generally cumulative and quite possibly synergistic.

In contrast to disturbances to surface sites, traces or effects of human activities in medium or low-energy underground environments may persist for hundreds or even thousands of years. For example, what is believed to be a Cro-Magnon footprint, up to 48,000 years old, has been discovered on the surface of a sediment deposit in Chauvet Cave, France. Of particular concern is White-nose Syndrome (WNS), a very infectious fungal disease that has killed millions of cave-dwelling bats in North America and elsewhere since its first appearance in 2006. It is caused by the fungus *Pseudogymnoascus destructans*, which has been identified on bats in both Europe and China without causing population declines. Preferring high humidity, it grows on and adversely impacts hibernating cave-dwelling bats while they are in torpor. Visible symptoms include fuzzy white patches on the bat's nose and white patches on the body and wings. It is often fatal. The fungus was first found in a North American show cave, suggesting it may have been introduced on the shoes of a tourist from another country. Humans can spread the fungus from one hibernation cave to another by accidentally carrying the fungus on shoes, clothing or caving gear. Tourists visiting show caves may also spread the disease widely. Procedures such as footwear decontamination stations have now been established at show caves such as Mammoth Cave in Kentucky, and are widely adopted by recreational cavers throughout the United States and some other countries. Procedures to decontaminate caving gear and equipment were proposed by the WNS Decontamination Team (see Internet Resources). While these procedures were a response to a specific problem, they are recommended for all cavers, particularly those visiting Protected Areas. However, the primary transmission of WNS is from bat to bat. Many bats are social mammals and migrate from summer feeding areas to nursery caves, then to winter hibernation sites. The fungus is found both on bats as well as on sediments within the cave environment.

In addition to the potential for cavers to inadvertently impact cave microbiology, in some parts of the world entering caves poses a potential risk to human health. The most widespread and well-known risk is from histoplasmosis, an infection caused by breathing in spores of a fungus often found in bird and bat droppings. Bats may also be vectors of other diseases and should only be handled by experienced individuals undertaking approved research. Health risks should form part of any risk assessment for a cave.

Procedures to decontaminate caving gear and equipment

For items submersible in water:

- Thoroughly clean caving gear by removing all dirt and grime.
- Immerse in hot water, maintaining a temperature of greater than 55 °C for a minimum of 20 minutes.

For items not submersible in water:

- Disinfect using 6% hydrogen peroxide spray or isopropanol disinfectant wipes.
- Boots should be scrubbed to remove all mud and dirt, then sterilised as above.

Any gear that has been taken into potentially infected caves, and cannot be treated using the appropriate decontamination procedures, should NOT be taken to other cave areas or caves in other countries. Some protected areas will not allow equipment that was in potentially infected caves, even if decontaminated.

Incidental users of caves

During the 21st century CE, an ever-increasing demand for 'adventure experiences' has led to some caves being used as part of running events, and there are instances in which motorised vehicles have been used in caves. Running events that take place in show caves and use existing infrastructure are unlikely to have substantial additional impact beyond those already experienced. The same applies to running on walkways that pass through relict caves that form natural arches. However, the use of wild caves for this type of event, or for other competitive or sporting events, should not be permitted as it is impossible to avoid damage to geoheritage and ecosystems. Similar considerations apply to the use of electric-powered vehicles underground as although there is a long history of their use in some show caves, it is totally inappropriate to allow any form of motorised vehicle into wild caves because of the damage that will inevitably result.

Guidelines

(12) An inventory of caves is desirable as a basis for management. Features of particular interest in each cave should be identified on a map.

(13) A risk assessment is desirable and should cover groups of caves, individual caves, or sections within a cave as appropriate to the site. The assessment should cover both the risk to human explorers and the risk that human explorers pose to the cave. The vulnerability of each type of feature should be assessed to facilitate identification of caves, or zones within caves that are suitable for particular uses.

(14) Management of caving impacts is best approached through a strategic planning process with stakeholder involvement. An appropriate approach is likely to require a combination of initiatives, of which access policy will always play a key role.

(15) Any instructor offering adventure caving should be able to provide evidence that they have received adequate training in safety aspects and in cave conservation.

(16) All cavers should be expected to be familiar with, and to follow, a minimal impact caving code (MICC). Where no national or regional MICC applies to a protected area, a specific code should be devised based on published codes.

(17) Digging, original exploration and research in caves within protected areas should be controlled either via specific agreements or by requiring permits.

(18) Protected area managers are recommended to draw up a plan that can be implemented should a caving accident occur in the area. The plan should be drawn up with involvement from the regional or national caving body and of state bodies responsible for accident and emergency situations, and should include guidelines to minimise the impact of the rescue on the cave and on the surface.

(19) It is totally inappropriate to allow any form of motorised transport into wild caves and wild caves should never be used for running events or for other types of sporting event.

Show caves

Introduction

In this document we use the terms show cave and tourist cave interchangeably to describe a cave to which the public can obtain access on payment of a fee. Some of these caves are owned and/or operated by federal, state or local governmental authorities. Some government owned show caves are operated by concessionaires while many other show caves are privately owned and operated. In most protected areas, there will only be a few show caves, with the bulk of sites used for either adventure or recreational caving (see Recreational and adventure caving). Caves used for religious purposes, such as shrines or churches can be considered to be a special type of show cave. The association of caves and religious practices (including shamanism) is common in many religions and some caves have been converted to places of worship. These caves are especially frequent in Catholic and Buddhist countries and receive a substantial number of visitors, including both tourists and people wishing to pray or worship (see Some values of karst and caves). The degree of modification varies widely, from simple shelters or grottos with religious images to large chapels. Some caves are used as churches, with seating areas, altars and shrines and have regular masses and a designated priest. Caves used for religious practices are normally controlled by the religious authorities and the impacts of their use on the cave environment are rarely considered. Therefore, the remainder of this chapter discusses only non-religious cave use, although the principles are equally applicable to caves used for religious purposes

The International Show Caves Association (ISCA) has developed 'Recommended International Guidelines for the Development and Management of Show Caves' in association with the IUCN and UIS (see Internet Resources). The purpose of those recommendations is to provide guidance in the best practices for the development and management of show caves, wherever they may be situated in the world. It is not the purpose of the Recommended International Guidelines to create rigid rules, or that they be construed as laws. They are guidelines for a professional approach to cave development and management. Many show caves have been operating for decades and some for hundreds of years. In their guidelines, ISCA recognises that existing show caves may find it difficult, and in some cases impossible, to comply with all of the Recommended International Guidelines. In these cases the ISCA Guidelines provide examples of best practice and standards that can be worked towards over time.

The Recommended International Guidelines should be considered the definitive source for show cave development and management best practices and are intended to be kept in an updated format to take into account new information and findings. This is particularly important in protected areas where show caves should be managed to the highest possible standards and provide exemplars to those show caves that operate outside protected areas. Where it is necessary to replace infrastructure, for instance, this should be done after assessing the best option for the cave environment rather than simple 'like for like' replacement.

The Big Room on the tourist path through Carlsbad Cavern, New Mexico, USA. This is the only show cave in the Carlsbad Caverns National Park World Heritage Property. There are many other caves some of which are open for adventure caving, while others can only be accessed by scientists and others working under a permit system. Photo by Csaba Egri.

It is a fact that general rules can never be absolutely applicable to all situations. There could be unusual parameters in some caves around the world where, for acceptable reasons, some parts of these guidelines could not be applied without huge difficulties. These Guidelines and the ISCA Recommended International Guidelines are provided as goals that show caves can work towards as provided by their circumstances and economic ability. In addition, there are many national show cave management associations, such as ABIS (the Association of British and Irish Show Caves), ACKMA (the Australasian Cave and Karst Management Association Inc., ANECAT (the French National Association of Operators of Caves Developed for Tourism) and NCA (the USA National Caves Association) that share best practices for show cave development and management with members and peers. The guidelines that we provide complement those provided by ISCA.

Considerations for developing a cave into a show cave

Where show caves have already been developed, the entry fee and revenue from other amenities, such as retail souvenirs, café food and beverages and other ancillary attractions, is commonly an important income-stream and the caves provide a valuable source of local employment. They may also provide protection to the cave environment if issues, such as vandalism, threaten. This provides an incentive to open up new caves, particularly in developing countries. However, before any such development occurs, there should be a thorough study of the economic impact and viability of the proposed project, as well as an environmental impact assessment that includes consideration of the effects of development on the biological and earth science interest in the cave. Development should only proceed if it can be shown 1) that impacts can be successfully managed and that there is sufficient funding in place for construction that complies with environmental and public safety requirements, and 2) that the likely income stream will allow the cave to be managed in an environmentally responsible and sustainable manner. In particular, it is important to prevent development being started but not finished, thereby leaving the cave in a more vulnerable state, or a show cave being opened but not attracting sufficient tourists to provide the income required for continued sustainable and responsible operation. In addition, it can be acceptable to open caves for visitation by the public when the economic plan is not positive, but the economic success is guaranteed by the State or even by a local club of volunteers. A well-managed show cave usually provides protection for the cave, as well as providing a source of income and education for the local economy.

Show caves are the medium by which the majority of the public experience the underground environment. As such they provide a great opportunity to explain the cultural, historical and scientific importance and the fragility of cave environments. This is particularly important in protected areas where caves are commonly a primary reason for designation.

Paradise Cave is a show cave in the Phong Nha-Ke Bang National Park, a UNESCO World Heritage Property in Vietnam. Photo by Steven Bourne.

Safety

The safety of the visitor and employees must be a fundamental objective of any show cave. This includes above and below ground and includes all parts of the property. Traffic entering and exiting the property should be via appropriately surfaced roads and parking areas. Good organisation is essential. It is not always possible to comply with building code standards below ground. In planning paths in the cave, the safety of the visitor must be the primary consideration. Headroom is especially important underground – where adequate headroom is not achievable, warnings should be given to prevent potential injury. Handrails should be provided where necessary.

Safety planning includes making sure that emergency services can gain access to the cave in the best possible way. A relationship should be established with local emergency services, so that all are aware of the constraints and difficulties that will be encountered in cave rescue, which usually involves a lot of physical effort, and may have a severe impact on the cave environment itself, unless plans are in place. Appropriate training for rescue and first aid should also be provided to the show cave staff.

Visitor carrying capacity

The 'visitor carrying capacity' of a show cave is a planning and management tool for establishing the maximum number of visitors the cave can accommodate on a tour or over a given time period. Determining a show cave's visitor carrying capacity finds the balance between providing a safe, informative and enjoyable cavern tour experience for visitors and minimising the impact on the cave environment while achieving economic goals. All of these factors must be considered when determining if the appropriate visitor carrying capacity for a show cave is to be truly sustainable.

The focus of the following information will be on the factor of minimising environmental impacts. Tourism visitation in show caves will have some degree of impact, but negative impacts can be minimised and visitor satisfaction enhanced by good visitor management procedures and practices. The first step is considering physical parameters. Visitor flows should be routed into, through and out of the cave in an efficient manner that minimises impact. Factors to consider include the size of passages, distance from speleothems, infrastructure (such as railings), and if guests will enter and exit the cave at different locations providing linear visitor flow or if they will enter and exit at the same location. If visitors will be passing each other in the cave, these locations should be considered to ensure adequate space.

The second step is considering the environmental parameters, such as air flow, air quality, temperature, humidity and cave fauna. Large numbers of visitors in some caves can significantly raise the air temperature and the carbon dioxide concentration. A single person releases heat energy at 80–120 W, about the same as a single incandescent light bulb. Thus, a party of 50 or 60 people on a cave tour can locally raise temperatures by 1–2 °C. Show cave management should ensure that these fluctuations lie within the range of natural variation for the cave, and that they return to normal levels within a short period of time under normal circumstances. Increases in CO_2 concentration due to visitor respiration can range from 1,500 – 5,000 ppm, at which point some people may start to be distressed. Managing carbon dioxide levels, in some caves, may require effective monitoring in line with appropriate health standards. Ventilation shafts or modifying doors to improve air circulation may improve air quality in some caves, however measures such as this must be carefully considered and applied as to not create problems, such as altering the natural cave environment.

Visitors on a guided tour in the Baradla Domica Cave which first opened as a show cave in 1806. The cave system crosses beneath the border between Hungary and Slovakia and is in the Caves of Aggtelek and Slovak Karst World Heritage Property. The cave is also in two separate UNESCO Biosphere Reserves - Aggtelek, Hungary and Slovensky Kras (Slovakia) – and two separate Ramsar Sites (Baradla Cave system and related wetlands, Hungary and Domica, Slovakia). Photo by Csaba Egri.

The presence of cave fauna, such as bats or cave adapted species, should be factored in as well, with a goal of minimising impacts on those creatures that find their home in the cave. Where bats roost in a show cave, special care should be taken in order to ensure that they are not disturbed by visitors, particularly when the bats are hibernating or breeding.

As the physical attributes and environmental parameters of each cave are specific to that cave visitor carrying capacities cannot be applied uniformly but must be individually determined for each specific show cave and show cave tour experience. Many show caves utilise economics as a tool to maximise visitor experience and minimise environmental impact. One example is increasing the admissions fee seasonally or during busy time periods – called 'variable pricing' – to reduce overcrowding at busy time periods, which can improve visitor experience while at the same time minimising the environmental impacts of overcrowding. Another example of show caves considering all factors when making visitor carrying capacity decisions could be a busy holiday weekend where management may determine the economic benefits outweigh the environmental impact of a larger than normal number of visitors, thereby causing the temperature in the cave to rise higher than normal for a limited number of days.

It is the responsibility of show cave management to take each of these environmental impacts into consideration and weigh them alongside visitor experience and economic factors in order to establish the maximum cave visitor carrying capacity for their specific show cave.

Show cave access

One of the first and most obvious impacts of developing a cave for tourism is modification to the existing entrance (an activity that is also sometimes undertaken to control access to a wild cave), or construction of a new entrance. In many show caves it is necessary to provide a different access into the show cave for visitors, than the access into the natural cave that was used before the conversion of the cave into a show cave. Such an artificial access could be via a tunnel, or a new entrance, excavated into the cave. When an artificial entrance is created this could change the air circulation in the cave and cause a disruption to the cave ecosystem. In order to avoid any disruption of the air circulation in the cave, an airlock should be installed in any artificial entrance into a cave. A decision not to install an air lock should only be made after a special study is carried out. The preferable method of installing an efficient air lock system is through the use of a double set of doors.

When show caves have a natural entrance suitable for visitors, an appropriate form of access control must be installed. In the past, it was common to either infill or install gates across any entrances that would have allowed visitors to by-pass the desired primary point of entry, at which a fee is charged. This had the adverse impact of restricting or even totally preventing the introduction of nutrients and movement of cave fauna, especially bats. If gates are installed in entrances and passageways used by bats, it is advisable that the top section have horizontal bars with an air gap of 15 cm high, and 45–75 cm wide. These air gaps will enable bats to have free passage. All new cave gates should be designed such as to allow free passage for bats, and old gates should be replaced with bat-friendly designs. Some species will avoid any gate, however, in which case an alternative solution such as fencing must be found (see Internet Resources: cave gates).

Above ground level works

In order to relate the topography of the site to the underground void of the cave, it is necessary to have a site plan that depicts the surface detail and the underground detail of the cave. This information is as critical to an existing show cave, as in the case of one that is being planned. Once the relationship between the above ground features and the subterranean detail is known, then the factors related to water can be assessed. In many cases, the only factor may be the percolation of surface water down through the rock above the cave, which should not be perturbed. In addition, the risk of surface water gaining access to the cave as flood water, needs to be very carefully examined.

It is important that hard surfaced areas, such as buildings and parking areas, not be positioned above the immediate cave catchment (the enterable cave and those conduits draining into it) where the natural seepage of rainwater from the surface to the cave occurs. If there is the potential for natural percolation to be interfered with, other solutions should be sought. These solutions can be as simple as converting the surface of a watertight parking area into a form of surfacing that permits the passage of rainwater through it. Where buildings are situated above the cave, they should preferably be relocated or, if finances do not permit relocation, be relocated when the building comes to the end of its life span. Run-off water from roofs and other hard surfaces must not be allowed to concentrate and should be dispersed widely. It is also critical to ensure that any effluent generated on the site is disposed of properly and not allowed to contaminate the below ground world.

There is a natural tendency to try and place those buildings necessary for the operation of a show cave as close as possible to the cave entrance and in some cases the entrance to, or exit from, a show cave is within a building that has other uses, commonly as a museum, interpretation centre or gift shop. However, many caves have naturally high concentrations of radon, a radioactive gas, and if this is allowed to leak from the cave into places where staff are working, they will accrue a radiation dose. Hence, it is good practice to ensure there is a ventilated area between an entrance and/or an exit to the cave, and any building in which staff work.

Infrastructure inside a show cave

The development of caves for tourism commonly requires the physical alteration of natural passages, as well as the installation of lighting, pathways, platforms and associated infrastructure. In all new development, whether in existing show caves or new sites, infrastructure needs should be carefully assessed, designed and installed. Clearly, there is a need to provide visitor satisfaction and safety, but the aim should be to minimise alteration or disturbance to the cave's natural environment. Development should aim to minimise changes to passage morphology and damage to sediments and speleothems. Issues associated with cave walkways and cave lighting are considered in more detail, below. In some large show caves mechanised transport is used to facilitate access and allow for a larger number of tourists, including elevators, buses and trains. These types of transport, while being friendly towards visitors with mobility problems, may involve major modifications to the cave environment and as such must be carefully planned.

Show cave pathways

Pathways are an essential component to providing a durable and safe walking surface and definite boundaries for visitors to stay within. Tourist routes through the cave should be designed to have minimum impact on biological habitats within the cave and on speleothems. The cave pathway alignment should lead the visitor close enough to the major points of interest so they can see and photograph them, but not so close that they can touch or disturb them. Cave sediment floors should be protected by raised walkways whenever possible in order to preserve their habitat value, fossil record and sediment history.

The pathways in a cave need not be overly wide. For example, it is not necessary – though desirable – for two people to walk side by side. A single file path is adequate but it is advisable to create some occasional broader areas where a tour group can be gathered to listen to the guide. The pathways in a show cave can be used for the placement of utility pipes, conduits and cables, either underneath the surface of the pathway, or beside it. It is preferable that these utilities are not encased in concrete. The control switches of the lighting system should be readily accessible from the pathway.

The pathway should consist of three fundamental components, comprising a walking surface, side kerbing and handrails. It is desirable that the materials used in installing the pathways should have the least possible impact on both the aesthetics of the cave and its underground environment.

Walking surfaces

A raised walkway in the Gouffre d'Esparros show cave, France. The arrow indicates a net used to provide extra protection and prevent sediment falling onto speleothems below. Photo by John Gunn.

Materials used for walking surfaces should be nontoxic to the cave environment. Traditionally, and particularly in limestone caves, the favoured material for the walking surface has been concrete, which is generally the closest substance to the rock that the cave is formed in. Concrete has also been widely used where walkways cannot be elevated. Concrete has distinct advantages, including aesthetically blending into the cave, and durability, however its disadvantages include its weight, the potential mess when its mixed and poured, and the difficulty of removing it once it is in place. There is also some evidence that leachates from concrete may have adverse biologic impacts. Low-density concrete can be made using perlite, pumice, or volcanic scoria, and which offer some advantages in terms of reduced weight, while retaining adequate walkway strength. Stainless steel grating has also become increasingly popular as a material for constructing walkways. Stainless steel has the distinct disadvantage that it is expensive and requires special techniques to assemble and install. Fiberglass reinforced plastic (FRP) grating with stainless fasteners is another popular material for cave pathways with a lower cost and weight than stainless steel.

Elevated walking surfaces constructed of stainless steel, FRP or other suitable grating materials have the advantage of lasting a long time, require very little maintenance, having a reduced impact on the cave floor and are relatively easy to remove, so that if necessary, the cave can be almost returned to its natural condition. However, grating (grids) of all types allow lint, trash, dirt, mud and small objects to fall through onto the cave floor and, unless design takes this into account, it can be very difficult to remove the grating and clean the cave floor beneath.

Kerbs

Kerbs or kickplates have several distinct purposes. One is to contain the feet of visitors, which protect cave features beyond the walkway. Another is that the outside of the kerbs, facing away from the walkway, provides a convenient place for utility conduits, pipes and cables. Kerbs can also help to contain lint, and other residue, from visitors.

Handrails

Handrails (or guardrails) provide stability or support for visitors, while preventing them from going off the pathway where it may be delicate or dangerous. The favoured material for the construction of handrails in show caves has been stainless steel. This material has the advantages of requiring little, to no, maintenance, being able to be assembled and welded in the cave and having the potential to be used as water piping to carry fresh water into the cave. The disadvantages of this material are its cost and brightness – as it is not aesthetically pleasing. The use of stainless-steel wire rope, rather than solid intermediate uprights or solid rails that are installed below the actual handrail itself, can reduce the visual impact of solid steel significantly. Curves rather than acute angle bends also help. Fiberglass reinforced plastic (FRP) rails with stainless steel fasteners are now becoming more popular and provide an effective and lower cost solution.

While infrastructure, such as pathways, are intended to provide safe access for visitors and protect the cave from their impact, the installation of the infrastructure itself can cause major impacts if not done carefully. An environmental impact assessment should be conducted and an environmental mitigation and management plan (EMMP) should be drawn up before construction work commences. The EMMP should be implemented and monitored to minimise damage to cave resources during construction.

Cave lighting

The energy balance of a show cave should ideally be within the range of natural (pre-development) variations. Electric lighting releases both light and heat, thus any lights should be of high efficiency, producing the lowest amount of heat as possible. Many show caves have replaced older lighting systems with modern, high efficiency, light-emitting diode (LED) lighting energised by a low voltage power supply, and these should be used in all new development and cave lighting upgrades.

In show caves where visitors move in groups, it is beneficial to divide the tour route into zones in which lights are switched on or off by the guide. This enables only the part or parts of the cave that are occupied by visitors to be lit. This is important for reducing the heating of the cave environment and preventing lampenflora growth, as well as reducing the amount of energy required and its financial cost. In show caves where visitors move independently, lighting may be linked to movement sensors and timers. The electrical system should be installed in safe, well-balanced circuits.

It is important that some form of emergency lighting should always be available in the event of a failure in the main power supply. Emergency lighting should always be available whether it is a complete non-interruptible power supply or an emergency lighting system with an independent power supply. Local codes may be applicable and these may permit battery lamps or similar devices.

One important consideration in any lighting scheme is how to position light fixtures, wiring and power cabinets to minimise both visual impacts and damage to the cave. Lampenflora is a common consequence of the introduction of an artificial light supply into a cave. Many kinds of algae, and other superior plants, may develop as a result of the introduction of artificial light. Lighting should have an emission spectrum with the lowest possible contribution to the absorption spectrum of chlorophyll in order to minimise lampenflora growth. Another way to prevent the growth of lampenflora is to reduce the energy level reaching the surface where plants may live. The safe distance between the lamp and the cave surface depends on the intensity of the lamp. As a rough indication, a distance of one metre may be safe. Light should be carefully directed onto the feature to be illuminated and light spill onto surrounding areas or into visitors' eyes should be avoided – the shielding of light fixtures is very useful in this regard. In the past, warm lights located too close to speleothems or cave art have caused significant damage, though this is less of an issue when cool LED lighting is used.

A lighting design that avoids over-illumination not only minimises environmental impacts on the cave, but can also enhance the visitors experience with the deliberate use of darkness and sequencing of illumination on selected cave features. There are two important principles to be borne in mind when designing the lighting for a show cave: access and atmosphere. Lighting for access should be at the minimum level consistent with the safe movement of all cave visitors. Effective lighting can be used to create safe access through an unfamiliar environment, a zone of familiarity that relaxes the visitors. The use of LED strip lights, 12 V downlights, and other low-energy technology can achieve this aim. These can be attached to railings or path edges, with necessary inverters or batteries well-hidden below. In general, all fixtures and cabling should be well hidden from visitors, yet remain accessible for maintenance without further damage to the cave and its contents. Reduced power consumption has benefits beyond the reduction of CO_2 emissions, in that lower power requirements facilitate the use of a local uninterruptible power supply when there is a mains power failure. Less heat is produced as well. There are now many such technologies available, but they should be used as tools to achieve an end, not as an end in themselves.

Lighting for aesthetics should be based on an underlying philosophy, for example to illustrate aspects of cave, exploration, development or history. Where possible, lighting should be sequential, with visitors led from one scene to the next, possibly culminating in the illumination of a whole chamber. Any light in a dark environment will have a dramatic effect, and a very distant light sometimes can enhance an illusion of depth and mystery. The lighting of water features can be very effective and aesthetically pleasing to visitors. Some show cave lighting designs utilise coloured lighting to enhance certain features while others utilise neutral and cool light to showcase the natural colours of the cave, neither of which have any great impact on the cave environment. Some show caves have lighting shows synchronised to music compositions to enhance the visitors experience, which has no known adverse impact on the cave environment.

Cave cleaning

In many show caves, pathways and sometimes speleothems are cleaned on a regular basis because of the accumulations of dust, lint, inwashed sediments, fungus and algae (lampenflora). A number of approaches have been tried, with high-pressure water jets being the most common method employed, though in some cases, scrubbing, the use of surfactants and steam cleaning have also been tried. All of these methods can be expected to have some impact on the speleothem surfaces being cleaned. When high pressure water jets are used, operators should try to limit the number and frequency of washes and use the minimum number of nozzle passes over a calcite surface.

Lampenflora is the infamous scourge of show caves – a persistent problem. The use of strong cleaning agents, such as chlorine bleach, appeals to the desire to get rid of contaminating organisms like algae. Unfortunately, chemical use, including chlorine bleach, does not work well in the long term because lampenflora grows quickly under the right conditions. The only way to minimise algae growth is to control the development of lampenflora by reducing light and heat, rather than a periodical chemical treatment, which only kills the growth for a short period.

Yet, when lampenflora proliferates, it *is* necessary to destroy it with chemical compounds. Herbicides, however, should never be used in a cave, as they are too toxic for the cave environment. Used frequently in agriculture, herbicides must be avoided because their degradation is slow, and their toxicity may seriously affect cave fauna. The use of strong bleaching chemicals for the reduction or removal of lampenflora has been investigated by Cigna (2011). The two most widely used chemicals are sodium hypochlorite (chlorine bleach at 5% by vol) and hydrogen peroxide (at 15% by vol). Sodium hypochlorite releases chlorine into the cave environment and, although an effective cleaning agent, is poisonous to cave life, though it may disperse quickly. Hydrogen peroxide may also have unintended biological effects where iron-rich sediments are present. A new study in the USA (Kieft et al., 2021) shows that bleach and hydrogen peroxide should not be used because of the toxicity of bleach and that hydrogen peroxide degrades speleothems. Benzalkonium chloride is an effective non-toxic biocide that removes lampenflora when used in concentrations of 1% – 10%. The authors also recommend using germicidal UV light (UV-C). Irrespective of what agent is used, thorough washing of the surfaces after cleaning is recommended, preferably using cave water rather than chlorinated water from a public supply. Annual cleaning is probably the most appropriate frequency, but some sites may benefit from more frequent cleaning using cave water alone.

New materials

New materials are constantly being developed and some appear to have good, and even great, potential for use in caves. However, while some new materials have proven to be excellent, others, such as composite lumber, have not, giving rise to adverse impacts on the cave. One aspect of the problem is that there are many types of composite material and those that contains wood fiber should be avoided as they can support bacterial growth, algae and mold. Specification sheets of all composite material should be carefully checked to ensure that the material contains no wood or paper products. If it is planned to use composite material in a cave, it should only be used after the type of composite material that is being proposed has been the subject of extensive testing in the cave environment in which it is proposed to be used. Stainless steel has proven to be an excellent material for use in a cave. However, stainless steel comes in a variety of different grades and qualities. Much of the cost of using stainless steel is in finding the right type for the intended use. It is recommended that higher grades of stainless steel be used when this material is planned to be used in a cave. New plastics have been developed that have great potential for use in caves. A great advantage of these new plastics is that they are lightweight, have mechanical characteristics close to steel and are easy to work with simple tools. The plastic portions are joined with stainless steel bolts, which make it easy to update the design in the future. Pathways can be constructed through pultrusions – which is a plastic created by drawing resin-coated glass fibers through a heated die. These are often coated with grit to provide better traction, but they can wear very quickly if there are large numbers of visitors. Handrails can also be created with fiberglass reinforced plastic.

Materials that usually don't belong in a show cave

In considering the matter of what materials do not belong in a show cave, it has to be acknowledged that many of the materials listed in this section have, at some time in the past, been considered to be appropriate for use. As a consequence, it is probably difficult to find an existing show cave that does not contain one or more of the materials that are now considered undesirable. Caves that are in the process of being developed as a show cave should avoid the use of all of the materials now known to be undesirable as described below.

Galvanised metals

In previous decades, galvanised steel piping was the material of choice for use as show cave handrails, stairs and platforms. However, the zinc in the galvanised material is easily oxidised and leaches out into the cave environment. The leaching of galvanised coatings may have adverse impacts particularly on sensitive invertebrate cave faunas and calcite deposition. Where the galvanised steel is in use in an existing show cave, a programme should be developed for its replacement with another material.

Dissimilar metals

The use of dissimilar metals such as different aluminium grades, will always induce corrosion when in contact with each other in a moist environment. The first and best solution is not to use dissimilar metals in contact with each other. The next best solution is to isolate the materials from each other, using devices such as neoprene or nylon washers, but this may only delay the inevitable if a film of water extends across the barrier. It is also recommended that sacrificial anodes not be used, as these will produce some sort of chemical compound, which may have an adverse effect on the cave.

Non-ferrous metals

Many non-ferrous metals have also had past use in caves. Perhaps the most common of these has been copper, and its related alloys, which have been the source of many green stains in caves.

Iron and steel

Untreated iron and steel are susceptible to rusting. Even those forms of mild steel that contain a small percentage of carbon are susceptible to oxidising (rusting). Consequently, raw steel and iron should not be used in show caves as rust stains are bound to result.

Bitumen (asphalt)

Bitumen (asphalt) is a black viscous mixture of hydrocarbons obtained from petroleum. Bitumen has the capability to leach products, which are toxic to biota, and may interfere with calcite deposition. If bitumen is found in an existing show cave, plans should be developed to remove it as soon as possible. Bitumen should never be used inside a cave being developed as a show cave.

Wood

For many centuries, wood has been a favoured material for building and making items, such as furniture. It was therefore natural that wood would be used in the early days of show cave development. Unfortunately, wood has a relatively short life before it starts to decay. This includes creosoted and pressure-treated wood. Generally, the environment of a cave is isolated and energy introduction from the outside will change the equilibrium of the cave. Exceptions to this occur where a river or stream runs through a cave or where there may be a high organic content for some reason.

When wood breaks down and decays in the cave environment, the decaying wood can become part of the food chain. Decaying wood can support fungal or bacterial growth and even presents the risk of invasions by exotic species that can replace native cave species. If any form of wood is used for formwork, scaffolding and similar temporary purposes, it should not be worked in a cave, if at all feasible. It should be removed on completion of the work, with care taken to remove any scraps or splinters resulting from the work or the dismantling of a structure. If decaying wood has to be removed from a cave, care should be taken to ensure that it does not disintegrate during transport, and thus provide an unnatural nutrient windfall. Even small traces of rotting wood can cause population explosions among cave dwelling species, which should be removed from the wood before the wood is removed from the cave.

Where wood is found in an existing show cave, a plan should be developed to replace it with other materials, as economics permit and where the introduction of wood would cause a significant change in the natural environment. The time period covered by such a plan should be limited by the anticipated life span of the in situ wood. During the development of a show cave, other materials than wood should be selected. Only in ice caves are the environmental characteristics compatible with wood, which is frequently used for the construction of pathways and handrails as it is not slippery and can be easily worked on in freezing conditions.

Monitoring

Basic monitoring of the cave climate should be carried out on a regular basis and a formal monitoring schedule adopted. The air temperature, humidity, radon (if its concentration is close to or above the level prescribed by the law) and water temperature (if applicable) can be monitored. Monitoring of the carbon dioxide should be included if its concentrations are substantially outside the range of natural variations. Airflow in and out of the cave can also be monitored. When selecting scientists to undertake studies in a cave, it is very important that only scientists who have good experience with cave environments be engaged for cave related matters. Many, otherwise competent scientists, may not be fully aware of cave environments. If incorrect advice is given to the cave management, then this could result in endangerment of the cave environment. Cave science is a highly specialised field.

Show cave managers

Show cave managers should be competent in both the management of the business of the show cave and its environmental protection. The managers of a show cave must never forget that the cave is 'the goose that lays the golden eggs', and that the cave must be preserved with great care.

Show cave guides

The guides in a show cave have a very important role as they are the linkage between the cave and the visitor. It is very important that the guides are properly trained. The management of a show cave should produce a guide’s manual, specifically written about guiding in their particular cave. Guides should be trained in group dynamics, as well as the attributes of the cave including geology, biology, paleontology, cultural and historical significance, and the effective ways to provide that interpretation to visitors in an informative and entertaining manner. Show cave guides have a wonderful opportunity to inspire visitors to become advocates for our caves and karst landscapes. They are also responsible for visitor safety and cavern protection.

Interpretation

The purpose of interpretation is to provide information about the cave and its natural and cultural heritage values to visitors, to enhance their appreciation and understanding of the cave experience. Another aspect of interpretation includes effectively communicating rules and regulations for the protection of the cave resources and for the safety of cave visitors and staff. These 'dos and don’ts' should be developed, displayed and verbally communicated to visitors in a way that helps them understand and hopefully appreciate their importance, and to enlist voluntary compliance. In those caves where visitors enter in tour groups accompanied by a cave guide, or individually while being monitored by guides stationed throughout the cave, the cave guide should be appropriately trained to ensure adherence to the rules and regulations for cave protection and visitor safety.

The experience of a cave visitor is shaped by a number of factors that operate before, during and after the actual visit. Of these factors, awareness, anticipation, reception (arrival) and recollection may be more important than the actual cave experience itself, and in the long run, the recollection probably counts most to the individual. Any monitoring of the visitor experience must be designed to assess these factors.

Some basic principles in designing the visitor experience are:

- Information made available to the public, either online or at the site, should be accurate and not convey a misleading impression. Making this information available prior to the visit can reduce undesirable behaviour and enhance anticipation.
- Ensure that the best possible appearance is given at the entry to the cave area.
- In those caves that have guided tours, each tour should be tailored for an appropriate number of visitors, for an appropriate amount of time and be led by a knowledgeable guide who tries to develop a relationship or rapport with the visitors.
- Every effort should be made to identify the specific cultural needs and interests of all visitors and provide for them.

One of four interactive stations providing multimedia information in German and English, Wendelstein Cave, Germany. Photo by Peter Hofmann.

It is recommended that each show cave develop a particular theme or themes for use both in tours and in promotional material on the internet, and which could easily form the basis for an education programme. Although developing these themes presents some challenges for guides and managers, they can result in more meaningful cave experiences for visitors and a more fulfilled workforce. In the past, most cave tours were guide-led, but during the 21st century CE there has been a move towards self-guided tours that allow visitors to move through the cave at their own speed. The move to self-guided cave tours, in some cases, is driven by a desire to reduce costs by employing less guides, but it is also possible to adopt a model where guides are deployed at particular locations through the cave to ensure safety, prevent damage and provide additional interpretation where required. The latter model is particularly appropriate where local rural communities are involved in cave tourism and guiding provides significant local employment. Some show caves will use each of these models or hybrids seasonally as visitation fluctuates.

Self-guided tours require a different approach to interpretation and the following approaches are currently being used:

Approaches to interpretation used in self-guided show caves

Interpretive type	Used at these caves:	
Signage only	Many caves, including those in the following countries:	
	Australia	Fig Tree Cave, New South Wales
		Mammoth Cave, Western Australia
	Austria	Lamprechtsofen Cave
	China	Furong Cave, Chongqing
		Tenglong Cave, Hubei Province
	Malaysia	Deer Cave, Sarawak
		Niah Great Cave, Sarawak
	Slovenia	Škocjan Caves
	USA	Mammoth Cave, Kentucky
Handset with messages in several languages	Laos	Vieng Xai Caves
	Spain	Cueva de Nerja
	USA	Carlsbad Cavern
Fixed stations with audio messages	Mexico	Balankanche Cave
	UK	Dan yr Ogof
App available for visitors' smart phones	UK	Treak Cliff Cavern

Whichever type is used, good interpretation is critical, including the use of thematic interpretation and incorporation of a strong conservation message. Explanation boards should be in the local language, as well as any international language that prevails.

Guidelines

(20) Existing show caves should be managed to the highest possible standards and should work towards compliance with the ISCA Recommended Guidelines, as well as the guidelines provided here.

(21) A thorough study must be conducted to determine environmental and economic sustainability before developing a cave into a show cave.

(22) Safety must be the number one priority for every show cave.

(23) Determining the visitor carrying capacity of a specific show cave is the balance between providing a safe, informative and enjoyable cavern tour experience for visitors and minimising the impact on the cave environment, while achieving economic goals. All three – visitor experience, environmental impact and economic goals – of these factors must be considered.

(24) It is necessary to have a site plan that depicts the surface detail and the underground detail of a cave in order to analyse the potential impact surface works could have on a cave.

(25) Appropriate infrastructure at the entrance of a show cave is essential for maintaining the natural cave environment.

(26) In all new development, whether in existing show caves or at new sites, infrastructure needs should be carefully assessed, designed and installed, taking current best practices into consideration.

(27) The electric lighting network in a cave should preferably be divided into zones, thus enabling only those parts of the cave currently occupied by visitors to be lit effectively. The use of light should be minimised to only illuminate certain features and create an atmosphere that enhances visitor experience.

(28) Effective show cave management is underpinned by monitoring to allow adaptive site management. At a minimum, basic monitoring of the cave, fauna, climate and carbon dioxide concentrations should be carried out according to a monitoring schedule.

(29) Show cave managers should be competent in both the management of the business of the show cave and its environmental protection.

(30) The guides in any show cave play a very important role as the linkage between the cave and the visitor. It is essential that guides are properly trained in the values of the particular cave and in their interpretation for visitors.

(31) All show caves should develop high quality interpretive information to help the public better understand and appreciate the cave environment.

Visitors can experience the beauty and texture of ice in Eisriesenwelt cave, Austria. Photo by Csaba Egri.

Adventure and tourism activities on surface karst

During the 21st century CE, there has been an increase in adventure and tourism activities on bare surface karst, including areas of limestone pavement, pinnacle karst, cliffs and canyons. These rugged and sometimes remote habitats may have unrecognised biodiversity and geodiversity values that should be conserved, especially in protected areas. Therefore, it is important to survey these areas for rare or endemic species of plants (e.g., orchids) or animals (e.g., langurs), or for fragile karst features (e.g., pinnacles), as part of the decision-making process about whether to allow such activities, under what conditions (regulations) and where (zoning).

Any infrastructure necessary and permitted to support such activities should be designed and installed so that it has little impact on the karst, both visually and in terms of its integrity, and can be readily removed in the future, if necessary, returning the karst nearly to its natural condition.

Karst circuits based on *via ferrata* originated in the 19th century CE in alpine karst areas of Europe. *Via ferrata* have become much more popular since the late 20th century CE, especially in Europe and are spreading around the world. Karst circuits with access facilitated by various combinations of infrastructure have been developed through pinnacle karst in several locations. At the Tsingy de Bemaraha WHP in Madagascar, the Big Tsingy circuit involves walkways, platforms, ladders, suspension bridges and cable safety lines in places. A karst circuit through the Phu Pha Marn pinnacle karst in central Laos involves ziplines, *via ferrata*, suspension bridges, a net bridge and platforms, with cable safety lines throughout the circuit. These circuits allow visitors to explore and experience the spectacular pinnacle karst landscapes and see endemic wildlife (e.g., lemurs and langurs), which otherwise are virtually inaccessible. Visitors in small groups are led through the circuits by trained guides. The extremely rugged and exposed landscapes assure that visitors stay on the defined route, leaving as small an impact as possible on the natural ecosystems. Visitors should not be allowed to walk or climb on fragile pinnacle or other karren features which may be easily broken.

Rock climbing has a long history, but during the 21st century CE, there has been a marked increase in the numbers participating, particularly in 'bouldering' where no fixed aids are employed and no ropes are used. Cliff habitats, historically one of the least disturbed by human activity, are facing more human pressure than ever before. Studies have shown that climbing routes have less plant cover and lower biodiversity than similar cliff areas not used for climbing. Limestone generally does not fracture cleanly like granite or sandstone. This can make it difficult to set 'traditional' removable anchors (chocks and cams) for protection on limestone cliffs. Instead, most limestone aid-climbing areas use pre-placed bolted anchors for protection. There are codes of conduct for rock climbing, such as the Climber's Pact (see Internet Resources), which address the protection of biodiversity, geodiversity and cultural values (e.g., indigenous rock art) in climbing areas.

Zipline through pinnacle karst in the Phou Pha Marn protected area, Laos. Photo by Green Discovery Laos.

Canyoning is an outdoor recreational activity that consists of traversing along a canyon or gorge, usually with a flowing stream, using a variety of techniques such as abseiling, scrambling, climbing, jumping and swimming. Although canyoning was made popular by Americans and Europeans in the 1970s, its origins can be traced back to the late 19th century CE in France. Edouard Alfred Martel, known as the 'father of modern speleology' and a pioneer of cave exploration and study, first introduced canyoning techniques to conduct scientific research in hard-to-reach areas of gorges. To minimise the environmental impact of canyoning, it is recommended to keep to stream channels and avoid sensitive stream banks and vegetation. Where possible, use natural anchors and removable rigging in a manner that avoids damage to and protects natural karst surfaces. A canyoning code of conduct from the International Canyoning Organization for Professionals (see Internet Resources) includes discussion of environmental awareness and protection.

Guidelines

(32) Rugged and remote surface karst habitats may have unrecognised biodiversity and geodiversity values that should be surveyed and assessed as part of the decision-making process about whether to allow adventure and tourism activities on them, under what conditions and where.

(33) Infrastructure necessary to support surface karst activities should be designed and installed such that it has little impact on the karst, both visually and in terms of its integrity and, if necessary, can be readily removed in the future, returning the karst nearly to its natural condition.

Scientific research

Caves are one of the best places to study the past histories of our planet and humankind, as well as biological evolutionary processes. They are effectively well-insulated time capsules, predisposed in many ways to preserve organic material such as bone, shells, pollen, charcoal and plant material and inorganic material, including both clastic sediments and speleothems. Caves and cave entrances serve as temporary shelter or permanent refuges for many species of plants, animals and micro-organisms unable to survive on the surface, especially in those regions where aridity, low humidity and temperature extremes are limiting for organisms.

A biospeleologist sampling invertebrates in Frauenhaldenhöhle, Germany. Photo by Rainer Straub.

Organic and inorganic materials are transported into caves via a variety of natural geomorphological processes, most commonly involving water and, in some cases, wind. Once underground materials accumulate and when passages become relict the accumulated deposits are shielded from the weathering processes that operate on the surface. Most active karst hydrological systems are characterised by rapid flow-through times, though in some areas, groundwater follows deep flowpaths and can take hundreds or thousands of years to return to the surface. Providing there is no mixing with near-surface waters they emerge without any anthropogenic pollutants, such as chlorofluorocarbons or the human introduced atomic radiation of the 1950s. For the study of palaeo-environments or archaeology, caves now supply the 'supermarket' of multi-disciplinary information that includes isotopes preserved in speleothem, skeletal material and environmental DNA (e-DNA) preserved in sediments. For research focussing on climate change indicators, a well-preserved cave site offers many clues and study materials. These include volcanic ash layers, slackwater deposits from floods and a wealth of isotopes and organic residues present in drip water and speleothems.

For biological research, caves have been likened to 'subterranean laboratories' because of their strongly insulated and buffered environments where many of the variables and perturbations that affect surface environments are absent or strongly muted. These include constant darkness, near constant temperature and high humidity, low food supply and absent or strongly muted diurnal/seasonal cues. These relatively stable and predictable conditions make caves and cave fauna highly suitable for research into fundamental biological questions such as those relating to adaptation, energy flow and evolutionary processes. Active caves commonly receive regular inputs from the surface, but relict caves can become isolated 'subterranean islands', in which specialist, locally endemic, 'troglobiont' species may evolve. As these species are rare and commonly have restricted distribution ranges, it is important to assess the potential impacts that research activities may have on them.

Cave dwelling bird and bat populations are especially vulnerable to disturbance from people entering caves, irrespective of scientific research. The capturing of bats and birds, or nest collecting, in cave roosting and breeding sites, whether for research or for traditional food/medicine purposes, can have very significant impacts on the local bird and bat populations. Most populations of cave invertebrates appear to be less reactive or obviously disturbed by human presence. Trampling is an obvious direct threat to individual cave invertebrates, and heavy human traffic may have significant impact on vulnerable floor dwelling species, which tend to be cryptic. Trampling of soft sediments is thus a general problem for all cavers, not just scientists. Walking on loose stones can crush species sheltering underneath. However, most invertebrate populations are likely to be in meso-cavities, and will only come out into cave passages when conditions are suitable.

Over-collecting by scientists has also been perceived as a threat to cave fauna. This was the case in some European countries where the Olm salamander (*Proteus*) was a prized museum exhibit. Cave beetles are still sought-after as collectible specimens, much like butterflies, by amateur and professional entomologists. Scientific over-collecting is only likely to be a threat where research project requires large numbers of specimens, such as population genetic studies, and only when the population being sampled is small and isolated. Most modern biologists are aware of the potential impact of over-collecting, and the vast majority of biological studies are undertaken with minimal disturbance to populations and species viability. This includes the removal of pitfall traps no longer in use. However, the occasional collection of individual specimens for scientific identification and taxonomy should not be perceived as a threat; rather it is essential for accurate identification and conservation of species. Poorly designed (or conducted) scientific experiments can result in environmental impact. During the 1970s, for example, there was an attempt to replicate the famous Moulis Underground Laboratory (France) in a Brazilian cave inside a protected area. The attempt failed, resulting in the death of many cave-adapted fish, with the problem then exacerbated by a failure to remove the degrading laboratory structures.

It is important to keep in mind that the greatest threats to cave fauna and to cave ecosystems do not originate from scientific research, rather that they originate from activities outside the cave, including mineral extraction, deforestation, agriculture, groundwater extraction, water pollution and sedimentation. Cavers in general may inadvertently impact on caves by introducing microbes into underground ecosystems (see Recreational and adventure caving).

The designation of protected areas is commonly underpinned by extensive scientific research, which is sometimes reflected in the site name. Sometimes the protected areas are created because scientific research has demonstrated the existence of valuable environmental assets that merit protection. Such is the case in areas with rare or threatened species or key geosites. However, there are many karst protected areas, particularly those designated primarily for landscape reasons, where there is limited understanding of how the landforms evolved or of the processes and linkages that operate to keep the system working. Many karst protected areas have become centres of high-quality research because they present significant natural values, and also because in many parts of the world, protected areas welcome scientific activity.

Research in protected areas has contributed significantly towards the understanding of karst systems. Mammoth Cave National Park (NP), in Kentucky, and Carlsbad Caverns NP in New Mexico, both World Heritage Properties in the USA, have been key areas for the development of karst hydrogeology and speleogenesis (Mammoth) and of hypogene speleogenesis and cave geomicrobiology (Carlsbad). There is research infrastructure in both parks, including accommodation, as well as a supportive staff, which is sometimes not the case when research is undertaken on private lands. A further advantage of research in protected areas is that there may be greater protection for valuable field equipment. Monitoring instruments such as fluorometers and loggers monitoring environmental parameters commonly need to be deployed for extended periods in order to collect meaningful data, with an ever-present risk of damage or theft. Protected area staff can also assist in collecting data, checking equipment integrity and providing scientific insights otherwise unavailable to a scientist in a remote location. A few protected areas have local scientists on their permanent staff, sometimes called 'cave specialists'. This has allowed high quality research to be performed on a routine basis. In Mammoth Cave NP, research by resident scientific staff yielded the world’s most detailed mapping of groundwater basins in karst. A further advantage of having resident scientists is the possibility to provide students and the general public with in-depth information on karst and caves. In the USA, collaboration between Mammoth Cave NP and the nearby

Western Kentucky University has allowed the implementation of the 'Karst Field Studies' programme, a series of week-long karst and cave focused field seminars led by both resident and non-local scientists that has been running since 1979.

What may be termed 'inwards-focused research' aims to increase understanding of the protected areas and can therefore feed directly into management. A well-structured programme of monitoring (see Developing effective monitoring and mitigation) is likely to represent a form of research in that it will yield scientific data that should be the subject of rigorous analysis. However, inwards-focused research differs from routine monitoring by addressing specific questions (e.g., a programme of water tracing using dyes to establish the catchment area of a spring or springs) or problems (e.g., investigating a decline in a particular species of plant or animal that has been identified by monitoring). In contrast, 'outwards-focused research' uses data or material collected within the protected area to address wider issues (e.g., reconstruction of past environments using the record preserved in speleothems, or the use of a cave as an underground laboratory). A good example of the latter is the Vivarium located 50 m inside Postojna Cave, Slovenia, part of which is a laboratory used for scientific work and research. Terrestrial caves are also being used as testing grounds for robots that may be used to explore caves on other planets. In some situations, funding for research is preferentially channelled towards protected areas. In Brazil, where caves are protected at a federal level, environmental compensation money related to impacts in caves should be preferentially directed towards research in caves. Some show caves, such as the popular Nerja Cave, near Malaga, Spain, have also funded karst research, including scientific conferences.

In all protected areas, research in caves and on karst should ideally only take place following a written application and the granting of a research permit. Permits should be applied for well in advance, and it is advisable that the research team work in conjunction with local communities, including appropriate payment for services. Some countries have specific rules for researchers from other countries who wish to undertake karst and cave research. The aim is to ensure that the researchers do not adopt a 'colonialist' approach and that the host country shares in the knowledge gained. The UIS has adopted a Code of Ethics for international caving expeditions, some of which include a specific research component (see Internet Resources). It is particularly important that those undertaking research in countries with no history of cave exploration help local peoples understand the purpose of their work, in order to avoid possible misunderstandings. One unfortunate case was an expedition to Ethiopia where locals were told that speleothems were "valuable for scientific research", which led to some people going into the caves and removing speleothem in the belief that they could be sold.

Wherever possible, protected area staff should be made aware of the research project and, if possible, they should be involved in data collection. This will enable them to refer to the research when providing tours to groups of visitors, and better assist subsequent research teams with field-specific details on prior studies. Researchers should be encouraged to make their work available in a form that can be understood by visitors. This could be via a poster presentation in the visitor centre, an article on the internet or via social media. In some cases, it may be possible to share data widely. The British Cave Science Centre (BCSC) at Poole’s Cavern, a Site of Special Scientific Interest in Buxton, England, has established a real-time cave climate monitoring system. Data are uploaded to the BCSC web site and can be downloaded and used by anyone free of charge (see Internet Resources).

It is recommended that application forms for research permits include:

- A description of the project and, for outwards-focussed research, reasons why it needs to be undertaken in the protected area rather than another site.
- The location(s) where equipment is to be installed or samples are to be collected (and volume and frequency of sample collection) with justification for the particular location(s) chosen.
- An assessment of the potential impacts and steps that will be taken to minimise those impacts. A good example is research that requires the use of speleothems, such as in paleoclimate/paleoenvironment studies. In the 1980s, when relatively large amounts of material were needed, it was common for whole speleothems to be removed from caves. For most studies, this is no longer necessary, as only small amounts of material are required and these can be obtained by careful extraction of a thin core. After the core has been extracted a small plug can be inserted, allowing the speleothem to heal-over if there is ongoing precipitation of calcite. If available, preference should be given to already broken speleothem samples, a common situation in caves that receive visitation. If no broken speleothems exist, a conservative approach should be adopted, choosing material hidden from view and of limited aesthetic value.
- Details on any planned biological or microbiological sampling. This is particularly important where researchers are based in countries other than the one in which the sampling is to be undertaken, as some countries do not allow these materials to be exported without additional paperwork due to frequent cases of biopiracy. Conversely, countries such as Australia and the USA have very strict laws regarding the import of biological material or soil.

- The use of drones and robots for cave photography and mapping by trained cave operators is a recent development that can provide high quality data for scientific analysis and interpretation, but any use of these devices should be approved as part of the research permit.

Those assessing permit applications should be aware that outdated techniques or protocols can result in lasting damage to cave and karst resources. This has occurred during archaeological and paleontological work when excavations and the removal of artefacts or biological remains was performed without contextual (taphonomic) in-situ studies, limiting considerably the chances of obtaining critical chronological and depositional information. If possible, a representative portion of the deposit should be preserved intact to allow for future work with more advanced techniques. The stable environmental conditions that tend to facilitate the preservation of paleontological assemblages and their contexts are those most vulnerable to disturbance. Excavations in such passages may entail significant changes to the energy regime, with corresponding impacts on the underground environment. All archaeologists are aware of materials that might impinge on their expensive dating methods, but decaying plastic sheeting and fraying shade netting are still to be found in many cave sites after the 'rehabilitation' of excavated areas. In contrast to surface site disturbance, traces or effects of human activities in medium or low-energy underground environments may persist for hundreds or even thousands of years. Researchers should be encouraged to take advantage of technological advances, particularly remote monitoring surface site opportunities, thereby reducing the number of visits. Photovoltaic panels and small wind turbines allow continuous monitoring without a need for visits to replace batteries and data can be uploaded using mobile phone or satellite networks.

Coring a speleothem for palaeoclimate research, conducted under a permit at a Site of Special Scientific Interest in the UK. Photo by John Gunn.

Guidelines

(34) All protected areas with caves and karst should develop policies for the management of research, which should only be permitted following receipt and approval of an application.

(35) Those wishing to undertake research in caves should be able to either demonstrate they are familiar with cave environments and the local Minimal Impact Caving Code, or that they are working with experienced cave scientists who will ensure adherence to the code.

(36) For those caves that have a management plan, there should be a section on research activities.

(37) All researchers working in caves or on karst whether inside or outside of protected areas are recommended to carefully evaluate their proposals, including a comparison of potential benefits with the risk of damage to the environment or cultural values.

(38) There should be an emphasis on minimal sampling methods for fauna, speleothems and sediments, and researchers should commit to publishing results in a form easily understood by the public as well as in academic media. Researchers should commit to equipment removal and site rehabilitation (if necessary) on the completion of the project.

Agriculture and forestry

The development of the human species has been inextricably linked to the removal of natural vegetation, mostly forests, and its replacement by agricultural land. Thus, human-forced vegetation succession has disrupted the naturally evolved ecosystems, with a specific floristic composition and a long-term adapted biota. Globally, the only karst areas that have not experienced some impacts from forestry and agriculture are located in remote locations or have received strong protection that has precluded agriculture or forest clearance. Many human impacts on karst are direct and localised, such as those from extractive industries, with the impact varying from small scale to profound. The rock desertification widespread in parts of the Mediterranean basin and in southern China, for example, is a consequence of soil erosion brought about by the removal of native vegetation and follow-up agricultural practices. It has been described as the most profound human impact on karst. Even in temperate areas where the karst is largely soil covered, the largest anthropogenic impact (in terms of areal coverage) is commonly from agriculture.

Karst landscape in the Făgăraș Mountains, Southern Carpathians, Romania. Formerly endangered by the illegal clear-cutting of forests, poaching and excessive hunting, the Piatra Craiului National Park has been the focus of extensive reafforestation and rewilding of wildlife, with the reintroduction of bison in 2020. Photo by Maria-Laura Tîrlă.

The Mediterranean region, the cradle of European civilisation, is a 'type-location' for human impacts on warm temperate karst. Its primeval pine and cedar forests were gradually replaced by secondary scrub associations known as *garrigue* or *phrygana*. Plant communities with similar physiognomy developed northwards, in the Balkans and Eastern Europe at mid-latitudes, under more temperate, though moderately continental climate conditions (the Serbian *shibljak* and the thorny mantle *Crataego-Prunetea* shrubland communities). These warm dry shrublands form the dominant plant associations on many limestone karst highlands. Outside of Europe, there have been similar but more recent trends. In Madagascar, native forest deforestation for conversion to agricultural land was a major threat to endemic cave stream fauna due to rapid shifts in the trophic bases of food webs, causing severe biodiversity losses. In some south-east Asian karst regions, the clearance of native forest and its replacement by palm oil plantations has been a particular concern. Those karst areas that remain in a fundamentally natural condition support a rich biodiversity compared to the adjacent lithologies. This biodiversity has in part been maintained by the traditional practices of the local communities, but could be rapidly destroyed by commercial activity. In contrast to their direct impacts on karst biodiversity, the indirect impacts of agriculture and forestry on karst geoheritage are largely indirect and relate primarily to changes to water quality and quantity.

Agricultural practices on karst terrains

Practicing agriculture on karst areas has often been challenging for rural communities and their attempts to solve issues such as lack of water have commonly impacted on karst systems. In some parts of Europe, a distinctive type of landscape, sometimes called 'agri-karst' has developed in response to local climate and agricultural approaches. Agricultural practices on karst, like the karst itself, are largely influenced or controlled by climate and three broad zones may be recognised:

- Humid-tropical areas with intensive agriculture (rice, sugar cane) which commonly have dramatic karst sceneries (e.g., south-east Asia).
- Temperate karst regions with mixed agriculture based mostly on grain (especially wheat and maise), vegetables and in the warm temperate zone, vineyards or olive trees. Livestock pastoralism/ranching can also have important impacts on water quality and quantity in karst.
- Cold environments, at high latitudes or elevation, where livestock farming and/or terraced, often subsistence-based crops dominate.

In the tower and conical karsts of south-east Asia many traditional practices relate to agriculture, for instance in the fenglin-fengcong of the Yunnan, Guizhou and Guangxi provinces of south-western China, the cone karst of Bohol, Philippines or the cockpit karst of Gunung Sewu, Indonesia. Over a long time, communities have shaped terraced hills and mountains in order to reduce slopes and retain rainfall water during the wet season. The wet-rice agriculture of Bohol, Philippines, stands as an example of harmonious integration between karst landscape and agricultural practice, seemingly succeeding in achieving sustainability at centennial scales. The seasonal-based calendar that has been used for centuries by local communities aimed at adapting the local agricultural needs to climate bias seems to best fit the natural regulatory system of the underlying karst. Unfortunately, the decline of irrigation systems has triggered socio-environmental changes (replacement of wet-rice crops by a less economically valuable corn-based agricultural system) with severe effects on 'wet' lowland karst areas. In contrast, historical occupation of karst in south-western China (one of the largest continuous karsts in the world) has resulted in severe vegetation cover loss and soil erosion due to agricultural use, the related deforestation and increased water consumption.

Intensive agriculture on the floor of a large depression in the Wan Fenglin karst, Guizhou, China. There has been significant deforestation of the towers in the background although some areas of forest remain. Photo by John Gunn.

In temperate zones, gently-inclined plateaux pitted by dolines form a common karst topography that at its most developed stage results in a polygonal karst. Where this landscape was originally covered by dense, old-growth forest vegetation, dolines can act as refugia for vascular plant species, which is important for conservation purposes in the current context of global warming. In these areas, forest removal commonly results in sediment transfer towards the lower parts of dolines, with consequent changes on the hydrological regime, as observed in the King Country karst, New Zealand. Dolines are commonly deliberately infilled in an attempt to increase the area of level ground. Karren may be destroyed for similar reasons and they may also be quarried for local wall building or, in some areas, for decorative stone. Each of these actions has the potential to trigger severe changes in the functionality of underground geoecosystems.

Agriculture is related to historical deforestation, soil erosion, and subsequent higher levels of sediment changes, as well as changes in food resource utilisation patterns in both surface and subsurface streams. These act as principal stressors on cave stream invertebrate communities. Sediment entering a cave, for instance, will be deposited in areas of lower velocity, thereby changing the habitat. Sediment inputs can also disrupt conduit hydraulics, particularly where they accumulate in phreatic loops. Organic pollution changes the community structure of cave biota, and generally results in its decreased distribution and richness. Dissolved organic matter and biofilms on pebbles are important energy sources for stream communities. Other anthropogenic stressors generate effects on the metabolism of subterranean organisms and include metals and metalloids, pesticides, fertilisers, emerging contaminants and volatile organic compounds. Common sources of contamination include fertilisers and manure applied to field crops, manure storage facilities, feedlots, milking sheds, poultry and pig houses and stockyards. Coxon (1999) provides examples of agricultural impacts and explains the crucial role of karst aquifers in transmitting the agrochemicals and pathogenic organisms to springs. These activities are not only felt by subterranean organisms but may directly impact on human health. In the Waitomo area of New Zealand, for example, piggery waste discharged into a doline contaminated a spring that supplied water to a farm. In Ireland, a karst spring that supplied water to the town of Castleisland had to be decommissioned due to pollution from slurry and other farm-generated pollutants. One of the most serious, and well documented, impacts of agricultural pollution on karst occurred in May, 2000, when the municipal wells at Walkerton, Canada, became contaminated with pathogenic bacteria, resulting in seven fatalities and illnesses in more than 2,300 people.

Sheshymore limestone pavement in the Burren and Cliffs of Moher UNESCO Global Geopark, Ireland. Pollen analysis suggests that this area had a thick mineral soil and was forested in prehistoric times. Forest clearance was followed by catastrophic soil erosion, a process now commonly referred to as rocky desertification. Photo by John Gunn.

Most pollution is generated by point-recharge and therefore can be minimised if 1) the direct discharge of agricultural runoff into areas of concentrated recharge, such as sinking streams, dolines or other natural openings, is not permitted, and 2) buffer zones are established around these areas. No ploughing or livestock grazing should be allowed in buffer zones and a complete vegetation cover should be maintained to filter out any sediment in runoff from ploughed land. Particular care is needed in areas where there is only a thin cover of soil over the karst, as was the case at Walkerton.

Agricultural land-use change may reduce soil carbon dioxide concentrations, which in turn will impact on the rate of dissolution in the epikarst and potentially on speleothem deposition. Soil CO_2 concentrations are commonly markedly higher under native forest, for instance, than under grassland, and pasture commonly has higher concentrations than land under crops. One consequence of the latter is that studies have shown that soil CO_2 concentrations can be rapidly raised by conversion of arable land to grassland, which could be a good practice to implement on degraded karst terrains. Reduction in the soil-cover through erosion will lead to more rapid infiltration, particularly following intense rainfall, and where this occurs above a cave, the unsaturated rapid-recharge waters will have the potential to redissolve speleothems.

Seasonally cultivated land in Cerkniško polje, Slovenia. Photo by David Gillieson.

Forestry on karst

Forests are a well-established, long-term evolved form of natural vegetation essential for the regulation and function of karst systems. In karst regions, forests are an important component of the biogeochemical cycle. For sustainable management of forested karst terrains, some principles regarding the nature of forests and the variability of soil carbon dioxide (CO_2) require consideration. After oceans, soil is the second largest carbon sink on the Earth. Forest vegetation and the soil below are both carbon stocks and carbon sinks, meaning that they can capture CO_2 from the air and store it, as well as gradually release it. Some of this CO_2 dissolves into the water that percolates down into the limestone, causing it to weather and ultimately form subsurface openings and caves. In this way, the carbon budgets of a karst system are crucial to its function, and a certain balance is reached within each karst area or basin between the vegetation, soil, rock and groundwater. Changing the land use or the vegetation will alter this balance, with climate change being another factor, affecting the availability of water and the activity of vegetation. Additional carbon is taken into the soil under forest vegetation, favouring further dissolution of the limestone with some of the dissolved carbonate ions eventually being deposited as speleothem growth. These chemical deposits, usually formed in caves by calcite precipitation, require a longer residence time for infiltration water and low drip rates to develop. These conditions are usually met in moderately fissured bedrocks, with small openings that uniformly lead and distribute the seeping water into the larger cavities. Tree roots respire more CO_2 into the soil, thus promoting the weathering of the rock, also imprinting a specific pattern to epikarst (the uppermost hydrological level of the karst system) by fissuring the bedrock during their growth. The activity of the soil microbiota is very important for regulating the carbon cycle, as they release stored CO_2 from the soil back to the atmosphere. The carbon released from weathering limestone eventually passes into the ocean via groundwater and rivers, though an unknown portion is lost to atmosphere through the soil or by direct degassing from emerging groundwater. Overall, limestone weathering is generally considered a carbon sink via 'coupled carbonate weathering', however, it is not certain this is always true, and the efficiency of the process is likely to vary in each area or basin.

Forestry is a significant type of land use with its own set of issues. Old-growth forests are usually classified as climax communities, very stable due to their long-term, undisturbed evolution. Some of these forests occupy remote karst terrains in mountain or tropical areas, but may be endangered by the continuous expansion of human habitat, tourism or timber extraction. These forests require strict protection and should not be subjected to any form of human exploitation. Forestry practices involve road construction (accompanied by slope cutting), logging, seedling growth and replanting of trees, as well as various post-logging activities. Forest clearance leaves the land temporarily or permanently devoid of the protection provided by a stable vegetation cover, which means a sudden change in the balance of the entire natural system. Rapid changes occur soon after the forest is cleared, resulting in the increased infiltration of rainfall, increased nitrogen production due to decomposition of wood remnants and the onset of soil erosion. Soil erosion triggers further changes in the epikarst pattern, and a decrease in the CO_2 sink, with negative consequences for the karst system balance.

Logging is not the only threat to the integrity of a karst environment. The introduction of alien, more economically productive tree species into well-established forest habitats developed on karst, and often a change of fundamental forest type (e.g., coniferous instead of deciduous forest, and oil palm plantations in the place of rainforest), could result in major hydrological and chemical disequilibrium of karst waters, increased soil acidity, accelerated corrosion of bedrock and speleothem degradation. Human-induced fires to forests or pasturelands adjacent to forests, if not limited to the intensity, duration and extent of those naturally-occurring fires on karst terrains, have long-term negative impacts, mostly consisting of calcination and spalling of bedrock surfaces; increased concentration of dissolved inorganic compounds into the groundwater; and changes of the groundwater chemistry and its hydrological regime.

Forested karst in Slovenia. Photo by John Gunn.

Fundamental to logging or forestry activities on karst areas is the need to carefully assess the values and sensitivity of the surface karst and its connectivity (or openness) to the subsurface. Prior to forestry activities, a methodology is required to inventory and map the karst area, assess its sensitivity to change (or vulnerability) and develop suitable management prescriptions. Consideration should be given to an analysis of the type and magnitude of forestry activities within a karst catchment.

Forestry activities can take place with the impacts on the integrity of karst landscapes with dolines (karst sinkholes). Roadbuilding and timber harvesting by clear-cut logging removes naturally evolved forest vegetation. Natural forest areas are commonly replaced by even-aged stands in 'plantation forests'. Dolines without adequate buffers can be infilled with logging debris and their steeper inner slopes destabilised. Bonanza Lake, Vancouver Island. Photo by Paul Griffiths.

Guidelines

(39) Agricultural activity has the potential to cause significant adverse impacts on karst geoecosystems. Protected area managers should (a) give particular attention to any proposed changes in land use and (b) provide guidance appropriate to the type of farming and the particular conditions on the ground in order to minimise impacts on water quantity and quality.

(40) With respect to land use, arable land requires careful soil management to minimise the erosive loss and alteration of soil properties such as aeration, aggregate stability and organic matter content, and to maintain a healthy soil biota. Pasture land should be managed to maintain the vegetation cover, giving particular attention to stocking levels. As dolines provide point recharge, they should be left in their natural state and should never be infilled or used for waste disposal.

(41) Wherever possible, buffer zones should be established around areas of concentrated recharge, such as sinking streams, dolines or other natural openings, as these are conduits for movement of contaminants and pollutants into the subsurface karst environment. On agricultural land, no ploughing should be allowed in the buffer zones and a complete vegetation cover should be maintained to filter out any sediment in runoff from ploughed land. In forests, the preservation and potential enhancement of the native vegetation in buffer zones is critical

(42) With respect to water quantity, controls should be placed on the amounts of groundwater extracted for irrigation. Rainwater harvesting should be employed to the fullest extent possible.

(43) With respect to water quality, pesticide and herbicide use should be discouraged unless absolutely necessary to control pests and weeds. Fertiliser usage should be reduced and, where possible, natural fertilisers should be used. Buffer zones around areas of concentrated recharge must be respected and chemical applications should not take place during times when the soils are at or close to saturation and there is a risk of overland flow washing chemicals into the karst.

(44) *Prior to any logging or forestry activities on karst areas, a procedure is required to inventory and map the area, assess it for sensitivity and/or vulnerability, and develop suitable management prescriptions. Consideration should be given to a prior analysis of the type and magnitude of forestry activities within a specific karst catchment, plus follow up monitoring to ensure how prescriptions were implemented and how well sensitive karst areas were protected.*

(45) *Natural forests developed on karst terrains, including mature trees and overgrowth forests, must not be clear cut, logged, or subjected to any human impact. Instead, these forests should be rigorously protected by adequate conservation management, so that surface and underground karst environments continue to enjoy the benefits of their ecosystem services.*

(46) *In areas where native forest has been cleared and replaced by other species, managers should plan for the replacement of the non-native species by the type of forest which is best adapted to the ecological conditions of the site.*

The removal of natural forest vegetation by clear-cut logging followed by wildfire can cause significant soil erosion resembling the 'rocky desertification' observed in some South China Karst and Dinaric Karst regions. This degradation of karst landscapes can alter hydrological inputs, as well as result in habitat loss and biodiversity decline. Fire causes calcination and breakage (e.g., spalling) of upper epikarst bedrock surfaces. Kinman Creek karst, Vancouver Island. Photo by Paul Griffiths.

The clear-cut logging of naturally evolved forests in karst areas with thin soils can lead to severe soil loss by gravitation into joints, enlarged fissures and other bedrock openings. Prescribed burning and/or wildfire can make these logging impacts worse. Formerly soil-covered karren forms with deep grooves are bared. Tahsish River karst, Vancouver Island. Photo by Paul Griffiths.

Extractive industries

A note on terminology. The terms 'mine', 'pit' and 'quarry' are all used to describe a site from which stone or minerals are extracted. Some authors use the term 'quarry' where stone is being extracted and 'mine' for the extraction of other minerals, but usage is inconsistent. In each case, the extraction may take place at the surface, in which case it is sometimes prefixed by the word 'open' as in 'open-pit' or 'opencast mine', or from beneath the surface. In this document we use the term 'quarry' for a surface excavation and 'mine' for underground workings.

Caves and karst areas host mineral deposits that have been used by humans since the so-called 'stone age'. Limestone, the most common rock on which karst landforms are found, has been used for millennia as a building stone. By the 21st century CE it has become one of the most widely used materials in the world including in construction as cement and as an aggregate, particularly in concrete; in the chemical and pharmaceutical industries; in the manufacture of paper and pulp; in agriculture as lime; in the manufacture of iron and steel; as dimensional stone and ornamental rocks; and in a variety of environmental processes including flue gas desulphurisation. Dolomite is commonly used as a fertiliser. Non-carbonate rocks forming karst also have practical uses. Gypsum is commonly applied in fertilisers and in the construction industry; salt finds many uses in the food and chemical industries; iron formations are essential for steel and iron manufacture; and quartzite is a common ornamental stone. It is therefore not surprising that extractive industries have the potential to impact cave and karst geoheritage and ecosystems.

In addition to bedrock, several economically important deposits are commonly associated with karst areas. Some minerals, notably those containing zinc, lead and silver, but also fluorite, barite and apatite, among others, fill collapsed structures or veins within carbonate sequences, sometimes associated with ancient dissolutional features termed 'palaeokarst'. Occasionally valuable minerals are intercepted by caves by chance, as can be the case with mineralised veins or joints, facilitating access to the site to be mined. Minerals of economic value can become concentrated in karst depressions or be washed into caves. In central Brazil, diamonds from conglomerates were mined inside quartzite caves, which required stone wall construction and cave passage modification. Worldwide, approximately 60% of all oil and 40% of all gas reserves are hosted in carbonate rocks, associated mostly with secondary porosity structures, such as high permeability horizons and isolated cavities (termed 'vugs' in the oil literature).

There are some minerals that, although not emplaced within karstic rocks, can have their genesis due, at least partially, to karstic processes. Such is the case with bauxite, an aluminium-rich weathering residue commonly associated with karst rocks. The excessive usage of groundwater (sometimes referred to as 'water mining'), although not specific to karst areas, can be considered as a form of extractive activity, especially if the water pumping exceeds recharge. This is often the case in large mine dewatering schemes.

Quarried cone and partially destroyed cave, Thailand. Photo by John Gunn.

A final category of minerals associated with caves is the chemical or organic deposits formed in dry passages. Saltpetre is a nitrate rich soil deposit that commonly occurs in caves, worldwide, and has been used extensively as the primary ingredient for the making of gunpowder, mostly during the 18th and 19th centuries CE. Guano, the organic rich excrement of birds and bats, was mined extensively in the Americas, south-east Asia and Australia during the 19^{th} century CE for the production of fertilisers. Carlsbad Caverns was one such site. Today 'subsistence' mining of guano by local farmers is widespread in the tropics. It is far from being a renewable activity – it is totally destructive of important paleoenvironmental archives and highly damaging to invertebrate communities dependent on the guano. To this day, bird nests, produced using the saliva of swiftlets, are legally collected in caves in Malaysia and Thailand to be sold as an expensive gastronomic delicacy.

Minerals associated with karst have been extracted since prehistoric times. In Carboniferous limestone near Llandudno, UK, copper mines date back around 4,000 years and mummies inside caves attest of the remarkable feats of Native Americans, who navigated kilometres of cave passages in Mammoth Cave NP, USA, to collect gypsum and flint using rudimentary torches. Similarly, Indigenous Australians negotiated around 1,000 m of passage to mine flint in Koonalda Cave, Nullarbor. The mining of limestone or travertine for construction purposes has been going on for millennia, especially in the karst rich Mediterranean region. Associated with the European 'discovery' of the Americas and Australia, the economic importance of karst deposits led to a boom in the guano-associated fertiliser industry and large-scale mining of saltpetre in caves, which in the USA was important for gunpowder production during its Civil War of the 1860s. Since the Industrial Revolution, there has been increased demand for several karst related mineral commodities.

The environmental impact of extractive industries varies widely between activities, type of deposit and mining technique, and as well as economic factors. Carbonate rocks comprise approximately 15% of Earth's continental surface, and the market price is therefore lower than less common minerals. However, there is an ever-increasing demand for carbonates and the high-purity stone used in the pharmaceutical and chemical industries commands a higher price. The extraction of other minerals hosted by karst rocks is also driven by economic factors, with prices of mineral commodities fluctuating widely according to demand. One cycle of increased demand is associated with the fast growth of the Chinese market since the later 2000s and involves base metals such as iron. The prices of other critical metals have also increased due to the rapid growth of the renewable energy sector, with lithium, nickel and cobalt essential to the manufacture of electric car batteries. These economic megacycles fuel the global mining industry and increase the pressure for mineral extraction to take place in or close to protected areas. This is a particular problem for developing countries where the high demand, and consequently the high prices, commanded by these metals have made them strategic commodities.

Extraction of carbonate rocks

Some very high purity limestone or dolomite deposits have been exploited using underground mines, but globally the vast majority of stone is extracted from open-pit quarries. In developed countries, early quarries were small-scale local enterprises, however, most stone is now extracted from a small number of large quarries commonly located on the flanks of hills or on the side of valleys. Many of these quarries have operated for decades and as permission for new sites is commonly difficult to obtain there is a tendency for operators of existing sites to seek to expand or go deeper. One particular problem for protected area managers is that sites may have been operating in, or on the boundary of, a protected area before it was designated, as is the case in the Peak District National Park, England.

In developing countries, and particularly in tropical areas, there are still many small limestone quarries and these can be particularly problematic in areas of cone karst or tower karst where a relatively small quarry may remove an entire hill that may contain endemic species. In these situations, the development of a large quarry outside of a protected area and the closure of small quarries is likely to significantly reduce impacts, particularly if higher environmental standards are required at the larger site.

Extraction of iron formations

In contrast to carbonate rocks which crop out over wide areas, iron formations are much less common rocks formed due to specific geological events that took place over a billion years ago. As the high iron concentration is due to silica leaching and iron mobilisation (the same processes that create voids and caves), most high-grade ore bodies are associated with caves. These rocks are in high economic demand and, in Brazil, a significant portion of the iron formation outcrops have already been mined, with many of the remaining areas included in future mining plans. Although it is true that most mines result in a localised impact due to the small relative size, even of the largest mines, there are usually industrial plants associated with the site, besides an extensive chain of suppliers that favours rapid urban development, resulting in considerable impact in much larger areas. In Carajás, Brazilian Amazonia, the world's largest iron deposit was not discovered until 1967 and is located in iron plateaus that contain over 2,000 caves. The area originally had a low population density, primarily Indian tribes living in pristine Amazon rainforest. Mining started a few years later and by 2020 there were over 300,000 people living nearby in new cities sustained by mining activities.

Impacts of extractive industry

As noted in the introduction, stone and minerals may be extracted from quarries or from underground mines. The impacts from these two forms of extraction tend to be very different, particularly on protected areas, and therefore are considered separately below.

Quarry impacts

Quarries have two broad types of impact; firstly, direct impacts within the site and, secondly, indirect impacts on the wider area. The first site impact is a consequence of the removal of any overlying soil and superficial deposits to expose the rock that is to be quarried. Where that rock is a carbonate, the loss of soil results in the immediate loss of most of the carbon dioxide that drives the dissolution process as that is generated in the soil zone. Following the removal of any soil and superficial deposits the first rock to be removed is from the epikarst, the region where the majority of dissolution occurs. Removal of this rock will directly impact dissolution and therefore the amount of calcium carbonate reaching springs whose catchment includes the quarry. For example, in the Forest of Dean, UK, there is a limestone quarry in the catchment of springs that are protected because they deposit tufa. The springs are monitored to determine whether quarrying is reducing the spring carbonate load and impacting on tufa deposition.

The relatively low value of carbonate rock means that few quarries are developed beneath thick overburden, but that is not the case where the quarry is extracting a more valuable mineral. In this case, material that has no economic value (overburden or the host rock for the mineral of interest) is deposited in tailings dams or as waste piles that can have a more adverse environmental impact than the quarry.

Older quarries were commonly located on the side of hills or valleys as it is easier to extract stone laterally than to go deep. This results in surface landform modification or total destruction, which is a particular concern in areas of cone or tower karst where quarrying may remove a complete hill. In addition to the obvious loss of geoheritage, many hills in tropical areas are bat roosts and host rare species some of which may be endemic to a single tower.

As quarries expand laterally or vertically, there is an increased potential to intersect elements of the karst drainage system (conduits) or caves. If a quarry has permission from the relevant authorities, there is no mechanism for avoiding cave destruction, however, permissions should include a requirement for scientific recording of cave morphology and sediments. In some countries, legislation is in place that requires compensation for cave destruction. In Brazil, for instance, the destruction of any cave that had not been classified as extremely important was legally allowed, provided that the destruction was compensated for by either a monetary payment or the permanent preservation of another cave or caves. This led to the creation of significant preservation areas, including new national parks that protect important karst areas and caves. However, placing a price tag on caves is not without risks as a preservation strategy, since the price is commonly tied to government economic indices, while ore prices vary widely. During the metal commodity booms that have prevailed since the 2000s, the cost incurred by destruction of caves may be considered a price worth paying when set against the vastly higher financial resources needed to open and operate quarries. Furthermore, the value of the mineral reserves blocked by any cave commonly exceeds the price to be paid for the cave destruction. In early 2020, total irreversible impacts in Brazil could reach a value of as much as USD 1 million per cave.

When a quarry, or part of a quarry, reaches a point where no further stone will be extracted, then there is an opportunity for restoration, which be particularly valuable if quarries are enclosed within a protected area. One possibility may be to construct a new epikarst made up of any waste limestone spread on the quarry floor (which may need ripping to improve infiltration) and covered by soil material or fine limestone (3 mm to dust) with an organic ameliorant. On the quarry margins, the technique of landform replication seeks to construct landforms similar to those found in natural karst outside the quarried area, such as rock buttresses, headwalls and screes.

Impacts outside of the quarry area relate primarily to blasting and water, and in both cases, there is a potential for a quarry outside a protected area to have impacts inside the protected area. Blasting impacts are complex and relate to both the blast design or execution and to the geology. There are examples of caves that have been intersected by quarries in which there has been no damage to passage morphology or to speleothems and other examples where caves a few hundred metres from a quarry have been damaged. A further consideration is the impacts of noise and vibration on cave fauna, which is poorly understood. These factors notwithstanding, it is clear that impacts can be minimised by modern blast design, in which the amount of explosive and its position in each shothole is carefully calculated and millisecond delays are used to reduce vibration and air overpressure. A further consideration is that in the past the most common explosive was ANFO (ammonium nitrate and fuel oil) mixed at, or even in, the borehole. This poses a risk of long-lasting DNAPL (dense non-aqueous phase liquid) contamination. Modern blasting employs pre-mixed ANFO, commonly with emulsion explosives. However, the storage of fuel oil creates the potential for release into the karst. Improper handling of ammonium nitrate can also result in nitrate contamination of the groundwater. Both the products used to create ANFO are commonly stored and mixed at the quarry before use.

A quarry face in the Lagoa Santa Karst, Brazil showing sub-soil pinnacles. Photo by Augusto Auler.

The hydrological impacts from quarries relate to water flowing into or leaving the site. As with blasting impacts, it is essential to carefully assess the hydrogeological context. Water may enter a quarry by surface flow or by intersecting major groundwater flow paths. Surface flows need long-range planning in order to manage water captured from drainage basins by quarry expansion that may disrupt quarry operation. Groundwater flow into a quarry can vary greatly. Some quarries have closed from groundwater flooding while others extend over 100 m below the original land surface but receive little lateral inflow. Where a quarry does capture groundwater from a wider area, this may be followed by the development of subsidence dolines (dropout or suffosion), and these can be several hundred metres beyond the quarry curtilage. All inflows into a quarry can potentially enhance mobilisation of contaminants within the quarry and transport them to wells and springs.

The hydrological impacts of water leaving a quarry depend on if the water flows away on the surface or is pumped from the aquifer. Overland flow from quarries often contain high level of silt that can clog karst aquifer recharge features or alter and damage stream flows and habitats. Contaminants from quarry operations are carried in surface flows and often adhere to the silts. Such impacts can be reduced by channelling the water into sedimentation basins, which must have the capacity to hold at least 100-year-probability floods. If high levels of contaminants accumulate in the sediments, they must be removed and disposed in an appropriately designed landfill. Aquifer impacts occur where it is necessary to pump water out of the quarry in order to lower the water table and allow quarry operation. Quarry dewatering raises the risk of triggering doline development, which can harm human infrastructure. It also has the potential to reduce or stop the flow of karst springs and wells. Conversely, the regime of streams that receive pumped water is changed with an increase in both the overall discharge and magnitude of flood peaks.

Quarry dust from mining and rock crushing activities can increase sediment loading when allowed to wash into karst features and, therefore, disrupting conduct hydraulics and sedimentation in surface streams. Dust control is an ongoing issue with many quarries and can result in widespread air pollution of fine particulates. After the service life of a quarry has been reached, there are long term issues associated with managing the facility to make sure that it doesn’t result in impacts to groundwater from the illegal dumping of household and industrial waste. Some governments require a reclamation plan and financial performance bonds for quarries and mines. Land use after the quarry has ceased operation may also need to be regulated in relation to development.

There is commonly a presumption against any new quarrying or expansion of quarries in a protected area, so it is important that any application is carefully considered in terms of evidence for impacts and the potential impacts if stone is instead quarried elsewhere. If a quarry has intersected and destroyed cave passages or there is evidence of rapid hydrological connectivity with springs, then this provides a good basis for opposing further expansion. However, in other situations deepening, or expanding the area of an existing quarry may not result in any new impacts on karst landforms and hydrology and may be preferable to opening a new site. Where deepening necessitates dewatering, this raises additional questions and, in all cases, applications need to provide strong evidence that there will be no adverse impacts on protected areas, and wells and springs that serve as important human and ecological water sources.

Mine impacts

The surface impacts of underground mines are confined to the area around the entrance(s) that lead down into the mine together with any areas where mineral is processed or residues are disposed of. No new mine should be located inside a protected area unless a very strong strategic case can be made and processing areas and waste mounds should be well outside the protected area boundary. However, it may be possible to extract mineral from beneath a protected area using a mine(s) with entrances outside the area. Modern mining techniques minimise the risk of collapse into workings and the most significant impact is likely to come from the need to remove groundwater from the mine workings. One technique that has been widely used in the past in some karst areas is to drive drainage adits from deep valleys to effectively reduce groundwater elevation throughout a large block. This results in springs, and streams fed by springs, losing flow and in some cases becoming completely dry whilst those rivers fed by the adits have their flow increased. Modern deeper mines commonly require large scale dewatering schemes, some of which involve pumping rates in excess of 6 m^3/s. In porous media, pumping results in a cone of depression in the water table, but in most karstic rocks the permeability is markedly anisotropic and the impacts of dewatering may extend many kilometres, particularly where mines intersect conduits. As with drainage adits, the common impacts are a loss of flow to springs and spring-fed watercourses and an enhanced flow in rivers that receive pumped water. Where the bedrock is overlain by more than 3 m of soil, drawdown of groundwater in superficial deposits commonly leads to the formation of subsidence dolines. Additional impacts relate to changes in water chemistry and to suspended sediment loads.

Mines and quarries can intersect cave passages that can impact or alter cave climates and result in the loss of habitat for endangered bats. Efforts to minimise impact to significant bat or endangered species habitats should be taken into consideration when permitting a mine or quarry. The Greer Limestone Quarry in West Virginia, USA, for instance, has worked closely with cavers to allow mapping of Hellhole Cave, a 50 km long cave located near the quarry and an important hibernaculum for two critically endangered bat species.

As is the case with quarries, mines have a limited lifespan, commonly no more than a few decades. In some cases, the mineral is exhausted but commonly mines are abandoned because they become uneconomic due to increased costs of extraction or a decrease in market prices. If new uses are found for a mineral, with a consequent increase in value, there may be pressure to re-open mines that have been disused for decades. In those countries with a long history of mineral exploitation, there are many mines and mining sites that have been abandoned, commonly with no attempt at restoration. In some cases, these sites have been given protection in recognition of their historical importance or because rare plants have become established on disturbed ground and waste mounds. Other sites pose environmental problems. such as soil erosion, acid mine drainage and the formation of collapse sinkholes. The proper closure of a mine, termed 'decommissioning' is often very complex and costly, and in the past has seldom been incorporated into mining operational costs. There have even been attempts to avoid any decommissioning costs by what has been termed 'strategic bankruptcy'. Decommissioning and correct post-closure of mines in karst areas should include long term monitoring of ground surface movement, groundwater quality and surface and underground ecosystems.

Summary

The task of reconciling extractive industry with conserving karst and caves is always challenging as it relates both to potential or actual environmental impacts and to political and economic factors involving stakeholders that operate at scales from international to local. In some cases, development has been permitted in a protected area because it is considered to be 'in the national interest' and there have been cases where protection has been completely removed to allow development. However, in the 21st century CE, there has been increased adoption of ESG (Environmental, Social, Governance) practices in the corporate industry and a recognition that failure to protect important sites can damage the reputation of a company and ultimately the executive officers. In 2020, the destruction of important archaeological sites in two iron formation caves in Australia led to substantial public outcry, initially from Indigenous Australians, but then globally following publicity on social media. Pressure from shareholders led to the removal of the CEO and several senior executives, followed by the resignation of the Chairman and several Directors. A parliamentary enquiry into the case is ongoing as this document is written, and may hopefully result in changes to the mining legislation, affording such sites greater protection.

Dowlow limestone quarry in the Peak District, UK. The quarry has an area of about 0.5 km^2 and in 2021 the lowest point was some 100 m below the original land surface, but no conduits or caves have been intercepted and there is no groundwater inflow from the quarry faces. Photo by Tony Marsden.

Most extractive industries have a high, unsustainable carbon footprint. It has been estimated that the cement industry, for instance, which involves the high temperature release of CO_2 that has been locked during carbonate formation and diagenesis, is responsible for 8% of global greenhouse gas emissions. An even larger percentage is attributed to the burning of fossil fuels (gas and oil) extracted from carbonate rock reservoirs. As the planet struggles to reduce emissions within acceptable limits of warming, these industries, already at an environmental crossroads, will likely face challenging times.

Although the fragile nature of karst and caves makes it difficult for them to coexist with extractive activities there is a need to pursue a balance. There have been situations where quarries operate very close to caves or mines extend beneath karst without generating noticeable impact, and others where there has been widespread disruption of hydrological systems, total destruction of geoheritage and loss of endemic species. It is unlikely that a perfect equilibrium between gain and losses can ever be achieved, however, with rigorous scientific assessment, detailed monitoring, and minimal impact operation it may be possible.

Guidelines

(47) There should be a presumption against new mines or quarries in karst protected areas unless it can be shown that there is no alternative source for a mineral that is in short supply and of high economic or strategic value.

(48) Any proposal for a new mine or quarry in karst should be subject to a detailed environmental assessment that considers both features in and on the boundary of the area, as well as the potential for distant impacts via surface water and karst groundwater.

(49) The environmental assessment should describe and assess the value of cave and karst landforms and ecosystems. It should assess whether there are alternative sites for extraction where there would be less significant impacts. Where there are no alternative sites, then there should be a carefully designed buffer protection zone, wherever possible, around significant caves and karst features in order to protect the integrity of the cave ecosystem, as well as the continuity of hydrological processes.

(50) Where there is no alternative to destruction, features should be recorded and, where relevant, removed for scientific study – i.e., record and remove speleothem and sediment for palaeo-environmental study.

(51) Where development is permitted, there should be a well-designed environmental protection system, as well as a monitoring protocol to record conditions during operation and the efficacy of the protection system so changes can be made if needed. There should also be a detailed closure plan that includes appropriate restoration and long-term monitoring, including a bond paid in advance to assure funding for closure will be available.

Development and infrastructure

Throughout history, people have used karst and caves for a variety of purposes. Structures were built for living, protection, agriculture or water supply. In the Middle Ages in Europe, fortifications and castles were built inside caves, such as Predjama Castle in Slovenia, to provide both protection and an escape route through cave passages in case of invasion. Small scale industries also took advantage of caves. Rope making has taken place in the large entrance to Peak Cavern, England, from the Middle Ages to the present day, and although ropes are now made largely for sale to tourists who visit the cave, there was once a small settlement of rope makers living in the cave. In the South China Karst World Heritage Property, there are still small dwellings in cave entrances. Many caves are used to mature cheese and the famed Roquefort blue cheese can only use its name if matured inside the Combalou caves in France. Mushrooms, beer, wine, kimchi and several other products have been, and in many countries still are, produced or stored in caves. Road construction has sometimes taken advantage of cave passages as a more convenient option than building costly tunnels. The roads that cross Mas-D'Azil cave in France and a section of Jenolan Caves in Australia are good examples. Many karst springs show some type of engineering structure. Further examples of infrastructure in caves and karst relate to water usage (see Water supply), quarrying and mining (see Extractive industries) and tourism adaptation (see Show caves).

Predjama Castle, Slovenia, was built in a cave mouth in the 13th century CE. Photo by David Gillieson.

It is only natural that as population increases in tandem with the need for infrastructure, karst areas will both affect and be affected by such developments. The exponential population growth that has occurred since the 19th century CE has been closely linked with industrial development and urbanisation. The total population living in karst areas or depending on karst resources, such as water, is ever growing, being estimated as 1.18 billion in 2020. In regions where karst is the dominant type of landscape, all development, including entire cities and industries, had to be built upon karst. This has resulted in increased environmental pressure over fragile karst ecosystems. Nevertheless, advances in the understanding of the karst dynamics, coupled with more sustainable approach, has led to important advances in allowing both development and karst protection to coexist.

Development and infrastructure in karst areas can be of different types and functions, resulting in diverse types of fragility and impacts. A broad classification is adopted, comprising:

- Linear infrastructures.
- Dams and reservoirs.
- Industries.
- Urban developments.

These different types are commonly associated and the dividing line between then is often blurred. As a general rule, unfortunately not enforced everywhere, an environmental assessment study involving the site and the immediate surroundings (a protection buffer zone) should be made prior to any installation. In this zone, a more detailed study involving inventory of caves and surface karst features should be performed in order to assess whether the project should go ahead or should seek alternative locations. Changing the location of a given project is sometimes impossible, and such as the case of some water reservoirs and dams. However, in most cases, this action, which may look costly and radical in the beginning can, in the end, prove to be a wise one as it will avoid the costly procedures associated with environmental reparation or litigation.

Linear infrastructures

Linear infrastructures comprise roads, railways, electrical transmission lines, water channels and other structures which are usually narrow and of significant length. Essential for transport of people, goods, water and energy, their density is directly associated with economic wealth and population size.

Because of the characteristic rugged terrain of karst areas, building such structures can be challenging. Tunnelling is a common alternative for crossing karst massifs and can result in the interception of unknown caves and lead to water inrush. A further consideration is the stability of nearby caves and how they relate to vibration during construction and operation. Partial or even total collapse of caves due to traffic vibration can occur, but is rare and depends on the local geology and depth of the cave – there are examples of roads that cross above caves, or run within them without noticeable morphological damage. Similar geotechnical considerations apply to the use of caves as natural bridges. In such situations, a case-by-case study should be made to assert that no damage to both caves and road occur. There is usually some degree of flexibility in planning linear structures and a diversion away from more fragile karst zones should be adopted, if at all possible, at an early stage.

Runoff from roads and railways is often contaminated and tends to be directed towards drains and ultimately sinking points in karst terrains, with the potential to contaminate springs and the water supply. This can be very serious if an accident results in a spill of dangerous chemicals. Chemical compounds behave in complex ways, depending on their density and composition. Cleaning contaminated karst soil and caves is often complex and costly. Due to the anisotropic characteristic of karst aquifers and generally fast infiltration rates, it is possible for part of a contamination plume to travel rapidly through conduits, emerging in high concentrations hours or days after input, while the remainder is stored in the epikarst and smaller channels so that it is still emerging in lower concentrations tens or hundreds of days after input.

Aerial (upper) and LIDAR (lower) images of dolines adjacent to a major highway near Divaca in Slovenia. Reproduced from the Atlas of the Environment, Environmental Agency of the Republic of Slovenia (EARS).

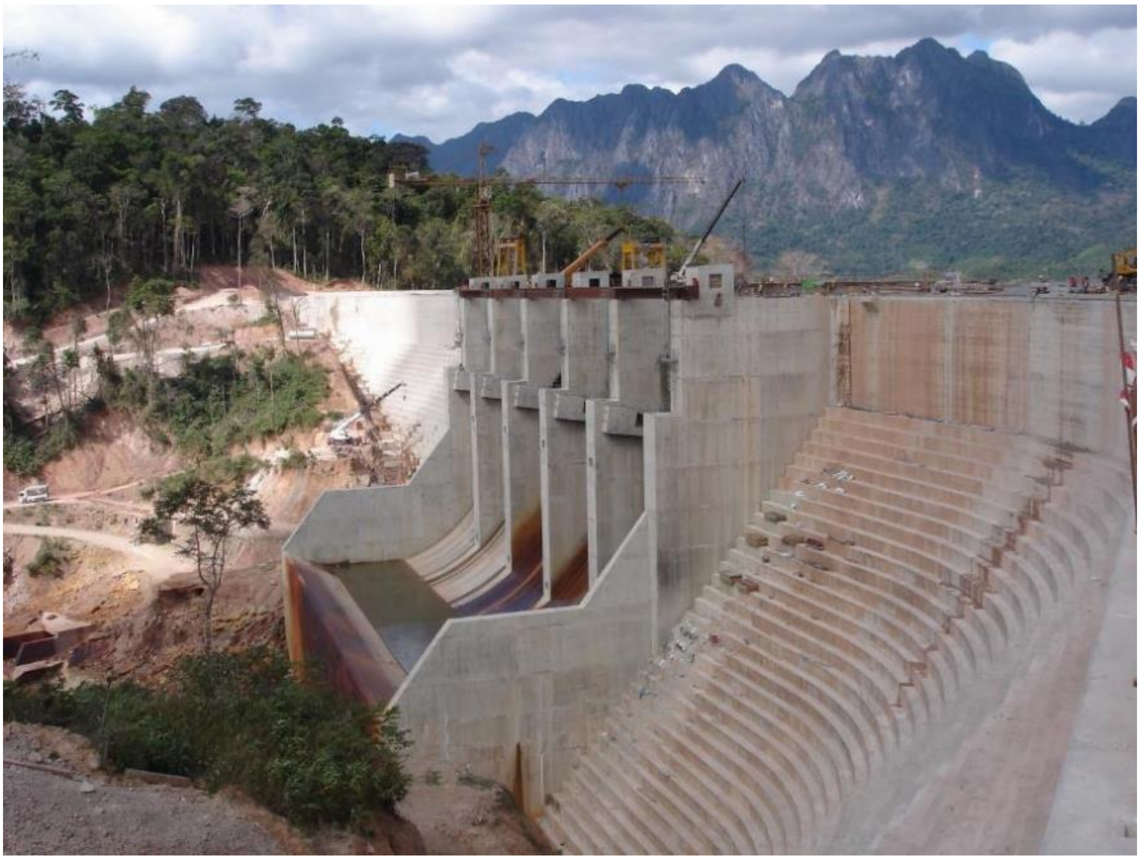
Karst can also affect linear structures, especially through the development of dolines or collapse into shallow caves. Geophysical studies can aid in locating voids and caves to be avoided, although cover-collapse sinkholes induced by water leakage from pipelines or loss along constructed drainage channels can form after those studies. There is less risk of impacts from electrical transmission lines, due to the wide spacing between towers (pylons) although there are cases of dolines forming close to pylons. Since around 2010, there has been a marked growth in the renewable energy market and particularly the generation of electricity using wind turbines. Although not strictly linear, the wind towers are commonly distributed in parallel rows and similar considerations apply. These heavy structures have some degree of locational flexibility and should be kept away from caves. Wind turbines can also kill bats, usually not from direct impact with the blades but by barotrauma, a sudden drop in air pressure that collapses bat lungs. Wind turbines should be located and operated in consultation with bat biologists to minimise harm to bat species in the area.

The diversion of a minor road around dolines, as shown above, is a simple and effective strategy, however, major highways are required to be as straight as possible. This photo shows a doline on the route of a motorway through Slovenia. The doline has been excavated and the outlet sealed prior to careful infilling with aggregate to reduce the risk of collapse. Photo by John Gunn.

The route of the same motorway in Slovenia runs over what was originally a sediment-filled unroofed cave. Co-operation between the constructors and the Karst Institute in Postojna ensured that the cave was carefully documented before being filled with aggregate and sealed to reduce the risk of collapse. Photo by John Gunn.

Dams and reservoirs

Water tends to flow underground in karst areas. Although stream sinks, dolines and springs are typical features, commonly there is limited drainage at the surface. Because of that, throughout history it has been critical to come up with ways to access and retain water for personal consumption or for agriculture. This has required engineering solutions such as drilling wells or placing pumping devices inside caves. A suitable alternative is the construction of dams or reservoirs, with the purpose of keeping water above ground and allowing for an easier control and distribution of flow. Karst rocks are natural targets for building dams where they usually represent low elevation areas in the landscape due to their high solubility. Furthermore, deeply incised valleys or canyons, sometimes resulting from cave collapse, are common landforms in many karst areas, and can provide attractive dam sites. Since antiquity, thousands of dams and reservoirs have been built in karst, especially in Europe and China.



Hydropower dam built in karst terrain, Laos. Photo by Terry Bolger.

Most dams and reservoirs in karst show some degree of leakage, which is normally accepted from the start, even when extensive and expensive grouting (i.e., filling voids with concrete or other impermeable material) is applied. This is due to the fact that geophysical techniques tend to lose resolution as depth increases, and present technology cannot reliably determine the size and location of the potential routes for leakage represented by conduits and caves. Additionally, any dam or reservoir generates a water surface at a higher elevation than the previously existing one, thereby increasing the 'hydraulic gradient'. This increased gradient will lead to increased velocity of groundwater flow, which operates in a turbulent mode, potentially removing sediments that once plugged existing passages. Another potential drawback is that this newly created gradient will increase the rates of dissolution, allowing for the enlargement of conduits during the lifespan of the dam, especially in evaporite areas where the rock is far more soluble than in carbonate karst. It is therefore not surprising that leakages tend to increase with time. In addition, leakage through fissures and cave passages downstream from the impoundment and the weight of the water column can induce the development of dolines, which can lead to a newly created zone of leakage, as well as result in small scale seismic shocks in the surrounding area. Additional environmental problems are related to hydraulic connections to other hydrographic basins and impediments to the movement of aquatic fauna, including water pollution. Once a dam has been rendered as uneconomic or too environmentally damaging, it is possible to have it removed, although this is an expensive and technically challenging enterprise, not without its own risks. It may prove less expensive than continued grouting, maintenance or other dam rehabilitation.

In some karst areas, dams are built to increase water storage in karst aquifers. The generally more effective and less problematic design places the dam upstream of the karst area, allowing sedimentation to occur where it does not occlude karst conduits and water is released at rates which allow all the flow to be absorbed into the aquifer. However, this design is not always possible. The alternative design places the dam in or at the downstream end of the karst, impounding the water directly over the karst. This method results in higher sedimentation of caves and conduits, and greater impacts on cave ecosystems not evolved for those hydrologic conditions. Additionally, a spill of pollutants into the impoundment will directly enter the aquifer, while in the upstream dam design there is more opportunity to trap and remove or remediate pollutants before they enter the groundwater. Neither design should be used in shallow, low groundwater storage karst aquifers where the additional water will quickly flow through and out of the aquifer. Some success has been seen in enhancing groundwater volume in large, deep, artesian karst aquifers, such as the Edwards Aquifer in Texas.

Industries

Industries come in various sizes, purposes and shapes. Processing plants associated with raw material derived from karst, such as cement or karst-embedded minerals, are commonly located close to the quarry or mine, which usually means they are built upon karst. Some common characteristics of these industries are 1) high water demand for mineral processing and cooling; 2) need for fossil fuels; and 3) disposal areas, which sometimes are much larger than the plant site, especially in mining areas where impurities or overburden are significant. These characteristics mean that some industries place a heavy toll upon the karst environment and require careful control of both liquid and atmospheric releases. Overpumping of groundwater can lead to land subsidence and sinkhole collapse. Air pollution involves not only harmful greenhouse gases but various particulates that can damage or impinge caves and karst features.

Those industries not associated with mineral extraction are commonly located closer to consumers or to transportation routes. Some modification of building or zoning codes is likely to be necessary because of the special vulnerabilities of karst. For instance, SUDS (Sustainable Drainage Schemes) commonly require developers to provide soakaways or infiltration ponds to avoid surcharging storm drainage. In karst areas, these have the potential to trigger sinkhole collapse and alter groundwater quantity and quality. Common to many industries is the large carbon footprint, which leads to impacts well beyond the karst regions.

Urban development

As discussed in the The special nature of karst environments and cave systems, concentrated recharge enters the karst through joints, dolines and sinks in natural conditions, though most recharge is diffuse and attenuated, especially where there is a cover of soil and vegetation, or superficial deposits. Urban areas over karst terrains represent an extreme example of changes to these conditions, scaling up some of the problems related to other types of development. Cities invariably profoundly alter the natural infiltration pattern by introducing large areas of impervious materials in the form of roofs, pavements and roads. These changes are likely to lead to concentrated runoff that is commonly turbid and contaminated with sediment, oil, grease, lead and other chemicals. Thus, there is a need for an efficient way to channel urban drainage off the karst, if possible, otherwise towards the bedrock and ideally improve water quality before it enters the karst. 'Storm water drainage wells' are critical in many cities, such as Bowling Green, Kentucky. Bowling Green is built on a rolling karst plain and is one among several cities that have a cave system underneath, increasing the potential for pollution to reach the karst aquifer. A lack of early zoning regulations allowed construction in dolines that are prone to flooding during large rain events. The infilling of other dolines has decreased their ability to drain and decreased floodwater storage. An inefficient natural drainage system leads to flooding in urban areas with large expanses of impervious materials – a common problem in some karst settings. The disposal of garbage and sewage is another key issue in karst areas, especially in less developed countries. Some cities lack any type of collective septic system, with sewage either disposed directly in drainage ditches or streams, dumped in homemade underground tanks or into fractures or sinkholes in the karst. These rudimentary systems neither filtrate nor attenuate the dispersal of contaminants and can pose a major threat to karst aquifers and cave ecosystems. In addition, impervious cover can alter the local hydrograph and create more rapid runoff, increasing stage heights in caves and sinkholes, and shorten the length of the storm response resulting in less water being available during dry periods.

Stormwater runoff from urban areas can be very toxic, with oil, grease, bacteria and other urban point and non-point source pollution. Bacteria levels in urban areas can also be very high due to exfiltration of septic sewer systems, domestic animal waste and urban wildlife, resulting in serious groundwater degradation.

Regarding solid wastes, specific areas termed 'landfills' are usually subject to strict planning conditions. These areas should be located, if at all possible, outside the karst, over impermeable rocks, and should be lined with impermeable barriers in order to prevent leakage. Unfortunately, in less-developed countries this seldom occurs, leading to contamination of soil and groundwater.

Atmospheric pollution due to vehicles, homes and industries is another type of environmental impact amplified in cities and can lead to acid rain and particulate dispersal.

Garbage transported by a cave stream in the Lagoa Santa Karst, Brazil. Photo by Luciana Alt.

Hazardous materials (HazMat) are commonly used and transported through karst, the releases of which have resulted in significant impacts to caves, karst and groundwater resources. The detection, monitoring and remediation of HazMat incidents is very difficult because of the following issues:

- Soils commonly provide little if any attenuation of contaminants.
- Rapid groundwater velocities (>1 km/day) in karst can transmit contamination over long distances before it can be contained and cleaned.
- Flow paths are poorly defined, so relationships between injection and discharge are commonly not known.
- Monitoring systems are difficult and expensive to install, sample and maintain.
- Monitoring systems may not be representative of the concentration or extent of contamination because of the anisotropic nature of groundwater flow in karst, nor representative of the concentration or extent of contamination.
- Limited number and availability of specialists in karst hydrogeology.
- Remediation methods may be difficult to install and operate and may have limited effectiveness.

Hazardous materials releases can originate from industrial accidents; intentional releases; through improper disposal of post-consumer waste (herbicides and pesticides) into dolines, sinking streams or septic systems; though the release of leaking underground storage tanks; through septic tanks and sewer systems; and oil and gas transmission lines. Petrol and other fuels along with solvents (from dry cleaning) are common materials that are released into the environment. In addition to contaminating groundwater, some of the vapours may be toxic or explosive if they accumulate and can result in explosive environments in caves, sewer systems and even houses and public buildings.

Emergency response to HazMat incidents in karst are very difficult and procedures should first include the protection of public safety followed by protection of the surface and subsurface. Remediation should, if possible, include containment and removal of any liquid and solid waste. Hazardous Materials should never be flushed into the surface as they may result in contamination of private and public water supplies, poisoning of cave biota, collection of explosive vapours in caves and buildings and degradation of water quality in springs impacting spring dependent ecosystems and downstream users. Investigation of the impact of a hazardous materials release in karst should be carried out by an experienced karst environmental professional.

Groundwater overpumping is common in urban areas. The combined extraction of thousands of public or private wells can have the same effect as a single large extraction scheme as is the case in mines and industries. Subsidence in urban settings is common in many areas of the world where groundwater is utilised and in Florida, USA, it is frequently included in home insurance packages. Sinkholes can occur due to leakage in water or sewage distribution pipes, leading to soil movement into fractures or the formation of voids in the soil, followed by collapse. The overpumping of groundwater in urban areas can also result in diminished or total loss of spring flow, which is an important resource for downstream users as well as spring dependent species.

An improperly built landfill in the Lagoa Santa Karst, Brazil. Photo by Luciana Alt.

Sinkhole flooding through improper management of storm water runoff can create issues in karst. The construction of homes and businesses in sinkholes, coupled with higher impervious cover associated with urbanisation, can result in rapid and longterm flooding. Improper regulation of land use practices can result in the plugging of sinkhole 'drains' with sediment, vegetation and garbage, and increase the height and duration of flooding.

Where cities occur at the edge of karst areas, urban growth is best directed to non-karst areas where development can usually occur more easily, less expensively and with fewer environmental impacts. Public education can aid such efforts. In Austin and San Antonio, Texas, residents concerned about their karst aquifers have voted to increase their taxes slightly to raise hundreds of millions of dollars over 20–30 years to buy large areas of karst that are set aside for aquifer and endangered species protection, and in some cases as parks.

Because most of the world’s population now lives in urban areas, cities have become key elements in the sustainability agenda. Several climate friendly initiatives and NBS (Nature Based Solutions) projects are aiming to mitigate the previously listed impacts in order to achieve a carbon neutral (or, ideally, negative) environment. This major recent shift should result in gains to the karst environment.

Development and infrastructure in protected areas

Protected areas can have various levels of 'protection', with some even allowing for the existence of industries or urban areas, provided some requirements are met, while others are pristine wilderness areas. Most of the more popular protected areas in karst have facilities such as visitor centres, restaurants and lodging for staff, scientists and tourists. The previously listed impacts also apply to these structures and should ideally be located away from the more fragile karst features. In the Gunung Mulu National Park, Sarawak, all facilities are a few kilometres from the caves. However, buildings close to or directly above caves and sinkholes exist in many protected areas. Care should be taken, as there have been numerous cases of environmental impacts from these structures, including one case of a direct connection between a toilet latrine and a cave stream that was proved by a water tracing experiment.

Structures inside caves are normally kept to a minimum. However, some popular protected areas have underground restaurants (including Carlsbad National Park and Mammoth Cave National Park, both in the USA), souvenir shops, toilets, amphitheatres for underground shows, elevators and railway tracks for trains and funiculars. All these structures involve some sort of environmental impact and should be installed only after a comprehensive environmental assessment. The protected area management plan should make clear whether these are justified as a means to provide comfort (or insulation from natural conditions) and visitor safety.

Conclusions

Karst and humans have coexisted since the first hominids emerged and a symbiotic association involving use and impact has occurred ever since. Very few caves or karst areas are entirely free of some sort of human modification, however, during the 21st century CE, there has been an increasing trend towards achieving a balance between preservation and impact. Achieving sustainability in highly populated karst areas is a difficult task but, increasingly, green infrastructure projects are making possible a move towards a more balanced use of environmental services.

Guidelines

(52) All feasibility studies for construction projects in karst areas should include careful examination of the planned location, a detailed environmental assessment and the size of a protective buffer zone. Where it is possible to move a project or urban development away from a karst area this can be an economic and environmentally positive decision.

(53) Protocols should be developed and applied to deal with the disposal of atmospheric, liquid and solid wastes generated during and following construction. These should extend to the whole of the karst critical zone, which includes the atmosphere, soil, epikarst and upper zone of karst aquifers.

(54) Building codes for karst must be enforced in the same ways as for earthquake or flood prone areas. Urban zoning in karst regions should take into consideration the specificities and fragilities inherent to the karst environment.

(55) A strong science-based legislative planning framework should be implemented at the local, regional and national levels.

(56) Educational initiatives should be put in practice, especially in less developed countries, in order to inform landowners or city dwellers of the fragile nature of karst terrains.

(57) In protected areas, infrastructure should be kept to a minimum and, if possible, be located away from caves and karst features.

(58) A proper protected area management plan should carefully weigh the pros and cons of building structures within the area, tending towards environment and visitor protection instead of providing unnecessary comfort. Large scale infrastructure projects in caves, unless indispensable, should be discouraged.

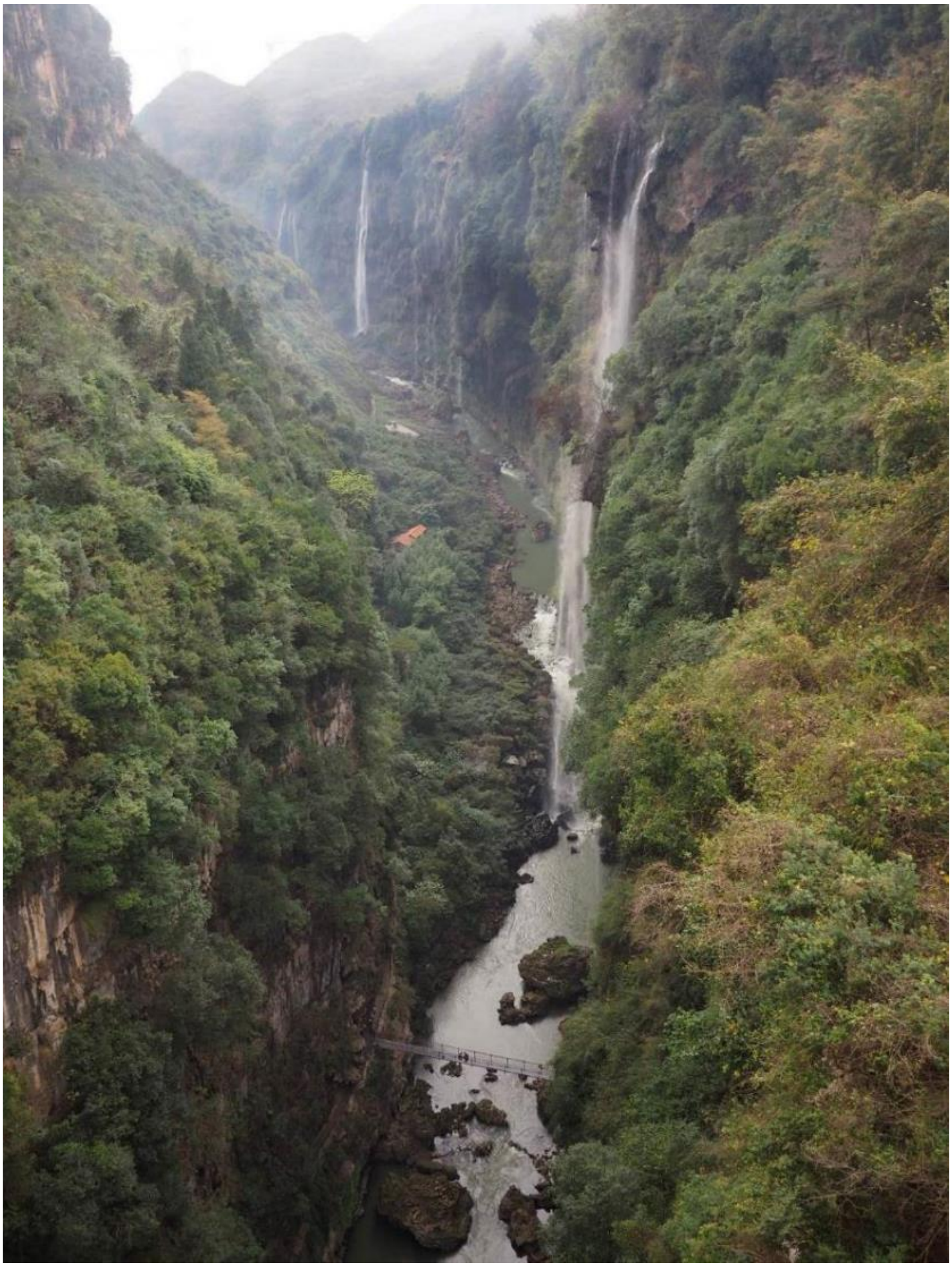
(59) Hazardous materials should be handled with great care and properly regulated to minimise releases. HazMat incident first responders should be trained in particular response methods for karst.

(60) Hazardous materials, be they gasoline or other fuels, solvents, sewage or other hazardous wastes should never be flushed into the subsurface. Groundwater investigation and remediation is extremely difficult and expensive. To the greatest extent possible, hazardous materials should be contained and removed on the surface. More detailed investigations of potential environmental impact should be carried out by experienced karst professionals.

Water supply

Access to water has played a major role in how humans have evolved through time. The Greeks, Minoans (Crete), Romans and many other societies learned how to deal with karst water resources, with many cities benefiting by being located close to karst springs either as a source of drinking water or for recreation, such as the thermal springs at Syracuse in Sicily, Italy, Nimes, France and Bath, UK. In the Americas, the Mayan culture largely evolved in a karst terrain in which water could only be accessed through collapse dolines known locally as cenotes. One of the main characteristics of karst terrains is that, due to the soluble nature of the rock, surface drainage is rare and water tends to flow underground, sometimes accessible through caves or, mostly frequently, only at springs. On the other hand, if present, the fertile soil (known as *terra rossa* in the Mediterranean) is suitable for agriculture. Agriculture and the growth of cities led to the widespread use of springs as reliable potable water sources in many parts of the world. Karst springs have been exploited since at least the 19th century CE for traditional liquor industries, such as bourbon whiskey in the USA and the Trappist beers in Belgium.

Based on the World Karst Aquifer Map (WOKAM) it has been estimated that 15.2% of the global ice-free continental surface is characterised by the presence of karstifiable carbonate rocks. As of 2020, there were about 1.2 billion people (16.5% of the global population) living in karst areas and around 700 million people were consuming water. This proportion is likely to increase, posing threats to the sustainable use of karst aquifers. Engineering solutions are commonly required to efficiently tap karst water supplies, including boreholes and reservoirs. Prior to 1986, over 17,000 dams were built in karst worldwide (excluding China), but many experienced significant leakage or never filled completely. These early engineering failures have led to the widespread belief that engineering in karst should 'expect the unexpected'. Besides the increase in population, the effects of climate changes are likely to exacerbate the dependence of humans on karst water, especially in some of the more densely populated karst areas in Asia, Middle East, Europe and North and Central America.



Perched karst springs in the Malinghe Gorge, Guizhou Province, China. Photo by John Gunn.

In karst terrains, infiltration tends to occur quickly through dolines or joints in the bedrock, though in areas with thick impermeable soil – commonly formed on superficial deposits such as loess or volcanic ash – lakes can form during rainfall events. Unlike in other rocks, groundwater flow can be very fast, occurring through conduits or caves. The depth of the water table varies depending on the region and in some regions there is no continuous surface as would be the case in permeable rocks. In flat-lying coastal areas, such as in Florida, or in the Yucatán, Mexico, groundwater can be just a few meters below ground, making access relatively easy.

However, in mountainous karst areas, there is commonly several hundred meters of vadose zone preventing easy access to groundwater and requiring ingenious solutions.

Overexploitation of karst waters occurs in many areas of the world, leading to lowered water levels. This has severe consequences for aquatic ecosystems in karst as springs and cave rivers may dry up. Lowering of several tens of meters has been observed in many karst areas, due to wells for both domestic water supply or industries. Karst groundwater overpumping can be point source, as in the case of mines and quarries that require large dewatering schemes in order to operate, but more commonly, water table lowering occurs through the combined volume of water pumped from several wells, either for urban consumption or for irrigation. Caves and voids below the water table (in the phreatic zone) are in part kept stable due to the support exerted by the water. Collapse can be triggered if this support is quickly removed due to pumping. A further impact associated with lowered water level occurs when the contact between soil and karst bedrock (known as the epikarst zone) is exposed above the water table. This leads to gravitational soil input into enlarged joints, generating unstable voids within the soil. The collapse of these voids is responsible for the dropout sinkholes (dolines) frequent in karst areas subject to intensive dewatering. The overpumping of freshwater resources in deserts, on islands or in coastal karst areas can also result in saltwater intrusion. Abandoned or improperly constructed or maintained water wells may also be a conduit for surface contamination to enter the subsurface and result in groundwater contamination.

Flooding occurs in some karst areas, commonly associated with urbanisation. The impermeable surfaces covering the ground in most cities means that natural infiltration is greatly reduced, being focused in a few runoff structures that drain towards the water table. The volume of runoff water is sometimes beyond the limit of these systems, resulting in widespread flooding, as frequently occurs in the urbanised karst areas of Kentucky. Flooding is likely to increase due to extreme wet events associated with climate change, posing additional challenges to karst areas, as both man-made runoff structures or cave conduits may not be able to cope with larger water volumes. Sinkholes may also flood, not from water flowing into them but from water rising from below, where large volumes of water are diverted into higher elevations sinkholes and transferred to lower elevations via caves and conduits.

With the exception of those karst areas with thick superficial deposits, recharge to karst, and the flow of water along karst conduits are commonly orders of magnitude more rapid than is the case in most groundwater systems. Thus, karst groundwater has limited natural attenuation and filtration, which means that any contamination from agricultural sources, such as nitrates, industries or accidental spills can readily reach the water table and spread quickly for long distances through conduits. This makes karst water contamination very complex to assess and mitigate. The contamination can adversely affect the ecosystem associated with the karst aquifers, threatening cave life. Improper septic tanks, or even the complete absence of any proper system for disposal of human waste, are common in many karst areas worldwide, increasing the potential for contamination by pathogens. Various chemicals and all sorts of garbage can find their way into karst aquifers. In some areas, the commonly held view of 'out of sight is out of mind' has led people to dump discarded material into dolines and caves. Some cave rivers in urban areas have been heavily polluted, being little more than 'natural' sewers and remarkable cleaning efforts have been required, such as in Hidden River Cave in Horse Cave and Lost River Cave in Bowling Green, both in Kentucky.

Forest clearance for agriculture and pastures or droughts exacerbated by climate change can remove the protective vegetation cover and trigger soil erosion. This may cause the plugging of doline bottoms or swallets, leading to flooding. An additional impact is the silting of surface and cave drainages, sometimes blocking passages and causing sediment aggradation inside caves. Catchment areas of caves worldwide are often improperly managed, thereby resulting in impacts on the hydrological cycle. Changes in land use above caves can trigger the infiltration of soil into percolation routes, affecting the colour and integrity of speleothems. This is especially critical for show caves, in which terrigenous sedimentation can change the colour of otherwise predominantly white cave speleothems.

Some of the environmental previously mentioned impacts occur due to point sourced short-lived episodes, such as the accidental spill of chemicals. But others such as contamination due to urbanisation or industries, or overpumping, can take place in the scale of years or decades. A further impact is associated with climate change, which paradoxically can affect the water budget of karst areas in opposite ways, exacerbating scarcity through droughts or increasing the potential for flooding due to record-breaking precipitation events. Both situations are now frequent worldwide. The karstified regions of Mexico, the Caribbean and south Florida, for example, are now subject to increased hurricane frequency, while drought prone areas are witnessing a decrease in cave drainage discharge. Climate change effects often occur superimposed on other factors, which serves to magnify their impacts. Rising ocean levels due to climate change have the potential to significantly impact karst aquifers as conduits provide pathways for sea water to flow inland thereby increasing groundwater salinity.

In addition, some karst areas extend across international boundaries, such as those in the Balkans and other parts of Europe and southeast Asia. Management of karst resources may require international cooperation to avoid conflicts over resource management in general and groundwater resources in particular.

Flood water discharged from the Marble Arch Cave, Fermanagh, UK, in the transboundary Cuilcagh Lakelands UNESCO Global Geopark. Photo by John Gunn.

Guidelines

(61) Define protection buffers for karst water sources, such as springs, wells and caves. In these protected areas, protocols should be established on agricultural practices, with proper use of fertilisers and controlled water pumping. Several schemes for the implementation of protection zones in springs have been proposed, but have only been widely applied in Europe and the USA.

(62) Educational initiatives should promote the awareness of both landowners and ordinary citizens in relation to the specificities of karst environments in order to avoid improper disposal of solid, sanitary and hazardous waste.

(63) A robust monitoring system should be established at major springs and selected wells in susceptible and highly utilised groundwater systems in karst. Long term, high resolution remote monitoring is now a possibility in many springs and should be implemented more widely.

(64) Countries should treat karst water as a fragile and finite resource, implementing laws to control and discipline water extraction, as well as allow appropriate funding for quick reaction in case of contamination. In particular, recommendations regarding the proper design and implementation of septic tanks and the location of landfills should be put into practice.

(65) Because little is known about the behaviour of many contaminants in karst environments, proper funding should be made available in order to advance the scientific understanding of this subject.

Managing karst in protected areas

Developing effective monitoring and mitigation

Monitoring Principles

Monitoring is an essential tool in managing and protecting caves and karst resources, especially in natural protected areas. Monitoring indicators and measurements are selected to provide reliable information on the current state of cave and karst resources that can be compared to a 'baseline' of conditions that existed when management commenced, and ideally before any human-induced changes occurred. Alternatively, for sites such as show caves where there is a long history of development, it may be possible to use a nearby undeveloped cave as the 'baseline'. In addition, many show caves were closed for varying periods during the 2020–2021 Covid-19 pandemic, and where monitoring continued using automated sensors, the data provide an approximation of natural conditions. Monitoring reveals changes over time in the condition of resources, both impacts and improvements, and thus the effectiveness of management actions. The results from ongoing monitoring can be used to inform management and to mitigate impacts (adaptive management).

Ideally, a monitoring program for caves and karst should be comprehensive and include abiotic resources, such as water, air and soil, and both geological and geomorphological features together with biotic resources, such as fauna, flora, habitats and ecosystems. However, protected area management agencies frequently have insufficient funding to support such a comprehensive evaluation program. Accordingly, monitoring efforts should be focused by prioritising natural resources based on their value or significance, their vulnerability or fragility, and the severity of actual or anticipated threats or impacts (either natural or from human activity). For caves, it is important to have an inventory of the main features, geolocated on a map of the cave (if one exists), to aid in identifying monitoring sites. This can be made an easier undertaking through GIS based techniques. Cave monitoring should include the area surrounding the cave, since impacts coming from outside can affect the dynamics of the cave system.

Once the resources to be monitored have been prioritised, appropriate indicators for monitoring need to be selected. Criteria for selecting indicators include whether it is relevant and scientifically credible, feasible, has a measurable low impact and is cost effective. Indicators may need to be supported by relevant environmental legislation in the event of legal proceedings. Monitoring indicators and methods should be selected so that they can be readily understood and performed by trained staff, wherever possible, in order to minimise the need for outside or specialist expertise. It is generally better to monitor an indicator which is simple and cheap to measure at many sites than one so complex and expensive that it can be afforded only at one or two sites. Measuring evaporation from many open petri dishes in a cave, for instance, may give a better picture of desiccation problems than a single hydrothermograph at one location.

Monitoring also requires consideration of replication, frequency and cost. Frequent monitoring of one key indicator is preferable to occasional monitoring of many indicators. Monitoring of key indicators or at key sites should be conducted as frequently as necessary to assess the effectiveness of management in minimising impacts. However, high frequency monitoring in fragile areas should be avoided, unless critically necessary, because this can generate impacts of its own. Automated monitoring, if feasible, should be prioritised. Protocols for monitoring each indicator should be developed.

Some Best Practices in Monitoring

Water quality and quantity

Stream-sinks, dolines that provide point-recharge (input sites) and springs and wells (output sites) should be used as water quality and quantity monitoring stations in karst areas. If resources permit, continuous and event based monitoring should be undertaken. Relatively inexpensive data loggers are available commercially to continuously measure key parameters, including water depth (which can be converted into discharge if a rating curve is established), temperature, dissolved oxygen, electrical conductance (a surrogate for total dissolved solids) and turbidity (a surrogate for suspended solids). Other parameters, such as nutrients, metals, hydrocarbons, organic pollutants and bacteria, are more suited to event-based monitoring as they commonly require specialist laboratories and are expensive to measure. Concentrations are commonly highest during low flow periods and this may present a particular threat to aquatic organisms, but it is during rainstorms and floods that the greatest load (concentration multiplied by discharge) of most pollutants and sediments is transported. A more general assessment of the condition of cave streams and surface water can be obtained by monitoring of biological indicators such as for water quality, for instance, the numbers of sensitive species with a low tolerance to pollution, such as aquatic macroinvertebrates (insects, worms, snails, crustaceans) or certain fish species.

Vegetation condition

Maintaining and improving the condition of native vegetation is often a priority for karst protected areas. Monitoring of vegetation condition is required for tracking progress towards management goals. The two main approaches to monitoring vegetation condition are site-based assessments and remote sensing methods. Site-based methods for forest mensuration and carbon accounting can be readily employed at a large number of sites, and local rangers and landholders can be trained to carry these out. Remote sensing is being employed increasingly for monitoring vegetation condition because of its advantage of offering broad scale, automated and repeatable methods. It is well-suited to detecting changes in vegetation condition. A number of metrics from plant ecology have remotely sensed proxy measures, such as the normalised difference red edge (NDRE) index, which provides a measure of photosynthetic activity. Shrub encroachment can also be estimated using persistent green cover measures.

Cave atmosphere

Climate and atmospheric monitoring in tourist caves is often accomplished using automatic weather stations with electronic sensors and dataloggers. Monitoring stations should be located at key or sensitive sites. Indicators to be measured include: barometric pressure, temperature, humidity, CO_2, airflow and evaporation. The measurement of radon concentration is commonly required as part of tourist cave health and safety regimes. The objective of these measurements should be to keep atmospheric conditions as close to the natural baseline values as possible, or to allow rapid recovery of conditions to baseline values after visitation.

Cave fauna

Where significant cave fauna exists, especially rare or endemic species, their presence and abundance should be monitored. Indicator species for monitoring may be troglobionts or stygobionts, which are often endemic species and perhaps the most vulnerable. However, 'keystone' species such as bats, swiftlets and cave crickets should also be considered as indicator species due to their importance in bringing food into the cave that other organisms depend on. Ideally, keystone species selected as indicators should be abundant and widely distributed in the cave(s). Certain troglobionts, such as Collembola, may be useful indicators of nutrient imbalances in a cave system.

Speleothems and sediments

Speleothems and cave sediments are often directly impacted by visitors to wild caves and in show caves may be impacted by lampenflora growth. Photomonitoring is an effective way of recording the condition of speleothems and revealing impacts. Speleothems and sediments should be selected for photomonitoring based on their being of particular scientific or aesthetic value or in a vulnerable location, such as close to the cave trail. Photomonitoring involves photographing selected speleothems or sediments from a fixed position and with fixed camera and light settings, so that photos can be precisely replicated and compared over time to assess visitor impacts. Photomonitoring should be conducted with a frequency appropriate to visitor numbers and their potential impact. A monitoring interval of one year may be appropriate for many show caves. New techniques such as laser scanning (LIDAR) show promise for use in monitoring. LIDAR creates a detailed three-dimensional image of a cave and this can be used as a baseline against which to detect alterations in speleothems or sediments, and other anthropic changes in the cave environment. The same approach can also be applied at the surface using aerial-borne LIDAR.

Climate change and extreme events

The effects of climate change are already manifest and will become profound for many karst areas. The increasing occurrence and nature of extreme events, such as floods, droughts and wildfires, present the most challenging climate change trend. The monitoring of meteorological and hydrological parameters, such as air temperature, rainfall, freshwater temperature, water discharge by rivers and springs, lake level and groundwater elevation, are priorities for detecting and responding to climate change. Gradual, long-term increases in air temperature and extreme temperature events (heat waves) are commonly lagged and damped in cave environments. In contrast, the impact of extreme hydrological events, such as floods and droughts, are rapidly transmitted from the surface to subterranean (cave) environments in karst hydrological systems. Monitoring of these parameters provides a basis for developing early warning systems for extreme events such as floods and wildfires. In addition, biological and ecological indicators of climate change may be identified. Examples include a change in timing of phenological events, such as leaf budburst and flowering in plants, as well as changes in the timing and range of migrations in animal species such as birds and bats.

Mitigation

Where monitoring reveals threats or impacts to key cave or karst resources, management action must be taken to mitigate further damage. For threats or impacts from human visitation, various strategies exist to achieve this, including limiting access to sensitive areas (zonation), reducing the number and frequency of visitors, marking preferred routes through wild caves, developing walkways with guardrails and requiring guides to accompany visitors.

Where damage has occurred to cave resources, good management requires that damaged features be restored as far as is practicable. There are a variety of methods for the restoration of cave passages and speleothems and for removing graffiti, lint and dust and lampenflora (see Show caves).

Often surface activities such as quarrying are translated into underground impacts. Rehabilitation of surface karst after quarrying can be costly and time consuming. The main rehabilitation issues include restoring underground drainage integrity, water quality, and the cave biology. A secondary objective should be to maintain a high degree of interconnected secondary porosity in the quarry for effective recharge, and to simulate as much as possible the original karst drainage and its vegetation cover.

Rehabilitated limestone quarry after twenty years, Tasmanian Wilderness World Heritage Property. During rehabilitation, the quarry was subdivided into a number of small closed drainage basins, each with a karst sink or infiltration zone as its focus. Each sink was protected by a filter structure, and areas under clay fans had additional structures installed to limit the movement of sediment after rain. Following this, hydromulching and careful revegetation will be carried out. Photo by David Gillieson.

Some basic principles for karst rehabilitation are:

- Maintain or restore natural systems and processes insofar as this is possible. If intervention is required, nature-based solutions that work in sympathy with natural processes are more environmentally sustainable and effective than engineering solutions that seek to control or halt natural processes. Maintaining or restoring natural flow regimes of rivers, streams and springs is critical for karst systems, for example. It is also crucial to restore the flow of percolation water and groundwater recharge where soil or sediments on karst have been compacted.
- Remove all sources of pollution, both surface and underground. This may involve regulating land use and activities upstream of caves or karst areas, the excavation and removal of contaminated sediments, the flushing of contaminated water or sediments from caves, or bioremediation using microorganisms or plants. This is a costly process, and often a portion of the cost will have to be borne by government agencies responsible for environmental management.
- Control active soil erosion and prevent sediment entry to the underground karst system. This may involve revegetation, stabilisation of steep slopes or construction of contour banks.

- Limit heavy use of groundwater (sometimes for agricultural purposes) in upstream areas as this lowers the water table and can decrease the discharge of underground rivers, affecting aquatic cave fauna.
- Encourage an active soil ecosystem. Invertebrates such as earthworms, ants and termites are effective at breaking down organic material, bioturbating the regolith and improving soil texture and nutrient status.
- Establish a stable vegetation cover, preferably of native perennial plants. Permanent vegetation is effective at controlling soil erosion, enhances soil biological activity and is aesthetically pleasing. However, be aware that vegetation also impacts soil carbon dioxide concentrations and uses water, thereby reducing recharge. Thus, there may be inadvertent impacts on speleothem growth.
- Monitor changes above and below ground. The success of rehabilitation can be gauged by regular sampling of karst waters. Sampling should be event-based to account for an increased transfer of sediments and solutes during rainstorms.
- Leave the site alone unless things go wrong. There is a great temptation to interfere with the rehabilitation when processes are slow. Revegetation should be assessed only after a minimum of two years, when sufficient establishment and growth has occurred. For many karst areas, especially where biological processes are limited by climate, the timeframe for rehabilitation may be measured in decades.

Guidelines

(66) Monitoring is an essential tool in managing and protecting caves and karst resources, especially in protected areas. The results from ongoing monitoring can be used to inform management and to mitigate impacts.

(67) Monitoring efforts should be focused by prioritising natural resources based on their value or significance, their vulnerability or fragility and the severity of actual or anticipated threats or impacts.

(68) Pollution of groundwater poses special problems in karst and should always be minimised and monitored. This monitoring should be event-based rather than at merely regular intervals, as concentrations of solutes and chemical pollutants are commonly highest during low flow periods, however, it is during rainstorms and floods that the greatest load of pollutants is transported through the karst system.

(69) Avoid high frequency monitoring in fragile areas, unless critically necessary, because this can generate impacts of its own. Automated monitoring, if feasible, should be prioritised.

(70) While recognising the non-renewable nature of many karst features, particularly within caves, good management demands that damaged features be restored as far as is practicable.

(71) As far as possible, natural systems and processes in karst areas should be maintained or restored. If intervention is required, the use of nature-based solutions is preferred, especially those which work in sympathy with natural processes and are more environmentally sustainable than engineering solutions.

Management planning for karst protected areas

Management planning for a protected area constitutes a key exercise in protected area management, helping to define and achieve an ideal condition, and ensuring that the financial, human and other resources of the protected area are utilised when addressing the priority management issues. Developing a management plan marks an important milestone in the planning and capacity building process, by involving the various government agencies and stakeholders with responsibilities and interests in the protected area and its immediate environs. Management plans should be succinct documents that identify the key features or values of the protected area, clearly establishing the management objectives to be met and indicating the actions to be implemented that will ensure that the conservation values of the protected area are protected.

In order for the management of the karst system to be appropriate and effective, management planning for karst protected areas must take into account the special nature of karst compared to other landscape types and ecosystems. This is more fully discussed in The special nature of karst environments and cave systems, with several key points outlined below:

- Karst integrity is intimately dependent upon maintaining the natural hydrological system. Thus, the need for total catchment management is vital for karst landscapes. The key issues in the management of all karst areas are the protection of dolines or fractured areas that provide point-recharge and water quality management of allogenic streams draining into karst. A hydrogeological map is a valuable tool for karst protected area management, highlighting the catchment areas critical for management and protection.

- Karst ecosystems are fragile – surface environmental conditions can be extreme (arid, calcareous), and in those areas where there are no superficial allogenic deposits, soils are typically shallow, rocky and easily eroded. The subterranean ecosystem is particularly delicate, being primarily dependent on energy flows transmitted from the surface by water, the quality of which is critically important to survival.
- Karst is unusually complex because it comprises both surface and subterranean features and values, and integrates surface and subterranean processes, both physical and biological. Because of the high degree of interconnectivity of karst ecosystems, direct impacts on a single element of the karst ecosystem can have serious indirect consequences for other elements or the entire karst ecosystem. Thus, a holistic approach is required for the protection of natural resources and biodiversity in karst.

Most management planning exercises work through a sequence of steps that give structure to the process and provide a logical approach. As the degree of protection and management required varies between different categories of protected areas, the management plan structure can be flexible in order to meet various needs. Privately owned protected areas may not involve outside parties in management planning, for example, or may not require a management plan at all. If time or resources do not allow for a full management plan to be developed, a simple, abbreviated document is better than no plan. A simple management plan will be easier, quicker and less expensive to develop and implement. Detail and complexity can evolve gradually as the management plan is updated over time, and as increased resources become available.

Protected area management planning steps (adapted from Thomas and Middleton, 2003)

1. *Pre-planning phase* – This phase defines what the planning process will achieve, how it will be carried out, the timing and budgetary considerations, and who will be involved. An inter-disciplinary and inclusive approach is advised to bring experts and stakeholders, including local communities, together to discuss the future management of the protected area.
2. *Data collection, background research and initial fieldwork* – Planning and management should be informed by reliable data. As a first step, collect existing and background information, as historical data and local knowledge can be invaluable. Next, conduct field inventories, surveys and research, as needed, to verify the existing information and to acquire any additional information required. Document the information collected in the form of a description of the protected area.

   For karst protected areas, guidance on information to collect is provided in following sections: Some values of karst and caves, The special nature of karst environments and cave systems, Recreational and adventure caving, Scientific research, Agriculture and forestry, Water supply, and Involvement of Indigenous peoples in karst management.
3. *Evaluating the information collected* – This step identifies the key features and exceptional values that must be protected and preserved to maintain the significance of the protected area. As an increasing emphasis is placed on including local people and other stakeholders in the planning process, it is important to have a mechanism through which the natural, cultural and socio-economic values they hold for the area can be identified and described. The development of a 'statement of significance' explains the importance of the protected area to society and places the protected area within its context at a regional, national and international level. The key features, exceptional values and statement of significance provide an important framework upon which the management plan should be based.

   For karst protected areas, guidance on identifying the key features and exceptional values is provided in the following sections: Some values of karst and caves, The special nature of karst environments and cave systems, Recreational and adventure caving, Scientific research, Agriculture and forestry, Water supply, and Involvement of Indigenous peoples in karst management.
4. *Identifying constraints, threats and opportunities* – Before defining the specific management objectives for the protected area, the constraints on its management should be identified, as should any major threats to the area's values. Some constraints are a function of the natural environment, such as the fragile and vulnerable nature of karst ecosystems. Threats to the protected area may be human-induced or natural, and may originate from within the protected area or from beyond its boundaries. Opportunities for positive change, remediation or restoration of the protected area should also be identified.

   For karst protected areas, guidance on identifying constraints, threats and opportunities is provided in the chapters: Some values of karst and caves, The special nature of karst environments and cave systems, Recreational and adventure caving, Scientific research, Agriculture and forestry, Water supply, and Developing effective monitoring and mitigation.
5. *Developing a management vision and objectives* – The management planning process should develop and articulate a vision statement that describes the ideal condition, state or appearance of the protected area in the future. Following on from the management vision, the objectives are more specific statements of intentions, setting out the conditions that management aims to achieve. The objectives should relate to the key features of the protected area, defining how these

will be conserved, and to other important areas of governance and management such as collaborative management arrangements, training and conservation awareness.

For karst protected areas, guidance on management vision and objectives is provided in the chapters: Some values of karst and caves, The special nature of karst environments and cave systems, Scales of management in karst areas, Recreational and adventure caving, Show caves, Agriculture and forestry, Water supply, Developing effective monitoring and mitigation, and Involvement of Indigenous peoples in karst management.

6. *Identifying and evaluating management options, including zoning* – With management objectives in place, the next step is to work out how the objectives will be achieved. As there are often several ways in which this can be done, the range of options for management actions should be identified, and the appropriate ones chosen. Zoning is a widely used tool for meeting management objectives. Zones identify areas where various strategies for management and use will best accomplish the objectives of the protected area. Zoning can be used to provide protection for critical habitats and sites such as stream sinks, caves, and springs. Classifying the caves in a karst protected area for different levels of protection and use is an effective form of zoning.

   For karst protected areas, guidance on management options is provided in the chapters: Some values of karst and caves, The special nature of karst environments and cave systems, Scales of management in karst areas, Recreational and adventure caving, Show caves, Agriculture and forestry, Water supply, Developing effective monitoring and mitigation, and Involvement of Indigenous peoples in karst management.

7. *Preparation of a draft management plan* – The integration of all of the above planning elements into a single document will result in a draft management plan. Although there is not a standardised format for management plans, they tend to contain certain standard elements. They start with an introduction to the protected area and a discussion of its importance and the factors affecting it, take the reader through the formulation of a vision for its future management and end with management actions outlining how this vision will be achieved, and how managers and others will assess the effectiveness of the plan towards the end of its life.

   A basic format for protected area management plans is provided in the chapter: Basic elements of a management plan.

8. *Public consultation on the draft management plan* – The opportunity for stakeholders and the general public to review the draft management plan and provide comment is a vital step in the management planning process. These people include local communities, local government officials, representatives of NGOs, commercial interests, user groups, interested individuals and the staff of the protected area itself. These groups will have a sense of ownership and a greater commitment to the management objectives and actions if they have the opportunity to be involved in the planning process. Levels of participation may vary among the various groups, from being informed and providing feedback to active involvement in collaborative management of the protected area.

   For karst protected areas, guidance on public consultation and community involvement is provided in the chapter: Involvement of Indigenous peoples in karst management.

9. *Revision of draft and production of the final management plan* – This step involves revising the draft management plan, taking into account the comments received from stakeholders and the public. All written comments received, and those recorded at public meetings, should be considered. It may be useful to prepare a report on the consultations to accompany the final plan, which will detail how the comments received have been taken into account and why some comments have not been used. This will help stakeholders and the public understand the final version of the plan and appreciate how the management actions included were selected.

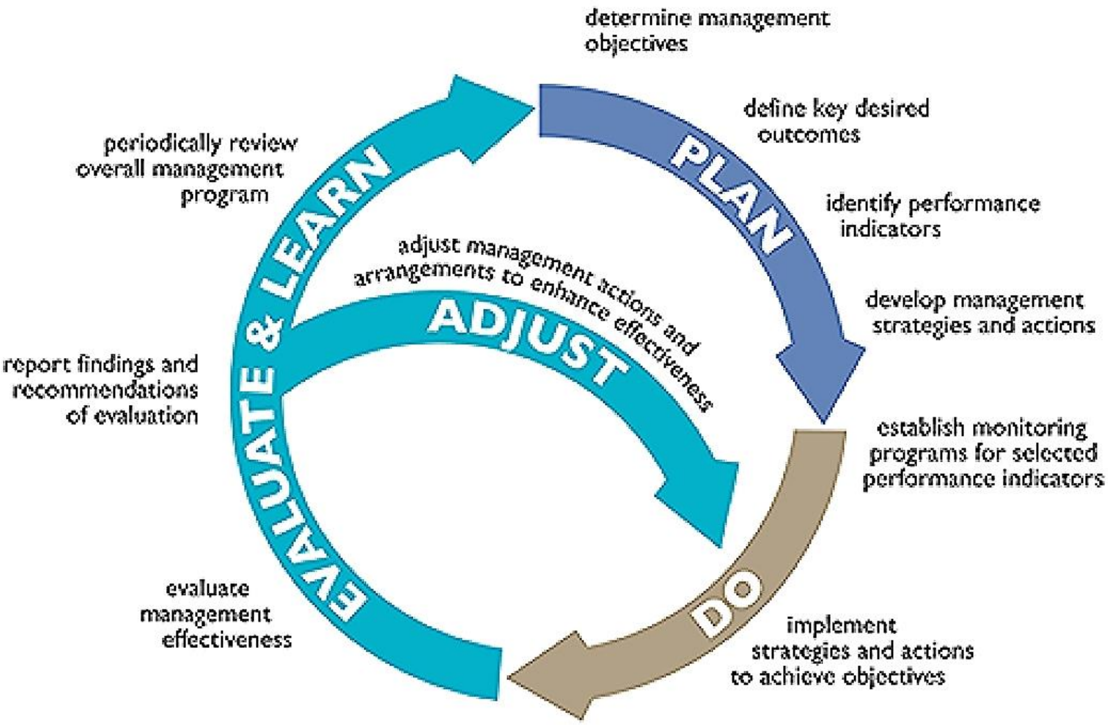
10. *Approval of the management plan* – This is a procedural step involving submission of the final plan for approval by the appropriate authority. Procedures will vary from country to country, but in most cases, there will be a formal process of adoption or approval to give authority to the plan.

11. *Implementation of the management plan* – The management plan sets out actions to be implemented to meet the objectives and attain the vision for the protected area. In many cases, the management plan provides the basis for preparing annual operational plans for the protected area. Where a collaborative management system is in place, the management plan should specify the roles and responsibilities of the various stakeholders in implementing the management actions.

12. *Monitoring and evaluation* – With implementation under way, monitoring and review will provide the feedback loop for management. The purposes of this step are 1) to identify whether the management plan is being implemented effectively and the objectives are being met, 2) to learn from observation of the impacts of management, and 3) to adapt the management actions accordingly. Where implementation runs into problems, monitoring and reviewal can be used to re-deploy resources and effort to improve implementation.

For karst protected areas, guidance on monitoring and review is provided in Developing effective monitoring and mitigation.

13. *Decision to review and update the management plan* – The final step in the planning process is to decide whether to either review or update the management plan. It is important to ensure that feedback from monitoring and evaluation is used to guide the development of the updated plan. It is recommended that management plans be updated at least every ten years. In many cases, the management plan will be time-limited by legislation, typically for five or ten years. Ideally, the decision to update a management plan is made with sufficient time as to allow the new plan to be in place before the old plan expires.



Schematic of the management process used in the Tasmanian Wilderness World Heritage Property, Australia.

Basic elements of a management plan

Executive summary – This summarises the important elements of the management plan in such a way that readers can quickly become acquainted with the plan without having to read all of the supporting detail. This is useful for high-level administrators who may not have time to read the entire document.

Introduction – This states the purpose and scope of the plan, and the basis on which the protected area was designated, its current status and the authority for plan development. It may contain some basic summary information about the protected area, such as its location, size, primary resources and values.

Description of the protected area – This summarises relevant descriptive information about the resources in and around the protected area, including:

- Historical – information about the site and its previous use and management.
- Biological – communities, habitats, flora and fauna.
- Physical – climate, hydrology, geology, geomorphology and soils.
- Cultural and Aesthetic – landscape features, archaeology and cultural associations.
- Socio-economic – demographics of local communities and their current use of natural resources from within the protected area.

Evaluation of the protected area – Identify the key features and exceptional values that must be protected and preserved to maintain the significance of the protected area:

- Outstanding examples of natural, cultural, scientific and recreational values, including significant caves and other karst features.
- Rare and endemic flora and fauna, both surface and subterranean.
- Archaeological, historical or cultural sites, both surface and subterranean.
- Areas and resources vital to local communities, both economically and culturally.
- Areas essential for protecting the integrity of the protected area as a whole, such as stream sinks, springs and catchment areas upstream of the protected area.

Analysis of constraints, threats and opportunities – An analysis of the constraints, threats and opportunities affecting the protected area and its conservation and management. Any current or previous impacts on the key features and values of the area should be stated, along with any other management considerations.

- Constraints – such as management of catchment areas upstream of the protected area boundary.
- Threats – such as the illegal hunting or collecting of rare or endemic animals and plants, breaking or theft of speleothems or cave minerals, looting or disturbance of archaeological or cultural sites, impacts from climate change and extreme events such as floods and wildfires.
- Opportunities – such as removing sources of pollution or the restoration of degraded habitats and natural processes.

Vision and objectives – The articulation of a vision statement which describes the ideal state or condition of the protected area in the future. This is followed by a set of objectives, which are specific statements outlining what is to be achieved by management in the timeframe of the plan. The objectives should relate to the key features of the protected area, defining how these will be conserved, and to other important areas of governance and management such as collaborative management arrangements, training and conservation awareness.

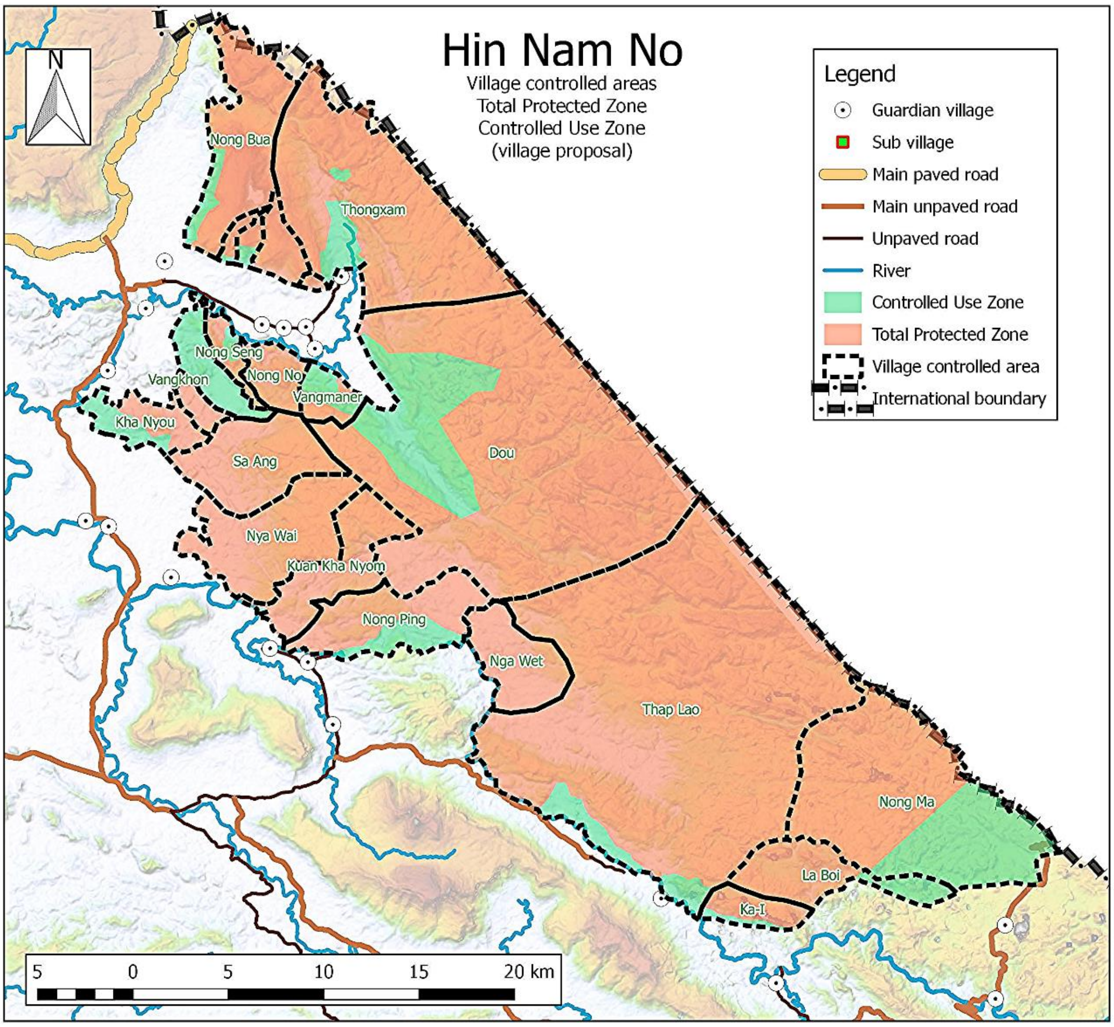
Zoning plan – A zoning plan with maps can be prepared to illustrate the boundaries, classification and management, as well as the activities allowed or prohibited for each zone. Many protected areas have a totally protected zone for nature conservation, visitor use zones for key attractions such as caves and scenic viewpoints, and a controlled use zone for the sustainable harvest of natural resources by local communities. Zoning can be used to provide protection for critical habitats and sites such as stream sinks, caves and springs, and for the recovery and restoration of degraded areas. Classifying the caves in a karst protected area for different levels of protection and use demonstrates an effective form of zoning. Zoning can be used within caves, with different passages having different levels of protection and access, depending on resource vulnerability and hazards.

Management actions – The specific actions to be carried out in order to achieve the objectives, with priority activities identified, and the roles and responsibilities of the various stakeholders. The details may be provided in a separate annual operational plan. Separate management plans may be developed for some actions or sites, such as for show caves or adventure caves, or for managing climate change and its impacts. These supporting plans may have the same basic elements as this example. Management actions may include:

- Biodiversity and geodiversity management.
- Catchment management.
- Cultural management.
- Restoration of degraded resources.
- Visitor management and associated infrastructure.
- Conservation awareness and outreach to schools.
- Monitoring.
- Scientific research.
- Exploration and survey of caves.

- Patrolling and law enforcement.
- Early warning systems, disaster response and rescue.
- Village livelihood development.
- Training and administration.

Monitoring and review – This section outlines how implementation of the management plan will be monitored, and when and how a review of the plan will be carried out. It should include the indicators against which the performance of the protected area will be measured. Monitoring efforts should be focused by prioritising natural resources based on their value or significance, their vulnerability or fragility and the severity of actual or anticipated threats or impacts.



Zoning for management purposes in karst, Hin Nam No National Park, Laos. Map by Ronny Dobbelsteijn.

Involvement of Indigenous peoples in karst management

Historically, protected areas established and managed by state bodies have been the primary mechanism for conserving the world's karst resources. However, experience has shown that conflicts commonly arise between those who live in or close to the protected area and the agencies tasked with managing those areas. Where most or all of the land in the protected area is owned by the state or public bodies, a greater degree of control over land use is possible, but where land is in private ownership this can be more difficult. In the developed world, local communities are commonly involved in the decision-making process, such as through locally elected representatives on management boards or through local consultations on contentious issues. In this respect, there is little difference between protected areas that contain karst and caves and areas that are protected for other values. However, during the 21st century CE, there has been increasing concern over the management of areas where there are a substantial number of Indigenous peoples.

The involvement of Indigenous peoples in World Heritage management is an increasing priority. Since 2005, the UNESCO World Heritage Operational Guidelines (paragraph 40) have promoted a "partnership approach to nomination, management and monitoring". These guidelines were revised and expanded in 2017, with the active involvement of Indigenous peoples in World Heritage management seen as essential and leading to best practice management. In 2015, the Word Heritage Committee established an *International Indigenous Peoples Forum on World Heritage*. This forum's aim is to elevate the role of Indigenous communities in the "identification, conservation and management of World Heritage properties" and is held every year, coinciding with the World Heritage Committee meeting. In 2018, UNESCO endorsed its *Policy on Engaging with Indigenous Peoples 201EX/6*. This important document includes the role of indigenous peoples in the conservation of natural and cultural heritage, and applies to all activities supported by UNESCO – not just World Heritage. Management planning should therefore take account of traditional or local governance systems used by Indigenous peoples. There may be existing land title under customary law which has persisted for centuries. This may not be formally recognised or even desired by the national government, but there is still an obligation to manage with this clearly in mind.

In this chapter, we provide four examples of protected area management on karst that have involved Indigenous peoples in the planning and management from the outset. Much has been learnt from this, and much still remains to be learnt as relationships develop and mature.

Hin Nam No National Park – Laos: Collaborative governance in action

Village guides with an inflatable boat used for cave tours, Hin Nam No National Park, Laos. Photo by Terry Bolger.

Hin Nam No is a protected karst area in central Laos, for which a nomination as a natural World Heritage site is being prepared. The area contains polygonal karst and totals 94,000 ha. The world's largest river cave, Xe Bang Fai, is an important feature of the area and is increasingly visited by adventure tourists. Due to limited financial and human resources, however, there is a lack of capacity and information to effectively manage and monitor the protected area. In response, a collaborative management (co-management) system has been established for Hin Nam No, in which local communities play an active role, and have more powers and responsibilities in the management of the natural resources on which they depend. Thus, there is a shared goal of biodiversity and geodiversity conservation, as well as poverty alleviation in and around Hin Nam No.

There are 18 'guardian' villages surrounding Hin Nam No, comprising about 8,000 people from seven ethnic groups. The development of successful collaborative management requires that both guardian villages and government agencies take on appropriate and clearly defined roles and responsibilities for conservation and protection.

Five 'building blocks' of the collaborative governance model in Hin Nam No National Park were identified and implemented:

1. *Governance assessment through participatory consultation* – a governance baseline assessment was implemented at village, district and province levels. The intention was to document the current status of the governance and management of Hin Nam No National Park. The results of the assessment subsequently led to the agreed interventions needed and became part of the Hin Nam No co-management plan.
2. *Setting up a collaborative management and governance structure* – There needs to be a legal and policy basis (national level) for establishing a collaborative management system. A Hin Nam No collaborative management committee was established. The primary stake- and rights-holders of the committee are the guardian villages (with customary rights) and protected area management authorities, with secondary stakeholders from concerned (district) government agencies, such as law enforcement, agriculture and tourism.

Protected Area staff and village guides at Hin Nam No National Park, Laos. Photo by Terry Bolger.

3. *Participatory land zonation based on traditional knowledge and customary rights* – the Hin Nam No National Park was zoned into areas for patrolling by each guardian village, based on used trails and customary rights of villages. Areas were also zoned as controlled use zones (CUZ) for the sustainable harvest of natural resources by guardian villages, based on areas traditionally used for this purpose. The CUZs comprise 14% of the area of Hin Nam No National Park. The remaining 86% of the Hin Nam No area is zoned at Totally Protected Zone for the conservation of nature.

4. *Collaborative management agreements* – developed between the Hin Nam No co-management committee and each guardian village, co-management agreements provide the rules for the use of natural resources from the CUZ, and including benefit-sharing arrangements with regard to patrolling, law enforcement and tourism.
5. *Involve local villagers in protected area management activities* – about 120 village rangers from the 18 guardian villages are paid for making regular trips into the protected area with Hin Nam No National Park staff to record wildlife sightings and threats and to become involved in patrolling for law enforcement. The village rangers assist exploration and research missions in Hin Nam No National Park, where their local knowledge of the karst, caves, forest and trails is invaluable. There are about 35 village ecotourism guides in several of the guardian villages with tourism activities. They guide tours to the Xe Bang Fai cave and several other caves, and lead walks in the spectacular karst landscape of Hin Nam No National Park.

Building blocks 3, 4 and 5 (above) are particularly strong components of the collaborative governance system – building upon the existing traditional resource management system rather than creating a new management system that undermines traditional customary approaches, inadvertently generating conflict. This homogeny with customary management systems encourages village participation, which is vital in sites with low government capacity and budgets.

There has been a 16% improvement in management effectiveness since co-management of Hin Nam No National Park was initiated in 2014, with major improvements in technical capacity and management skill. Further work on capacity enhancement, implementation of management plans and adaptive management and sustainable financing will be required to sustain this system of co-management, and thus protect and conserve the karst resources of Hin Nam No National Park.

Visitors on a trail and suspension bridge that is part of a karst circuit at the Phou Pha Marn protected area, Laos. Photo by Terry Bolger.

Haida Gwaii, British Columbia, Canada – Haida people: six ethical principles

Forestry is one of the most widespread land-use activities on the karst in British Columbia (BC) and is an example of why there continues to be a need for an improved understanding of karst. Caves were the prime focus in the protection of forested karst areas until the late 1990s, when the BC Ministry of Forests first announced a more systems-based approach to karst management. It is now widely accepted that any land-use or resource development activities that occur on or near karst require consideration of the environmental impacts on karst systems, the effects on karst aquifers and their catchments and the potential for karst-related geo-hazards.

An innovative project has engaged with traditional owners on Haida Gwaii. These continental islands, with the Gwaii Haanas NP, lie off the north-west coast of British Columbia, to the north of Vancouver Island. There is very extensive coniferous forested karst on the islands and caves with important scientific and cultural values. Forestry activities have taken place with impacts on the integrity of the karst and cave resources. The Haida Gwaii people have occupied these maritime lands since time immemorial and have built working relationships with government agencies at provincial and national levels. There is a clearly enunciated land use vision developed by the Haida Gwaii Council of Elders. This applies not only to the karst areas but the whole of Haida Gwaii, including the marine domain.

The six Haida ethics and values upon which this vision is built are listed below in Haida, then in English:

1. *Yahguudang or Yakguudang* – "Respect". Respect, for each other and all living things, is rooted in our culture. We take only what we need, we give thanks, and we acknowledge those who behave accordingly.
2. *Giid tll'juus* – "The world is as sharp as the edge of a knife". Balance is needed in our interactions with the natural world. If we aren't careful in everything we do, we can easily reach a point of no return. Our practices and those of others must be sustainable.
3. *Gina waadluxan gud ad kwaagiida* – "Everything depends on everything else". This principle is comparable to an integrated approach to management.
4. *Isda ad diigii isda* – "Giving and Receiving". Giving and receiving (reciprocity) is a respected practice in our culture, essential in our interactions with each other and the natural world. We continually give thanks to the natural world for the gifts that we receive.
5. *Gina k'aadang.nga gii uu tl' k'anguudang*– "Seeking Wise Counsel" Our elders teach us about traditional ways and how to work in harmony. Like the forest, the roots of our people are intertwined. Together, we consider new ideas and information in keeping with our culture, values and laws.
6. *'Laa guu ga kanhllns* – "Responsibility". We accept the responsibility passed on (to us) by our ancestors to manage and care for the sea and land. We will ensure that our heritage is passed on to future generations.

These six ethical principles and values are embodied in the working definition of Haida ecosystem-based management:

> *"Respect is the foundation of ecosystem-based management. It acknowledges that the land, sea, air and all living things, including the human community, are interconnected and that we have the responsibility to sustain and restore balance and harmony."*
>
> Gwaii Haanas Gina 'Waadluxan KilGuhlGa Land-Sea-People Management Plan, 2018.

There is resonance between these Haida Gwaii principles and best practice scientific management, as outlined in the table below.

Comparison of Haida and scientific principles for ecosystem-based management. From Council of the Haida Nation, 2007. Haida land use vision–Haida Gwaii yah'guudang (respecting Haida Gwaii).

Haida Principle	**Parallel Scientific Principle**	**Possible Applications**
Respect	Precautionary approach	Account for well-being of all species; prevent wasteful fisheries practices, e.g., bycatch.
Balance	Sustainable use over the long term	Ensure sustainable fisheries; consider ecological and socioeconomic information.
Interconnectedness (everything depends on everything else)	Integrated management	Link to land-use planning decisions; consider compatibility of marine activities and cumulative impact of developments.
Giving and receiving (reciprocity)	Equitable sharing	Appreciate the inherent value of all living things in planning; develop fair and equitable approaches to sharing limited resources.
Seeking wise counsel	Adaptive management Best information	Use traditional knowledge; improve understanding through research, education and monitoring.
Responsibility	Inclusive and participatory	Respect for Haida title and rights; ensure sufficient enforcement capacity.

Gunung Mulu WHA, Sarawak - Penan and Berawan peoples: awareness through education and training

A local Park Ranger at the upstream entrance of Deer Cave, Mulu, Photo by John Gunn.

The Gunung Mulu karst of northern Sarawak hosts some of the longest caves in south-east Asia. Mulu is located about 100 km east of Miri, a coastal city. The small town of Mulu is reached by daily air services and can also be reached by boats up the Baram and Tutoh rivers. Gunung Mulu NP has an area of 90,000 ha and most visitors concentrate on the southernmost karst, accessible from the park headquarters adjacent to the town. Over 90% of the park remains unvisited and is in pristine condition. Gunung Mulu NP was the subject of a Royal Geographical Society expedition in 1978 and the society subsequently wrote a management plan for the park in 1982. This was followed by a new management plan covering the period 1992–1995, and subsequent evaluations led to the World Heritage nomination. The park was inscribed on the World Heritage List in November 2000, and has subsequently become one of the most iconic national parks in south-east Asia, and a model for sustainable development that has been emulated elsewhere. The tourism resort firm Borsarmulu Sdn. Bhd. was tasked to draft a strategic management plan and to engage in a formal agreement with the government to manage and develop Mulu as an exemplary park and showcase for Sarawak and Malaysia. From 2001 onwards, tourism interest grew rapidly, as well as the international tourism profile. With it came the responsibility to pass the knowledge of Mulu on to the visitors, "to truly understand the importance", as the Gunung Mulu NP slogan reads.

One of the key requirements for ongoing World Heritage status is the need to provide correct, scientifically accurate information to visitors and to facilitate research. Coupled with this is the need to empower the local community and provide significant employment opportunities in this remote area. According to World Heritage principles and the management plan, local people should be trained as guides and interpreters. The local peoples already have a sense for the forest and amazing skills, but language disadvantages and a lack of education have prevailed, as far as the sciences are concerned. Gunung Mulu NP management has instituted a training scheme for training new guides and to refresh existing guides. This course is presented in modules covering the karst and cave aspects, as well as the forest, totally protected areas and associated ordinances, biodiversity and geodiversity. There is a special section dealing with the handling of clients and presenting a tour in both a show cave and an adventure setting. A course in basic accredited First Aid is normally part of the training.

The Gunung Mulu NP needs the local community and the community needs the park. Based on this mutual assumption, Mulu can be regarded as a success story, but it takes constant work. In 2021, Mulu businesses employed 97% of its workforce locally. These challenges to develop the community are met from an early age at the local school, Batu Bungan Primary, where the Educational and Research Liaison Officer, appointed by Mulu, has the privilege to work with the local children. For Gunung Mulu NP, the school is the common ground where all the locals of different ethnicities share a common goal – the children. Gunung Mulu NP regards this as a very practical way to raise awareness and interest for future generations of guides and other park workers.

Gunung Mulu NP lends itself to guided experiences for both soft and more extreme experiences. At present, the Park is serviced by 70 registered guides. Only twenty of these guides are employed directly. The remaining numbers are Agency or Tour operator guides, as well as a compliment of freelance guides. This means that a fair portion of the guides operating in Gunung Mulu NP are not on the park's payroll and are not under the jurisdiction of Borsarmulu, which often makes the operations challenging. These freelance guides can attend additional guide training sessions and do so episodically.

Local guides taking visitors to Sungei Lansat, Gunung Mulu National Park. Photo by John Gunn.

YUS Conservation Reserve, Papua New Guinea: Sustainable resource utilisation

The Yopno-Uruwa-Som Conservation Area (YUS CA) is located in the Saruwaged range in the Morobe province of Papua New Guinea (PNG). These high mountains (3,500 m plus) contain extensive karst areas developed on interbedded limestones and mudstones. There are numerous caves, termed *makna* in the Yupna and Nungan languages of the area. Caves have ritual significance, as well as being used as overnight shelters and sites where bats are hunted. Rural communities in PNG live a primarily subsistence lifestyle, relying on their natural resources and fertile soil as their ancestors did for generations before them. However, YUS community leaders have noticed worrying challenges previous generations never experienced: important resources are becoming scarce.

> *"Our hunters had to travel longer distances to find animals in the forest. Sometimes we had to hunt in areas belonging to other clans without their consent because we could not find enough in our traditional land to feed our families"*
>
> Matthew Tombe, Isan village, YUS.

Over 90% of PNG land is owned by Indigenous people, so local community support is vital for the protection of the YUS landscape. For over a decade, the Tree Kangaroo Conservation Program has been working with villages to sustainably manage this landscape and the resources upon which people and wildlife depend. To facilitate this, Karau Kuna has developed Community Land-Use Plans (LUP) with 50 villages to ensure a consensus on resource use that both takes into account people's welfare and their conservation priorities.

The YUS CA, gazetted in 2009, covers 76,000 ha of land and is composed of parcels of land that have been pledged by local landholders and clans in the area for biodiversity conservation. The conservation area was previously part of traditional hunting grounds that belong to five language groups. The pledged land is still under customary ownership, but logging and hunting are now technically illegal under the PNG Conservation Act (1978). Primary forest is the dominant ecosystem in the YUS landscape, covering 70% of the conservation area. Forests are dominant from sea level to 3,100 m and alpine grasslands are found above this elevation. The forests are critical habitat for Matschie's Tree-kangaroo, an endangered species, and other arboreal marsupials, as well as birds of paradise. These tropical forests are also an important carbon store. Other landcover types in YUS include frequently burnt anthropogenic grasslands, disturbed and secondary forests, and a mix of shifting and more intensive agriculture, shade coffee plantations, cocoa plantations and small-scale agroforestry plots.

The YUS Project seeks to conserve forest carbon, endemic biodiversity and ecosystem services, as well as to benefit local rural communities by providing income streams from sustainable activities that have low impact on traditional ways of life. Integrating sustainable development models that have multiple objectives is a major challenge in land use planning. At the outset, facilitated workshops were run in all clan territories to engage local landholders and find out their aspirations for the YUS CA. The zonation of the YUS CA into strict conservation reserve, and multiple use and village production zones was carried out by local clans and then mapped by local people using GPS and satellite imagery. In each clan territory, local people gained part-time work as conservation rangers and education officers. Shade coffee plantations have been established, with silvicultural training provided by a USA-based Fair Trade coffee marketer. This company also handles the processing and marketing of the YUS coffee as a distinctive 'tree kangaroo' brand. Agroforestry plots have been established in anthropogenic grasslands to increase the available timber resources for villagers. Other initiatives have improved school access and provided health care in the region, both issues identified in the workshops.

Uruwa valley in the Yopno-Uruwa-Som Conservation Area, from Wasaunon field camp. Alpine grassland on karst lies above upper montane forest, with an irregular lower boundary to the cleared areas around villages. Photo by David Gillieson.

A major initiative, funded by the German development bank KfW Bankengruppe, assessed carbon stocks using the REDD+ methodology (see Internet Resources) across the different land cover types in YUS. These assessments complemented vegetation mapping using remote sensing and field surveys for the region. This project provided representative carbon stocks by sampling primary forests across a broad environmental range. The project team also measured carbon stocks in secondary forest, shade coffee plantations, fallowed gardens and anthropogenic grasslands to inform future land-use management for increased carbon sequestration.

Because the REDD+ methodology stresses the inclusion of local people in the development, management and monitoring of carbon offset projects, the team devised a training module aimed at including local people in all carbon assessments as paid work. The collection of above ground biomass data and monitoring of forest carbon stocks by local people could serve to build baseline carbon inventories for carbon and to monitor forest carbon in existing REDD+ projects, as well as provide livelihoods for people forgoing forest exploitation. Livelihood landscapes, such as garden fallows, agroforestry systems or plantations can sequester and store significant amounts of carbon with sound land management. The integration of the Spatial Monitoring and Reporting Tool (SMART) methodology and tools enhances the ability of YUS Conservation Area Management Committee to receive and analyse data gathered by the YUS Rangers during monthly patrols, develop data-driven management responses to mitigate conservation threats and challenges, as well as highlight positive trends in the presence of key species.

Yopno-Uruwa-Som Conservation Area villagers and project mapping team making above ground carbon inventory. Photo by David Gillieson.

Guidelines

(72) For any protected area in which there are Indigenous peoples, there needs to be a legal and policy basis for establishing a collaborative management system, with a local management committee. The primary stake- and rights-holders of the committee are the local residents and protected area management authorities, with the secondary stakeholders being the relevant government agencies.

(73) For those karst protected areas in which there are Indigenous peoples, there needs to be a participatory land zonation based on traditional knowledge and customary rights. This should ideally include controlled use zones where some economic activities are practiced, and totally protected zones where nature conservation is the primary objective.

(74) Managers of parks in which there are Indigenous peoples should develop co-management agreements with local communities, written in appropriate language, such that each community has a clearly defined area for its management and economic activities.

(75) Managers of parks in which there are Indigenous peoples should involve local people in protected area management activities. Ranger activities and tourist guiding in caves and on karst walks provides significant employment opportunities and can help to empower the local community. Programmes to educate rangers and guides in the language likely to be used by the majority of visitors and in natural history are essential.

(76) A key requirement for best practice management is the need to provide correct, scientifically accurate information to visitors and to facilitate relevant, low-impact research.

Conclusions

Karst and caves are very special places, yet are often highly dependent upon wider influences over which very limited control is available to managers of land, water, and ecological resources, as well as protected area managers. Few karst areas are managed solely for nature conservation and many protected areas showcase their caves and karst scenery for tourism and recreation, performing an important role in encouraging public education about karst systems and their sensitivity to disturbance. Some jurisdictions also permit other activities with a social or economic purpose, or these activities may occur in that location by historical precedent. This situation requires careful consideration, to ensure that all activities within and around the protected karst area are managed in ways which are compatible with an overarching objective of nature conservation. Management authorities should identify karst areas not included within protected areas, and give consideration to safeguarding the values of these areas by such means as planning controls, programs of public education, heritage agreements or land use covenants.

Climate change has naturally occurred over the geological timescales within which karst systems have evolved. However, human intervention is now rapidly altering climate in ways that may radically affect natural karst processes. Management prescriptions must be flexible, recognise this reality and work to maximise the resilience of the system. The effects of high magnitude-low frequency events, such as floods, tsunamis, fires and earthquakes, must be addressed in management strategies at regional, local and site-specific scales. These events are becoming more frequent and are outstripping the ability of society to cope with their impacts.

Local factors will determine the specific pressures and opportunities which arise in each karst area. Thus, these guidelines seek to highlight options without being overly prescriptive, which would be impractical at the global scale. We necessarily focus on issues which differentiate karst from other styles of terrain, as opposed to more generic aspects of management which apply to all areas, karst or otherwise. It must be stressed that these guidelines must always be applied within a local context. This will include recognition of local biodiversity and geodiversity, plus sensitivity towards socio-economic and political factors.

There has been a marked shift globally in the underlying philosophy of natural resource management. Previous management regimes about protection were exclusionary and restrictive, with little regard for public opinion. We are now moving quite rapidly to more enlightened management regimes, where good relations with those living in or near vulnerable and valuable areas are seen as critical, and these areas are run using principles of adaptive management. The challenge for cave and karst managers will be to embrace the new paradigms while conserving what are essentially non-renewable resources.

This account and the guidelines will hopefully provide managers and planners with useful aids towards improving community awareness of karst and cave systems, and therefore increase opportunities to secure local acceptance of and involvement in improved protection and management. The guidelines should also assist in the preparation of more specific strategies or management plans at national, regional or site levels. In general, management agencies should seek to develop their expertise and capacity for karst management.

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Internet Resources

Australian Speleological Federation Minimal Impact Caving Codes in 1995, with the latest version (2010) available at *https://www.caves.org.au/administration/codes-and-standards*

British Cave Science Centre (free data source), available at https://www.cave-science.org.uk/

British Caving Association Minimal Impact Caving Guidelines, available at *https://british-caving.org.uk/our-work/cave-conservation/*

Canyoning code of conduct, available at www.icopro.org/pages/icopro-canyoneer-charter-104.html

Cave gates advice, available at https://digital.lib.usf.edu//content/SF/S0/05/10/33/00001/K26-00584-147-166.pdf

Climbers Pact, available at www.accessfund.org/learn/the-climbers-pact

Guide on digging to find new caves in protected areas (UK), available at https://thedca.org.uk/images/dca/publications/leaflets/Cave-Digging.pdf

Guidelines for applying protected area management categories, available at https://portals.iucn.org/library/node/30018

Information on training for cave instructors (UK), available at https://british-caving.org.uk/our-work/training/

International Union of Speleology (UIS) has a 'Code of Ethics for Cave Exploration, and Science in Foreign Countries', available at *https://uis-speleo.org/wp-content/uploads/2020/03/Code-of-Ethics-of-the-UIS-English-Language.pdf*

IUCN Protected Area categories, available at https://www.iucn.org/theme/protected-areas/about/protected-area-categories

Karst Management Handbook for British Columbia, available at https://www.for.gov.bc.ca/hfp/publications/00189/karst-mgmt-handbook-web.pdf

Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia, available at https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/nr-laws-policy/risc/karst_risc.pdf

Minimal Impact Cave Rescue Code, available at https://www.caves.org.au/administration/codes-and-standards/send/8-codes-and-standards/9-micrc2020

National Speleological Society (USA) has Minimum-Impact Caving Guidelines that are regularly updated, most recently in February 2021 to take into account the Covid pandemic, available at *https://caves.org/conservation/cavingcode.shtml*

New Zealand Department of Conservation has a 'Caving care code', available at *https://www.doc.govt.nz/parks-and-recreation/things-to-do/caving/caving-care-code/*

REDD+ Webb Platform, available at https://redd.unfccc.int/

Tasmanian Cave Access Policy, available at www.dpipwe.tas.gov.au/Documents/PWS%20Cave%20Access%20Policy.pdf

United States Fish and Wildlife Service, White-nose Syndrome Response Team, available at https://www.whitenosesyndrome.org

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Appendix 1: Karst and Caves in Non-carbonate Rocks

The karst landscape comprises a series of special landforms, including caves, which result chiefly from dissolution processes. Classically, karst was first studied and understood as occurring in carbonate rocks, such as limestone, dolomite and marble. These rocks are readily soluble in acidic water and generate the majority of caves and karst landscapes known on Earth. However, dissolutional processes can also operate in several other rock types, if adequate conditions are present. For instance, evaporite (gypsum and salt) rocks are more soluble than carbonates and thus may also develop karst landforms and caves. Various rocks that contain silica, such as quartzites and sandstone, can also develop karst landscapes. Although less soluble, dissolution in silica-rich rocks operates together with other non-chemical processes. Climate can play a major role in the occurrence of dissolutional caves in these rocks. Gypsum and salt are so soluble that they tend to be weathered away in humid climates. Thus, karst landforms in these evaporitic rocks tend to be present mostly in dry environments. On the other hand, silica is more soluble under warm climates and the most representative karst and caves in these rocks occur in the tropics.

Other caves are entirely created by mechanical (erosional) processes, with limited involvement of chemical agents. This is the case for sea or littoral caves generated by the impact of waves or caves in arid zones created by wind. A further category of caves includes the ones created together with the rock in which they are developed, such as lava tubes, or through tectonic processes (crevice caves). In summary, there are many ways to generate caves and karst and they are by no means restricted to carbonate rocks. It is thus essential to keep a holistic view when interpreting karst and caves.

Caves and karst in gypsum

Gypsum is more soluble than limestone and thus there is a potential for extensive karst landforms and caves to form. However, as a rock, gypsum is less common at the surface than carbonates and thus the worldwide distribution of gypsum caves and karst is more limited. In general, due to its high solubility, gypsum karst tends to be better preserved in dry climates. For example, Wood Buffalo National Park in Canada is a World Heritage Property that contains internationally significant gypsum karst in a dry boreal climate. Gypsum caves often occur in gypsum strata interbedded with other rocks and thus have limited or no outcrops, a situation known as 'interstratal karst'. Some of the longest caves in the world, such as the maze caves of Western Ukraine, developed in relatively thin layers of gypsum.

Relatively few gypsum caves have been adapted to mass tourism, the best known probably being the Sorbas caves in Spain. Gypsum caves and karst are, in many ways, more fragile than carbonates. The rock hardness is rather low, implying that it can easily be damaged or inscribed. Speleothems tend to be less common and are equally fragile. Because these caves occur mostly in arid zones, there is limited availability of drainage, resulting in a low energy environment that limits the regeneration of environmental impacts. The low mechanical stability of the gypsum rock results in relatively small cave passages. The longest gypsum caves usually comprise extensive mazes containing mostly small passages, such as the 257 km long Optymistychna cave in Ukraine. The collapse of caves within gypsum interstratal layers commonly result in sinkholes in the surface. The rapid development of passages in gypsum may also lead to engineering problems.

Caves and karst in salt

Salt is a highly soluble rock, much more than gypsum and limestone, and thus tends to quickly weather away. Salt caves and karst persists only in very arid environments. The hyperarid Atacama Desert in Chile, the desert area of Mount Sedom in Israel and Qeshm in Iran represent prime examples. Much of the considerations put forward for gypsum caves can also be applied to salt, although caves tend to be much smaller, with the longest one, Malham Cave in Israel, being approximately 10 km long. The rock is rather soft, cannot sustain large openings without collapsing and due to the dry climate lacks active drainage. Salt surfaces tend to be abrasive, although friable. Salt speleothems are often present but are very susceptible to damage. Being located in harsh and generally remote, little-populated environments contributes to the protection of these caves.

In Iran, some of the salt caves on Qeshm Island, which is a UNESCO Global Geopark, are opened to tourism, as are the ones located near San Pedro de Atacama, in Chile, although no adaptation or management plan has been implemented in the latter case. The extensive caves of Mount Sedom have been opened for adventure tourism and attract several hundred visitors each year.

Salt crystals in a cave, Mount Sedom, Israel. Photo by Rainer Straub.

Looking up a deep shaft formed in halite, Colonel Cave, Mount Sedom, Israel. Photo by Rainer Straub.

Caves and karst in silica-rich rocks

Silica-rich rocks, such as sandstone, quartzite, or even some igneous rocks such as granites, can be subject to dissolution. In these rocks, unlike carbonates, solubility increases with temperature and thus dissolution tends to be favoured under warm tropical climates. Due to the lower rates of dissolution, there needs to be long available timescales for the process to take place. Ancient landscapes which evolved under more stable tectonic conditions possess the appropriate conditions for the manifestation of this type of cave. Dissolutional caves in silica-rich rocks are widespread in many areas of South America (mostly in Brazil and Venezuela), Africa, Australia and Asia (India and Thailand). In South America, because the quartzites are old (Mid-Proterozoic) and chemically resistant, they tend to form high elevation ridges.

Caverna Aroe Jari, a sandstone cave in the Chapada dos Guimarães National Park, Brazil. Photo by Csaba Egri.

Several kilometre-long quartzite and sandstone caves have been mapped and studied, the largest being located in the Canaima National Park World Heritage Property of south-eastern Venezuela. In Brazil, these caves occur in several mountainous areas in eastern portion of the country, as well as in the lowland areas of the Amazon basin. These caves represent a new field of study and many areas remain to be adequately searched for caves. There are extensive sandstone karsts and caves in the Proterozoic sandstones of northern Australia, with the best-known being in the Purnululu National Park (a World Heritage Property), the Kimberley's of Western Australia and Kakadu National Park in the Northern Territory.

Quartzites and sandstones are rocks that display interlocking grains of quartz with or without a siliceous matrix. Conglomerates consisting of fragments of silica-rich rocks cemented by silica-rich matrix can also occur. Chemical alteration of these rocks initially disaggregates the grains, a process known as arenisation. As a result, the bedrock in these caves tend to be very friable. In the Ibitipoca State Park in south-eastern Brazil, the frequent passage of tourists in tighter spots in the 2.7 km long Bromélias Cave are known to have permanently altered the profile of some passages. Passage roof collapses, also caused by tourists inadvertently touching unstable portions of the cave, have led to the closure of this cave to tourists. The very fragile nature of cave walls appears to provide an incentive for carving inscriptions in the caves. Several sandstone caves show intensive abrasional graffiti.

Caves in silica-rich rocks can harbour a diverse troglobitic fauna; for example, there are two cave adapted species of catfish in the Chapada Diamantina National Park in north-eastern Brazil. These caves are largely devoid of the scenic speleothems common in carbonate rocks. However, many caves in South America regularly receive tourists, although none have, at present, been properly adapted to mass tourism with artificial lighting and planned routes. Cave management plans have been approved for a few caves, such as Saltire Cave in Diamantina, in south-eastern Brazil, and these documents tend to recognise the fragile nature of the caves and limit visitation to larger and more accessible portions of the caves. Quartzite and sandstone, being common rocks, have limited economic value. In addition, due to the poor sandy soil associated with this landscape and the frequent high-altitude location, human occupation is generally sparse. This limits human visitation and tends to favour cave preservation. Because of scenic views, the presence of waterfalls and the easiness of appropriation, many such areas have been converted to conservation units at the national, state and local levels.

Chamber of a thousand pillars in the Auyan tepui, a quartzite cave in the Canaima National Park World Heritage Property, Venezuela. Photo by Vittorio Grobu.

Caves in iron formations

Iron Formation caves were first recorded in the speleological literature in the 1960s, but have come into the spotlight since 2014 because of the remarkable expansion of iron mines due to increased worldwide demand. Presently, thousands of caves have been identified in iron formations, primarily in Brazil, but also in Australia and Africa. Although small in dimension, rarely surpassing 100 m in length, they host a remarkable cave fauna which inhabit not only the cave itself but also the interstitial rock porosity. Hundreds of new troglobitic species have recently been recorded.

The original, unweathered iron formation rock, known as Banded Iron Formation comprises alternate layers of silica and iron. Iron is even more chemically resistant than silica, so silica is leached first, leading to high grade iron ore. Cave genesis involves not only chemical processes, but also a complex interplay of geomicrobiological mechanisms in which iron reducing bacteria transforms insoluble Fe (III) into soluble Fe (II). Because these caves are commonly associated with high grade iron bodies, they face economic pressure from mining as there are usually no locational alternatives for iron extraction. Several iron formation areas with caves have been legally mined in Brazil, leading to substantial environmental compensation related to caves, such as new national parks, funding research, publications. However, due to the limited worldwide occurrence of this type of rock, and the fact that most iron areas have already been incorporated into mining plans, much of this compensation has been applied in caves in other rocks, leaving an imbalance in conservation units.

In Australia, a high-profile destruction of an archaeological site associated with an iron formation cave led to strong public protests. The Juukan Gorge site contained materials from human occupation dated to 46,000 years ago, but was totally destroyed by mining. There was a very strong reaction from the Traditional Owners, the Puutu Kunti Kurrama and Pinikura peoples, as well as environmental groups. A subsequent parliamentary enquiry highlighted the inadequacy of both state and federal heritage protection laws. Currently there are other sites in the region under threat from approved mining activities under this legislation.

Iron formation cave, Southern Espinhaço range, Brazil. Photo by Luciana Alt and Vitor Moura.

An iron formation cave showing canga (iron-rich conglomerate) in the roof and Banded Iron Formation (BIF) in the walls. Southern Espinhaço range, Brazil. Photo by Luciana Alt and Vitor Moura.

Iron formation caves are largely devoid of scenic speleothems and their inner configuration, comprising narrow passages, does not make them attractive candidates for tourism. Because of that they have been largely ignored by recreational cavers, though their importance has been highlighted through environmental consulting work. Only a few such caves are regularly visited and none have proper management plans and infrastructure. Some have been permanently preserved in Brazil, together with a protection buffer. Many of these caves, however, are located within mining sites, thus maintaining their integrity is challenging. Because little is known about these caves, especially the mobility and range of the cave fauna within porous rock, it is uncertain how to effectively protect their ecosystems.

Non-karstic caves

Many caves do not show the dominance of chemical processes in their genesis, but instead, are formed by various other geological agents and mechanisms. Due to the absence (or minor role) of dissolutional processes, these caves do not usually belong to a classical karst landscape. Typical karst features, such as dolines and karren, tend to be absent. Such landscapes are sometimes included under the somewhat dubious definition of 'pseudokarst'. Nevertheless, these non-karstic caves can have remarkable scientific and aesthetic values.

Some caves can be formed synchronously with the rock in which they are inserted. Such is the case of lava tubes, in which lava flowing downhill following an eruption has its outer limits in contact with the atmosphere or the basement, which solidify first, while the inner portion remains molten. Once the lava supply is exhausted, a long tube following the slope remains. These caves are common in active volcanic areas around the world and several have been adapted to tourism. In Lanzarote, Canary Islands, Spain, the Jameos de Água is one such lava tube opened to mass tourism. Lava tubes have intrinsic geological and biological value, and although many such caves are geologically young (generally with a maximum age of a few hundreds of thousands of years) they have been colonised and display a rich cave-adapted fauna. There are lava caves in eleven UNESCO Global Geoparks and four UNESCO World Heritage Properties: Galapagos, Ecuador; Rapa Nui, Chile; the Jeju Volcanic Island, South Korea; and Hawaii Volcanoes National Park, USA.

Layering of lava in Kazumura cave, Hawaii, USA. This complex cave with many entrances is located on the flank of Kilauea volcano, and is currently the longest (65.5km) and deepest (1100m) lava tube in the world. Photo by Philippe Crochet.

Caves can also occur in tufa, which is sometimes called travertine – although that term is best reserved for deposits from thermal water. Tufa and travertine are both rocks formed by precipitation of calcium carbonate, most commonly at or immediately downstream from springs. In common with lava caves, the caves in tufa are primary formed at the same time as the rock is deposited. Most are only a few metres in length and width, though some are longer. In Europe, there are at least seven tourist caves in tufa, the longest being Olga's Cave in Honau, Germany (170 m).

Caves opened mostly by tectonism, representing enlarged joints, occur in many areas around the world. These caves are sometimes referred to as crevice or fissure caves. They are more common in colder climates and tectonically active areas where dissolution is a minor process, such as on the Tibetan Plateau and in Greenland. These small caves may be of great biological interest and contain ancient speleothems. The deepest quartzite cave in the world, Centenário Cave in south-eastern Brazil, comprises deep joints opened to the surface at the top of a plateau, narrowing to impassable dimensions at a depth of 484 m.

Caves created by erosional processes are abundant everywhere in the world and can occur in several types of rocks. Numerous sea or littoral caves are generated by the erosional action of waves. Excellent examples occur on the coast of California, USA, and on the west coast of the Waitakere Ranges, New Zealand. One well known site is Fingal's Cave, off the coast of Scotland, visited by tourists for centuries and having inspired one of Mendelssohn's symphonies. Wind can generate caves, especially in 'soft' rocks such as sandstone in desert environments. Rounded shallow cavities of various sizes known as *tafoni* are often found in granites, sandstones and in some metamorphic rocks. They appear to be generated by a combination of mechanical, tectonic and chemical processes. The burrowing action of animals, including extinct armadillos, have created caves over 1 km long, as observed in the Brazilian Amazon basin. Erosion of outcrops by meandering rivers can result in caves, as can water flow within unconsolidated rocks or soil, which generate short lived and mostly small caves. They are known as pipes and tend to be rather common features, especially in arid zones. Good examples are associated with the 'Badlands' topography in the American West.

Sea caves in the Gennargentu National Park on the east coast of Sardinia, Italy. Photo by Csaba Egri.

A particular group of caves develop in ice. These glacier caves form mostly by melting and can be entirely enclosed by the ice or be located at the contact with the basement. Melting is faster during the summer, when these caves tend to experience higher rates of development. The heat needed to melt the ice may come from friction between the water and the ice or be due to external sources such as water warmed by volcanic processes. Ice caves can evolve quickly, especially under the rapidly changing climate, which is happening due to anthropogenic impacts. Many glacier caves, together with the glaciers in which they are located, are faced with a very uncertain future. Glacier caves have become a focus for adventure tourism in Iceland.

The chaotic arrangement of fallen blocks primarily found at the base of mountains (or associated with glaciers) can contain talus caves. This is another example of cave origin being synchronous with the deposit in which it lies. Many types of rock can generate talus caves, but they appear to be more common in igneous rocks subject to exfoliation. Talus caves in New Hampshire, USA, are popular tourist attractions. In Australia, the talus caves of Black Mountain, near Cooktown in northern Queensland, are extensive and host significant bat populations. Where deep weathering has occurred, boulder caves may form. These differ from talus caves in the sense that they are generated by subsurface weathering, with corestones or boulders surrounded by grus or weathering residue. Later removal of the weathering residue (regolith) between the boulders by sinking streams can produce extensive caves with amorphous silica speleothems and interesting biota. In Australia, there are documented granite boulder caves at Labertouche, Victoria, and Wyberba, Queensland. The Galicia region of northern Spain displays remarkable boulder caves of over 1 km in length.

In general, caves in rocks other than carbonates tend to be less well studied, although they may be equally important in geological and biological terms. Because they are often located in remote areas, are usually smaller and lack the elaborate aesthetic value provided by large chambers, underground rivers and especially speleothems, they are much less visited and less exposed to vandalism. Lava tubes are an exception to this as they are well documented globally, are regionally important for tourism and have an extensive scientific literature devoted to them.

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Appendix 2: Complete Guidelines

Some values of karst and caves

(1) Effective planning for karst regions demands a full appreciation of all their economic, scientific and human values, within the local cultural and political context.

(2) Managers should recognise that in karst catchments, surface actions result in direct or indirect impacts underground or further downstream.

(3) A good understanding of cave characteristics and their unique values is essential to the improved management of any karst area.

The special nature of karst environments and cave systems

(4) Safeguarding natural processes, especially the hydrological system, is fundamental to the protection and management of karst landscapes.

(5) Pre-eminent amongst karst processes is the cascade of carbon dioxide (CO_2) from low concentrations in the external atmosphere through greatly enhanced concentrations in the soil atmosphere to reduced concentrations in cave passages. Elevated soil carbon dioxide concentrations are a result of plant root respiration, microbial activity and healthy soil invertebrate fauna. This cascade must be maintained for the effective operation of karst solution processes.

(6) The need for total catchment management is more vital for karst landscapes than many other lithologies.

(7) There are now relatively few pristine karst landscapes and those that remain must be preserved and maintained as a high priority. Elsewhere, the focus must be on the correction of any negative impacts from past and present management practices.

Scales of management in karst areas

(8) A single management prescription applied to a complex karst hydrological system (or complex integrated cave system) is unlikely to adequately protect ongoing geomorphological and ecological processes across different parts of the system. Management planning must therefore take account of scale factors in the karst system.

(9) The biology of most caves is largely dependent on food sources brought in from the surface environment. The accession of food and energy from external sources is critical to the survival of viable populations of organisms, and the frequency and magnitude of energy inputs into the cave ecosystem is essential to the maintenance of organism populations.

(10) An individual karst hydrological system (or cave system) may contain several components or types of passage, from active stream passages to inactive, higher-level ones, as well as poorly connected relict passages. Each will require a different management prescription.

(11) Within a karst area, some sections may be highly sensitive to groundwater contaminants, while other areas may be less sensitive. Comprehensive land-use planning is therefore needed to protect karst groundwater resources.

Recreational and adventure caving

(12) An inventory of caves is desirable as a basis for management. Features of particular interest in each cave should be identified on a map.

(13) A risk assessment is desirable and should cover groups of caves, individual caves, or sections within a cave as appropriate to the site. The assessment should cover both the risk to human explorers and the risk that human explorers pose to the cave. The vulnerability of each type of feature should be assessed to facilitate identification of caves, or zones within caves that are suitable for particular uses.

(14) Management of caving impacts is best approached through a strategic planning process with stakeholder involvement. An appropriate approach is likely to require a combination of initiatives, of which access policy will always play a key role.

(15) Any instructor offering adventure caving should be able to provide evidence that they have received adequate training in safety aspects and in cave conservation.

(16) All cavers should be expected to be familiar with, and to follow, a minimal impact caving code (MICC). Where no national or regional MICC applies to a protected area, a specific code should be devised based on published codes.

(17) Digging, original exploration and research in caves within protected areas should be controlled either via specific agreements or by requiring permits.

(18) Protected area managers are recommended to draw up a plan that can be implemented should a caving accident occur in the area. The plan should be drawn up with involvement from the regional or national caving body and of state bodies responsible for accident and emergency situations, and should include guidelines to minimise the impact of the rescue on the cave and on the surface.

(19) It is totally inappropriate to allow any form of motorised transport into wild caves and wild caves should never be used for running events or for other types of sporting event.

Show caves

(20) Existing show caves should be managed to the highest possible standards and should work towards compliance with the ISCA Recommended Guidelines, as well as the guidelines provided here.

(21) A thorough study must be conducted to determine environmental and economic sustainability before developing a cave into a show cave.

(22) Safety must be the number one priority for every show cave.

(23) Determining the visitor carrying capacity of a specific show cave is the balance between providing a safe, informative and enjoyable cavern tour experience for visitors and minimising the impact on the cave environment, while achieving economic goals. All three – visitor experience, environmental impact and economic goals – of these factors must be considered.

(24) It is necessary to have a site plan that depicts the surface detail and the underground detail of a cave in order to analyse the potential impact surface works could have on a cave.

(25) Appropriate infrastructure at the entrance of a show cave is essential for maintaining the natural cave environment.

(26) In all new development, whether in existing show caves or at new sites, infrastructure needs should be carefully assessed, designed and installed, taking current best practices into consideration.

(27) The electric lighting network in a cave should preferably be divided into zones, thus enabling only those parts of the cave currently occupied by visitors to be lit effectively. The use of light should be minimised to only illuminate certain features and create an atmosphere that enhances visitor experience.

(28) Effective show cave management is underpinned by monitoring to allow adaptive site management. At a minimum, basic monitoring of the cave, fauna, climate and carbon dioxide concentrations should be carried out according to a monitoring schedule.

(29) Show cave managers should be competent in both the management of the business of the show cave and its environmental protection.

(30) The guides in any show cave play a very important role as the linkage between the cave and the visitor. It is essential that guides are properly trained in the values of the particular cave and in their interpretation for visitors.

(31) All show caves should develop high quality interpretive information to help the public better understand and appreciate the cave environment.

Adventure and tourism activities on surface karst

(32) Rugged and remote surface karst habitats may have unrecognised biodiversity and geodiversity values that should be surveyed and assessed as part of the decision-making process about whether to allow adventure and tourism activities on them, under what conditions and where.

(33) Infrastructure necessary to support surface karst activities should be designed and installed such that it has little impact on the karst, both visually and in terms of its integrity and, if necessary, can be readily removed in the future, returning the karst nearly to its natural condition.

Scientific research

(34) *All protected areas with caves and karst should develop policies for the management of research, which should only be permitted following receipt and approval of an application.*

(35) *Those wishing to undertake research in caves should be able to either demonstrate they are familiar with cave environments and the local Minimal Impact Caving Code, or that they are working with experienced cave scientists who will ensure adherence to the code.*

(36) *For those caves that have a management plan, there should be a section on research activities.*

(37) *All researchers working in caves or on karst whether inside or outside of protected areas are recommended to carefully evaluate their proposals, including a comparison of potential benefits with the risk of damage to the environment or cultural values.*

(38) *There should be an emphasis on minimal sampling methods for fauna, speleothems and sediments, and researchers should commit to publishing results in a form easily understood by the public as well as in academic media. Researchers should commit to equipment removal and site rehabilitation (if necessary) on the completion of the project.*

Agriculture and forestry

(39) *Agricultural activity has the potential to cause significant adverse impacts on karst geoecosystems. Protected area managers should (a) give particular attention to any proposed changes in land use and (b) provide guidance appropriate to the type of farming and the particular conditions on the ground in order to minimise impacts on water quantity and quality.*

(40) *With respect to land use, arable land requires careful soil management to minimise the erosive loss and alteration of soil properties such as aeration, aggregate stability and organic matter content, and to maintain a healthy soil biota. Pasture land should be managed to maintain the vegetation cover, giving particular attention to stocking levels. As dolines provide point recharge, they should be left in their natural state and should never be infilled or used for waste disposal.*

(41) *Wherever possible, buffer zones should be established around areas of concentrated recharge, such as sinking streams, dolines or other natural openings, as these are conduits for movement of contaminants and pollutants into the subsurface karst environment. On agricultural land, no ploughing should be allowed in the buffer zones and a complete vegetation cover should be maintained to filter out any sediment in runoff from ploughed land. In forests, the preservation and potential enhancement of the native vegetation in buffer zones is critical*

(42) *With respect to water quantity, controls should be placed on the amounts of groundwater extracted for irrigation. Rainwater harvesting should be employed to the fullest extent possible.*

(43) *With respect to water quality, pesticide and herbicide use should be discouraged unless absolutely necessary to control pests and weeds. Fertiliser usage should be reduced and, where possible, natural fertilisers should be used. Buffer zones around areas of concentrated recharge must be respected and chemical applications should not take place during times when the soils are at or close to saturation and there is a risk of overland flow washing chemicals into the karst.*

(44) *Prior to any logging or forestry activities on karst areas, a procedure is required to inventory and map the area, assess it for sensitivity and/or vulnerability, and develop suitable management prescriptions. Consideration should be given to a prior analysis of the type and magnitude of forestry activities within a specific karst catchment, plus follow up monitoring to ensure how prescriptions were implemented and how well sensitive karst areas were protected.*

(45) *Natural forests developed on karst terrains, including mature trees and overgrowth forests, must not be clear cut, logged, or subjected to any human impact. Instead, these forests should be rigorously protected by adequate conservation management, so that surface and underground karst environments continue to enjoy the benefits of their ecosystem services.*

(46) *In areas where native forest has been cleared and replaced by other species, managers should plan for the replacement of the non-native species by the type of forest which is best adapted to the ecological conditions of the site.*

Extractive industries

(47) *There should be a presumption against new mines or quarries in karst protected areas unless it can be shown that there is no alternative source for a mineral that is in short supply and of high economic or strategic value.*

(48) *Any proposal for a new mine or quarry in karst should be subject to a detailed environmental assessment that considers both features in and on the boundary of the area, as well as the potential for distant impacts via surface water and karst groundwater.*

(49) *The environmental assessment should describe and assess the value of cave and karst landforms and ecosystems. It should assess whether there are alternative sites for extraction where there would be less significant impacts. Where there are no alternative sites, then there should be a carefully designed buffer protection zone, wherever possible, around significant caves and karst features in order to protect the integrity of the cave ecosystem, as well as the continuity of hydrological processes.*

(50) *Where there is no alternative to destruction, features should be recorded and, where relevant, removed for scientific study – i.e., record and remove speleothem and sediment for palaeo-environmental study.*

(51) *Where development is permitted, there should be a well-designed environmental protection system, as well as a monitoring protocol to record conditions during operation and the efficacy of the protection system so changes can be made if needed. There should also be a detailed closure plan that includes appropriate restoration and long-term monitoring, including a bond paid in advance to assure funding for closure will be available.*

Development and infrastructure

(52) *All feasibility studies for construction projects in karst areas should include careful examination of the planned location, a detailed environmental assessment and the size of a protective buffer zone. Where it is possible to move a project or urban development away from a karst area this can be an economic and environmentally positive decision.*

(53) *Protocols should be developed and applied to deal with the disposal of atmospheric, liquid and solid wastes generated during and following construction. These should extend to the whole of the karst critical zone, which includes the atmosphere, soil, epikarst and upper zone of karst aquifers.*

(54) *Building codes for karst must be enforced in the same ways as for earthquake or flood prone areas. Urban zoning in karst regions should take into consideration the specificities and fragilities inherent to the karst environment.*

(55) *A strong science-based legislative planning framework should be implemented at the local, regional and national levels.*

(56) *Educational initiatives should be put in practice, especially in less developed countries, in order to inform landowners or city dwellers of the fragile nature of karst terrains.*

(57) *In protected areas, infrastructure should be kept to a minimum and, if possible, be located away from caves and karst features.*

(58) *A proper protected area management plan should carefully weigh the pros and cons of building structures within the area, tending towards environment and visitor protection instead of providing unnecessary comfort. Large scale infrastructure projects in caves, unless indispensable, should be discouraged.*

(59) *Hazardous materials should be handled with great care and properly regulated to minimise releases. HazMat incident first responders should be trained in particular response methods for karst.*

(60) *Hazardous materials, be they gasoline or other fuels, solvents, sewage or other hazardous wastes should never be flushed into the subsurface. Groundwater investigation and remediation is extremely difficult and expensive. To the greatest extent possible, hazardous materials should be contained and removed on the surface. More detailed investigations of potential environmental impact should be carried out by experienced karst professionals.*

Water supply

(61) *Define protection buffers for karst water sources, such as springs, wells and caves. In these protected areas, protocols should be established on agricultural practices, with proper use of fertilisers and controlled water pumping. Several schemes for the implementation of protection zones in springs have been proposed, but have only been widely applied in Europe and the USA.*

(62) *Educational initiatives should promote the awareness of both landowners and ordinary citizens in relation to the specificities of karst environments in order to avoid improper disposal of solid, sanitary and hazardous waste.*

(63) A robust monitoring system should be established at major springs and selected wells in susceptible and highly utilised groundwater systems in karst. Long term, high resolution remote monitoring is now a possibility in many springs and should be implemented more widely.

(64) Countries should treat karst water as a fragile and finite resource, implementing laws to control and discipline water extraction, as well as allow appropriate funding for quick reaction in case of contamination. In particular, recommendations regarding the proper design and implementation of septic tanks and the location of landfills should be put into practice.

(65) Because little is known about the behaviour of many contaminants in karst environments, proper funding should be made available in order to advance the scientific understanding of this subject.

Developing effective monitoring and mitigation

(66) Monitoring is an essential tool in managing and protecting caves and karst resources, especially in protected areas. The results from ongoing monitoring can be used to inform management and to mitigate impacts.

(67) Monitoring efforts should be focused by prioritising natural resources based on their value or significance, their vulnerability or fragility and the severity of actual or anticipated threats or impacts.

(68) Pollution of groundwater poses special problems in karst and should always be minimised and monitored. This monitoring should be event-based rather than at merely regular intervals, as concentrations of solutes and chemical pollutants are commonly highest during low flow periods, however, it is during rainstorms and floods that the greatest load of pollutants is transported through the karst system.

(69) Avoid high frequency monitoring in fragile areas, unless critically necessary, because this can generate impacts of its own. Automated monitoring, if feasible, should be prioritised.

(70) While recognising the non-renewable nature of many karst features, particularly within caves, good management demands that damaged features be restored as far as is practicable.

(71) As far as possible, natural systems and processes in karst areas should be maintained or restored. If intervention is required, the use of nature-based solutions is preferred, especially those which work in sympathy with natural processes and are more environmentally sustainable than engineering solutions.

Involvement of Indigenous peoples in karst management

(72) For any protected area in which there are Indigenous peoples, there needs to be a legal and policy basis for establishing a collaborative management system, with a local management committee. The primary stake- and rights-holders of the committee are the local residents and protected area management authorities, with the secondary stakeholders being the relevant government agencies.

(73) For those karst protected areas in which there are Indigenous peoples, there needs to be a participatory land zonation based on traditional knowledge and customary rights. This should ideally include controlled use zones where some economic activities are practiced, and totally protected zones where nature conservation is the primary objective.

(74) Managers of parks in which there are Indigenous peoples should develop co-management agreements with local communities, written in appropriate language, such that each community has a clearly defined area for its management and economic activities.

(75) Managers of parks in which there are Indigenous peoples should involve local people in protected area management activities. Ranger activities and tourist guiding in caves and on karst walks provides significant employment opportunities and can help to empower the local community. Programmes to educate rangers and guides in the language likely to be used by the majority of visitors and in natural history are essential.

(76) A key requirement for best practice management is the need to provide correct, scientifically accurate information to visitors and to facilitate relevant, low-impact research.